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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

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Acronyms and Abbreviations

ADB	Asian Development Bank
AQSIQ	General Administration of Quality Supervision, Inspection and Quarantine of China
bcm	billion cubic meters
Btu	British thermal unit
CHP	combined heat and power
CHUEE	China Utility-Based Energy Efficiency Finance Program
CNOOC	China National Offshore Oil Corporation
CNPC	China National Petroleum Corporation
CNY	Currency of China Yuan
DOE	U.S. Department of Energy
FYP	Five-Year Plan (China)
GDP	Gross Domestic Product
GEF	Global Environmental Facility
GHG	Greenhouse Gas
IFC	International Finance Corporation
LBNL	Lawrence Berkeley National Laboratory
LNG	liquefied petroleum gas
M&V	Measurement and Verification
MEP	Ministry of Environmental Protection
MIIT	Ministry of Industry and Information Technology
MMBtu	1 million Btu
MOF	Ministry of Finance (China)
MOHURD	Ministry of Housing and Urban-Rural Development
NAESCO	National Association of Energy Service Companies
NDRC	National Development & Reform Commission (China)
NEA	National Energy Administration
NGOA	National Government Offices Administration
t/h	tonnes per hour in steam production
tce	ton of coal equivalent
USD	U.S. dollar
WB	World Bank

Executive Summary

Introduction

China's industrial boiler systems consume 700 million tons of coal annually, accounting for 18% of the nation's total coal consumption. Together these boiler systems are one of the major sources of China's greenhouse gas (GHG) emissions, producing approximately 1.3 gigatons (Gt) of carbon dioxide (CO_2) annually. These boiler systems are also responsible for 33% and 27% of total soot and sulfur dioxide (SO_2) emissions in China, respectively, making a substantial contribution to China's local environmental degradation. The Chinese government - at both the national and local level - is taking actions to mitigate the significant greenhouse gas (GHG) emissions and air pollution related to the country's extensive use of coal-fired industrial boilers. The United States and China are pursuing a collaborative effort under the U.S.-China Climate Change Working Group to conduct a comprehensive assessment of China's coal-fired industrial boilers and to develop an implementation roadmap that will improve industrial boiler efficiency and maximize fuel-switching opportunities. Two Chinese cities – Ningbo and Xi'an – have been selected for the assessment. These cities represent coastal areas with access to liquefied natural gas (LNG) imports and inland regions with access to interprovincial natural gas pipelines, respectively.

Comprehensive Overview of China's Coal-Fired Boilers, Potential Resources for Switching Away from Coal, and Relevant Policies

As of the end of 2012, there were 467,000 registered coal-fired industrial boilers in China with a total annual capacity to produce 1.78 million tons of steam. The majority of these industrial boilers is coal-fired. China's industrial boilers are characterized as small in size with an average capacity of about 3.8 tons/hour, dominated by the use of raw coal, operated at relatively lower efficiency without automated controls, and lacking advanced pollution controls. Although coal is the dominant fuel used by industrial boilers to produce heat and steam for industrial operations, China has cleaner resources, namely natural gas and biomass, which can be used instead of coal.

Natural gas is the primary fuel-switching option for industrial boilers. China's government is increasing natural gas use by seeking additional supply and building more pipelines with the aim to increase the share of natural gas in China's primary energy consumption from 6% in 2013 to 8% by 2015 and to 10% by 2020. There are some recent changes in the natural gas regulations and in the market in China that could expand the horizon for wider use of natural gas. For example, the Chinese government has made attempts to reform industrial gas pricing. China's National Development & Reform Commission (NDRC) has urged large natural gas users to negotiate gas prices directly with suppliers, instead of using government guide prices. NDRC has also announced that they will merge the two tiers of natural gas prices for non-residential users by raising the lower band (the "existing supply") and significantly cutting the higher band (the "incremental tier") that is linked to imported fuel oil prices. The net impact of this change is an overall 5% reduction in natural gas prices for non-residential users. Further, China is developing a domestic gas-trading hub to facilitate natural gas spot trades. In addition, falling LNG costs abroad, high domestic gas prices in China, and underutilized LNG terminals have led China's independent players to request state-owned LNG importers to import LNG on their behalf, accommodate third-party cargoes, or even grant them direct access to state-owned importers' receiving terminals (Platts, 2015).

Biomass is another alternative resource that can be considered for fuel switching in China's industrial boilers. In 2010, biomass supplied 24 million tons of coal equivalent (Mtce) of energy, meeting about 1% of China's primary energy needs. Although the Chinese government has launched demonstration programs that use biomass boilers to provide heat, biomass is primarily used for increasing the nation's installed capacity of biomass-generated electricity from 5.5 GW in 2010 to 13 GW by 2015.

Since 2007, a series of policy documents related to industrial boilers, including a national *Boiler Action Plan,* have been issued by various Chinese Ministries. These policy directives set specific targets and requirements for reducing energy use and controlling pollution from coal-fired industrial boilers. These policies also encourage solutions such as fuel switching from coal to alternative fuels and developing natural gas based distributed energy (DE) and combined heat and power (CHP) as alternatives to coal-fired boilers.

Techno-economic Assessment of Alternatives to Industrial Boilers

A comprehensive techno-economic analysis is conducted to assess the cost-effectiveness of various alternatives to coal-fired industrial boilers. The analysis utilizes case study information from the cities of Ningbo and Xi'an and focuses on three options that align with coal-fired boiler policies[1] mandated by national and local governments of the two cities.

Option 1: Fuel switch by replacing coal-fired boilers with boilers fueled by natural gas, biomass, oil, and electricity

This option evaluated the costs-effectiveness of replacing a small-sized coal-fired boiler (10 ton/hour capacity in this study) with a boiler that uses other resources (including natural gas, heavy oil, biomass, and electricity) assuming that each system would produce 30,000 tons of saturated steam per year at 1.0 megapascal (MPa). Key findings include:

- Among the studied fuel switching options, the fixed cost of these units does not differ much but operational costs differ significantly due to distinctive fuel prices, which are much higher than fixed equipment costs. Annual operational costs of coal-fired boilers are significantly lower than other types of boilers.
- Natural gas can be a viable option for fuel switching if its price can be kept competitive. For Xi'an, due to relatively lower natural gas price, the operational cost of natural gas-fired boilers are lower than biomass, heavy oil, and electric boilers. For Ningbo, however, due to its relatively high natural gas price, the operational cost of natural gas-fired boilers is higher than biomass, but lower than oil and electric boilers.
- If simply converting chain-grate stoker boilers to natural gas-fired boilers, the operation costs in Xi'an and Ningbo would increase by 139% and 198%, respectively. Thus, the current high natural gas price is the most important barrier to replacing coal with natural gas in small industrial coal-fired boilers.

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[1] Under central government mandates and local plans, coal-fired boilers of smaller than 20 ton/hour (steam generation capacity, or t/h) are required to be eliminated while boilers of 20 t/h or above need to be retrofitted for improving efficiency and controlling pollution.

- Electric boilers are the most costly option mainly due to the energy conversion losses (from thermal energy to electricity, and then from electricity to thermal energy) and higher electricity prices for industrial customers in China.
- Although electric boilers are not an economical option for a complete replacement of coal-fired boilers based on the current higher electricity rates for industrial customers, they can be used as a supplementary energy storage option that can supply or store heat during electricity grid off-peak hours when electricity is inexpensive and the use of excess power (from sources like wind) is desirable. Using Xi'an as an example, for instance, if the electricity price went down to below 0.1 RMB/kWh and 0.25 RMB/kWh, using an electric boiler would be more economical than operating a coal-fired boiler and a natural gas-fueled boiler, respectively.
- Biomass could be a good fuel switching option but the Chinese government's focus on promoting biomass-based electrification can make it hard to bring industrial use of biomass boilers to scale.
- Among boiler fuels, natural gas-fired boilers have a better cost efficiency compared to other alternative fuels. For the same fuel, the lower the fuel price, the higher the cost-efficiency of pollution reduction. For example, Xi'an has lower natural gas price than Ningbo; thus, the cost efficiency of using natural gas to replace coal to reduce pollution is much better than Ningbo. Therefore, lowering natural gas price is beneficial to promote natural gas boilers and reduce pollution. Electric boilers are quite low in cost-efficiency of pollution reduction due to their high operation costs even though they do not directly emit pollution.

Option 2: Retrofitting existing boilers to improve energy efficiency

In the national *Boiler Action Plan*, China's government encourages industrial facilities pursuing cost-effective retrofits to improve boiler energy efficiency for larger size boilers in addition to eliminating small-size boilers. Therefore, the second option evaluated various retrofit measures for boiler size of 20 t/h, assuming an annual production of saturated steam of 50,000 ton at 1.0 MPa pressure based on typical operation conditions in the assessed facilities. The nine retrofit options that were evaluated are either listed in the National Development and Reform Commission (NDRC)'s *Recommended Technologies Catalogue* or recommended by the experts in the field. The net cost[2] per unit of coal saved and coal-saving potential were calculated to create an energy-saving cost curve for various retrofit measures to determine these measures' economic and technical potential for energy efficiency improvement. To understand how fuel prices affect the cost-effectiveness of these measures, two cost curves under different coal prices were constructed (i.e., Ningbo vs. Xi'an). Of the nine energy efficiency measures, five and six are cost effective in Xi'an and Ningbo, respectively. The assessment shows that fuel prices play an important role in affecting the economic potential of these measures. Compared the results of the two cities, adopting these measures could create more cost savings in Ningbo than in Xi'an due to its relatively higher coal prices.

Option 3: Eliminate scattered boilers and build a community-scale system to serve the aggregated demand

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[2] Net cost-saving is derived from annual avoided operating cost of using saved energy due to efficiency gains plus incentives received for pursuing the retrofit minus the annualized investment cost.

This option assessed the case of replacing separate natural gas boilers in five industrial facilities within a 10-kilometer diameter[3] in Xi'an with a potential community-scale system that can serve the aggregate steam and heat loads of the existing facilities. Under this option, the costs of three types of community-scale systems (i.e., a natural gas-based CHP, a large coal-fired boiler, and a large natural gas-based boiler) were compared with that of dispersed natural gas boilers operated individually by facilities. This analysis also considered the added cost of facilities meeting environmental obligations and the reduced cost due to natural gas price adjustment when compared these systems. Several conclusions can be drawn:

- Although the three types of community-scale system differ in cost, all of them are more economical than five facilities building and operating their own boilers. From this perspective, replacing separate self-operated boilers with a community-scale system capable of serving the aggregated heat/steam loads of these facilities can be a cost-effective solution.
- A community-scale coal-fired boiler system seems to be the most economical option among all the four supply options studied. If the facilitates' environmental compliance costs are not considered, the cost ratios between community-scale coal-fired boilers, community-scale natural gas boilers, natural gas-based CHP, and facilities operating their self-built natural gas boilers are: 1: 2.62: 2.73: 2.94. However, when considering the environmental compliance costs, the cost ratios change to 1: 2.00: 2.12: 2.24, indicating that the cost advantage of community-scale coal-fired boilers decreases when environmental compliance costs of burning coal is added. More stringent regulations on air pollution and greenhouse gas emissions will increase the cost of using coal.
- Among all community-scale systems assessed in the analysis, the natural gas-based CHP system that is equipped with micro-turbines has the highest cost, which is close to the total cost of five facilities operating their own boilers. The high cost of the system is due to the high equipment cost of micro-turbines in addition to the relatively high natural gas price. Micro-turbines which are the main component of such natural gas-based CHP systems currently have a very limited use in China. With the scale-up of the CHP equipment market, the gradual decline of natural gas prices, and stronger policy support for natural gas-based distributed energy development in China, the economic benefits of natural gas-based CHP systems will be further improved. A further reduction of natural gas prices (e.g., a reduction of 0.50 RMB/m^3 from the current level) can make the CHP system more economical than a community-scale natural gas system and change the cost ratios between community-scale coal-fired boilers, natural gas-based CHP, community-scale natural gas boilers, and facilities operating their own natural gas boilers to: 1:1.43:1.61:1.84.

Barriers to Adoption of Solutions for Industrial Boilers

The techno-economic analysis has shown that retrofitting existing coal-fired boilers, fuel switching from coal to natural gas, and using resources via a community-scale distributed CHP system can be effective alternatives to industrial coal-fired boilers. However, our field investigation visits in Ningbo and Xi'an and our desktop research on challenges revealed that China faces many barriers that can prevent these solutions from being fully realized. Key barriers to efficiency improvement, greater use of natural gas, and deployment of combined heat and power (CHP) and distributed energy (DE) in China include:

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[3] Serving loads within an effective geographical range is desirable for a community-scale system so that heat losses from delivering steam/heat from the system to loads can be minimized.

Barriers to improving boiler efficiency

- Lack of comprehensive efficiency standards
- Technologies focus less on boiler energy performance and lack of boiler system-wide solutions
- Lack of good operation practices and effective management for boilers
- Lack of technical capacity in operating boiler systems
- Lack of strong monitoring and enforcement

Barriers to fuel switching

- Lack of effective boiler phase-out compliance plan and strategies
- Lack of market competition and uncertainty in policies, fuel prices, market risks, and technologies
- Shortage of natural gas supply for industrial gas use and high natural gas prices

Barriers to deploying CHP and distributed energy systems

- CHP and DE systems lack access to the electrical grid and thermal distribution network
- Burdensome permitting prolongs the process to approve and construct CHP and DE
- Lack of comprehensive plans for CHP and DE leads to highly fragmented operations and creates improper economies of scale
- Lack of coordination between heat supply and heat distribution systems
- Lack of active participation of third-party players like energy service companies
- Lack of support from utilities that view CHP and DE as potential competitors
- Actual costs for producing and distributing power and heat from CHP and DE are not always reflected in the tariffs
- Heat services for residential and public sector are often at a flat rate, disincentivizing energy savings while discouraging investments in CHP and DE
- First-cost hurdle and lack of access to finance hinder the expansion of CHP and DE
- Lack of tax and fiscal incentives and other stimulating measures
- Lack of experience and tools for designing optimal system configurations, creating over-sized, inefficient systems

Roadmap to Remove Barriers to Capturing Greater Opportunities for Industrial Boilers

China needs effective strategies to realize cost-effective opportunities and to remove the barriers identified in this assessment. Based on relevant experience in the U.S., we recommend the following strategies:

- *Taking a holistic approach to addressing coal-fired industrial boilers*
- *Developing and deploying cost-effective compliance strategies*
- *Creating enabling policy*
- *Accelerating technology development and deployment via incentives*
- *Developing effective standards and guidelines*
- *Promoting advanced technologies and integrated solutions via implementation of pilots*

- *Stimulating greater investment via innovative business models and financing mechanisms*
- *Strengthening enforcement and enhancing its effectiveness via great flexibility*
- *Enhancing technical support and building strong capacity*

Recommended Areas for U.S.-China Collaboration in Implementing the Roadmap

Potential areas for joint collaboration include:

- *Supporting city pilots to demonstrate and deploy advanced efficiency and fuel switching technologies*
- *Sharing policy experiences to promote the adoption of effective policy solutions*
- *Developing localized decision tools and resource kits to identify optimal opportunities*
- *Strengthening collaboration on developing standards and enforcement strategies to increase the effectiveness of enforcement practices*
- *Expanding collaboration in capacity-building to improve skills in implementation*

There are a series of specific activities that U.S. and China could carry out for implementation of the recommended actions:

- *Conduct policy exchange with Chinese policy-makers through study tours and workshops*
- *Carry out pilots in Ningbo and Xi'an to deploy advanced technologies in energy efficiency and fuel switching*
- *Pilot innovative financing and business models to materialize efficiency and fuel switching opportunities*
- *Leverage available funding offered by multinational donor agencies and development banks in the U.S. and China*
- *Customize and disseminate DOE MACT decision tree analysis tool and other relevant DOE tools*
- *Organize trainings and technical workshops*

1. Introduction

China's industrial boiler systems consume 700 million tons of coal annually, accounting for 18% of the nation's total coal consumption (MIIT, 2014). Together these boiler systems are one of the major sources of China's greenhouse gas (GHG) emissions, producing approximately 1.3 gigatons (Gt) of carbon dioxide (CO_2) annually (Dechert, 2015). These boiler systems are also responsible for 33% and 27% of total soot and sulfur dioxide (SO_2) emissions in China, respectively, making a substantial contribution to China's local environmental degradation (MIIT, 2014). The Chinese government - at both the national and local level - is taking actions to mitigate the significant greenhouse gas emissions and air pollution related to the country's extensive use of coal-fired industrial boilers. The United States and China are pursuing a collaborative effort under the U.S.-China Climate Change Working Group to conduct a comprehensive assessment of China's coal-fired industrial boilers and to develop an implementation roadmap that will improve industrial boiler efficiency and maximize fuel-switching opportunities. Two Chinese cities – Ningbo and Xi'an – have been selected for the assessment. These cities represent coastal areas with access to liquefied natural gas (LNG) imports and inland regions with access to interprovincial natural gas pipelines, respectively.

Researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory carried out this collaborative boiler assessment project with the support of the Development & Reform Commissions of the two target cities and a team of Chinese industrial experts selected by China's National Development & Reform Commission (NDRC). The members of the Chinese expert team came from six Chinese institutions including the National Energy Conservation Center, the China Special Equipment Inspection and Test Institute, the China Machinery Industry Conservation and Resource Utilization Center, the China National Offshore Oil Corporation, the China Energy Conservation and Environmental Protection Group, and Tsinghua University.

This report discusses the assessment and its results. It consists of eight sections. It first discusses the methods employed in this assessment and the main data sources for the analysis. It then provides information on a comprehensive literature review we conducted to understand other boiler energy efficiency and fuel switching assessments related to China. Third, it gives an overview of China's industrial boilers, available resources for a switch from coal to alternative fuels, and national policies related to addressing coal-fired boilers. Fourth, the paper presents specific information on the two cities – Ningbo and Xi'an – where the assessment was conducted. Fifth, the report discusses results of the techno-economic assessment of a wide range of industrial boiler solutions including improving energy efficiency of coal-fired boilers, switching from coal to alternative sources of energy, and adopting decentralized energy systems employing combined heat and power. Sixth, the report examines various policy, institutional, market, and technical challenges to the adoption of cost-effective solutions. Seventh, the report offers a series of policy recommendations that China could consider to remove the barriers. Since addressing industrial boilers becomes a key area for close collaboration between the U.S. and China on mitigating the climate change, specific opportunities for collaboration are identified and discussed in the last section of the report.

2. Assessment Methods and Data Sources

Methodological Framework

This assessment was carried out using a systematic approach that included a comprehensive literature review, expert interviews, city investigative study, and a techno-economic analysis. These activities were conducted to assess the technical potentials of various solutions for addressing the coal-based energy use of China's industrial boilers, evaluating the cost-effectiveness of these solutions, and examining the barriers to the wide adoption of the solutions. The analysis and evaluation included development of a policy roadmap and identification of actions to implement the roadmap to capture energy efficiency improvement and fuel switching opportunities for industrial coal-fired boilers in China. Figure 1 illustrates the methodological framework used in this assessment. More detailed information on the research activities is provided below.

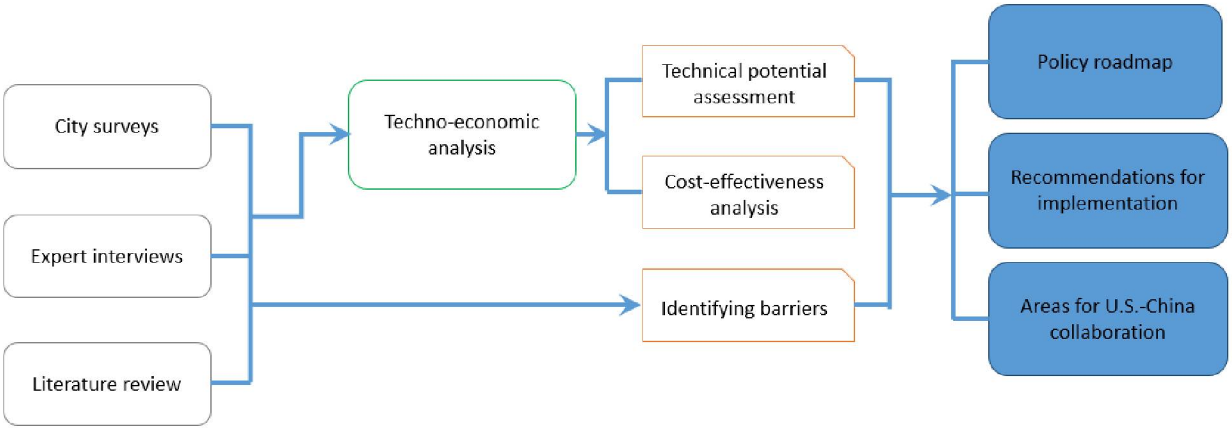

Figure 1. Methodological Framework

Literature Review

The research team conducted a comprehensive literature review for two purposes. The review first helped the research team understand the landscape of China's coal-fired boilers, potential resources for switching from coal, relevant policies, and challenges China is facing to address its industrial coal-fired boilers. Another purpose of the literature review was to examine research projects conducted by other organizations related to assessing industrial boiler energy efficiency and fuel switching opportunities in China in order to avoid repetitive analysis.

City Surveys

The National Development and Reform Commission (NDRC) suggested four Chinese cities - Ningbo, Tangshan, Xi'an, and Zhengzhou – as potential sites for conducting the assessment. Ningbo and Tangshan are coastal cities while Xi'an and Zhengzhou are inland cities. The LBNL research team together with a group of U.S. and Chinese experts visited each of the four cities in [give month and year]. Prior to the visits, requests for information related to the local status and use of industrial coal-fired boilers as well as each city's plan for eliminating and retrofitting existing boilers were made to each city. The visits of the four cities included meetings with key local government agencies including the Development & Reform Commission, Economic and Information Commission, Energy Office, Environmental Protection Bureau, Planning Department, Finance Department, Quality Inspection Bureau, and the municipal heat provider as well as on-site visits of coal-fired boiler operations, a CHP facility in a petro-chemical plant, a city district heating system, and a gas-fired boiler that replaced a coal-fired unit.

The visits to four candidate cities resulted in the final selection of two cities – Ningbo and Xi'an – by NDRC as the sites for carrying out the assessment. The selection decision was based on a series of criteria that was determined by the joint research team and approved by NDRC, which included a strong desire for participating in the assessment, representativeness of the city's economic structure, the city's level of energy consumption, the number of existing industrial boilers, good capacity for environmental and energy-use monitoring, quality boiler performance test and inspection capacity, and natural gas supply security. The joint research team then conducted a second trip to Ningbo and Xi'an in [give month and year] to meet officials and industrial stakeholders in the two cities to collect more detailed information to support the assessment.

Expert Interviews

The LBNL research team carried out a series of interviews with both U.S. and Chinese experts from a number of organizations including the International Finance Corporation, SolarTurbine, Cummins, the China Gas Association Distributed Energy Committee, the China Special Equipment Inspection and Test Institute, the China Machinery Industry Conservation and Resource Utilization Center, the China National Offshore Oil Corporation, the China Energy Conservation and Environmental Protection Group, Tsinghua University, China Northeastern University, Xi'an Jiaotong University, Xi'an Boiler Inspection Institute, and Xi'an Yinqiao Bio-Tech Ltd. The interviews helped the LBNL research team to understand the characteristics and dynamics of industrial coal-fired boilers and in identifying key issues and barriers to addressing industrial boilers. The interviews also provided valuable information for the techno-economic analysis. In addition, insights provided through the expert interviews were of assistance in developing the policy roadmap and recommending activities for roadmap implementation.

Techno-Economic Analysis

The research team conducted a comprehensive techno-economic analysis to assess the cost-effectiveness of various alternatives to coal-fired industrial boilers. The analysis utilized case study information from the cities of Ningbo and Xi'an and focused on three potential options: (1) fuel switching from coal to alternative energy sources such as natural gas, oil, electricity, and biomass, (2) improving boiler energy efficiency through retrofitting existing coal-fired boilers, and (3) replacing scattered boilers with a community-scale boiler system. The techno-economic analysis evaluated both the technical potential and the cost-effectiveness of these options in terms of energy savings and reductions of CO_2 and other air pollutants, compared to existing coal-fired boilers.

Data Sources

The assessment collected data from various sources including: 1) national government policy documents, especially those published by the National Development and Reform Commission (NDRC), the Ministry of Industry and Information Technology (MIIT), the Ministry of Environmental Protection (MEP), and the National Energy Administration (NEA); 2) information provided by the local governments in Ningbo and Xi'an, such as boiler inventory data, relevant local policies, as well as city energy supply, consumption, distribution and price data; 3) information provided by interviewed industrial experts and facility managers; 4) relevant online databases on boiler products and boiler retrofit measures; 5) research articles, published discussion papers, and project information sheets on related topics, 6) boiler performance test reports of local boiler inspection agencies; and 7) public information on pollution levies and CO_2 prices from China's cap-and-trade pilots.

3. Summary of Review of Relevant Studies

Review of Research Publications

To better support the assessment, the research team conducted a comprehensive literature review which focused on various topics that relate to the assessment. This section briefly summarizes the findings of the review. Appendix 1 provides the details of the literature review. On fuel switching from coal to natural gas, studies were published to analyze the potential climate impacts of fuel switching from coal to natural gas. These studies found that air pollution and climate change are inextricably connected because fossil fuel combustion generates both greenhouse gases, aerosols, and criteria air contaminants (Morgenstern et al., 2004; Reynolds and Kandlikar, 2008; He et al., 2010). For developing countries, large synergies exist between climate and air pollution and policies are needed to leverage the opportunities (Reynolds and Kandlikar, 2008; Coria, 2009). Publications (Song, 1999; Mao et al., 2005; Coria, 2009) also discussed the implications of replacing coal with natural gas as a cleaner combustion fuel and concluded that use of natural gas could achieve energy savings when compared to using coal. Other studies focused on cost-benefit analyses of natural gas substitution with results showing that substituting natural gas for coal could make economic sense in large cities with dense populations and intensive economic activity (Fang et al., 2002; Aunan et al., 2004; Mao et al., 2005). Barriers to addressing natural gas penetration in China were also discussed in the literature along with recommendations to increase natural gas adoption rates (Song, 1999; Mao et al., 2005; Coria, 2009; Li et al., 2012a).

A number of studies focused on switching from coal to biomass in boilers and covered many related aspects including composition of biomass, comparison between biomass and other fuels, combustion of biomass, co-firing of biomass and coal, transportation of biomass, densification of biomass, economic and social impacts of biomass, and future trend of using biomass energy (Sims et al., 2003; Demirbas, 2005; Zhang et al, 2010; Saidur et al., 2011; Li et al., 2012b). Most researchers agree on the climate benefits of using biomass but most researchers also agree that "care should be taken" when co-firing biomass in coal-fired boilers. Environmental impacts of using biomass in industrial boilers, such as land and water resources, soil erosion, loss of biodiversity, and deforestation were discussed in the literature along with the assessment of technical issues such as fouling, marketing, low heating value, storage and collections, and handling (Laursen and Grace, 2002; Sims et al., 2003; Li et al., 2010a; Li et al., 2012b). Existing literature also discussed some of the issues that are largely impacted by regulations and environmental requirements and discussed the way to improve existing methods of using biomass in order to improve efficiency and address the associated problems.

On the need for and ways to improving boiler energy efficiency, reports show that China's industrial boilers generally have relatively low energy efficiency, at 60 percent on average, compared with more than 80 percent in Europe and the United States (Gao, 2013). To make improvements, researchers have focused on identifying applicable energy efficiency measures and determining the cost-effectiveness of these measures in reducing coal use and minimizing CO_2 emissions as well as local and regional pollutants (Fang et al., 1999; Fang et al., 2002). A study by the United Nations Industrial Development Organization looked at the system-wide efficiency opportunities in the steam system and developed a modelling framework to quantify the energy saving potential and associated costs of implementation of an array of steam system optimization measures (UNIDO, 2014).

Studies also focus on factors that contribute to the failures to recognize and realize the energy efficiency potential of boilers and steam systems in China and policy solutions to addressing the problems (Yang and Dixon, 2012; Habib et al., 2008).

The existing literature also gives attention to environmental and health-related topics for industrial boilers. Researchers have pointed out that pollution control technologies are constrained to large-scale boilers and monitoring costs associated with implementing pollution control measures are high with great difficulties to monitor the emissions from large numbers of small boilers (Fang et al., 1999; Yang and Dixon, 2012). Many studies have been carried out to estimate the environmental, economic, and health impacts of improving industrial boilers and quantify the co-benefits of reducing carbon emissions and improving air quality in addressing industrial boilers in China (Fang et al., 2002; Aunan et al., 2004; Mao et al., 2005; He et al., 2010).

Review of Other Boiler Assessment Work

To understand previous efforts and avoid repetitive work, the LBNL research team conducted a research on relevant boiler assessment done in China. Appendix 2 provides detailed information on LBNL's review of previous assessments. The research found very few projects that had been conducted to assess the technical potential and economic cost-effectiveness of possible solutions to industrial coal-fired boiler problems in the country. This may be due to the Chinese government's approach to addressing energy and environmental issues, which places more focus on industrial sectors and less on specific industrial equipment and systems. The large quantity and geographically dispersed distribution of small industrial boilers also add great difficulties in carrying out such an assessment.

LBNL's review found that previous assessments relative to boilers have mainly concentrated on district-heating networks as well as combined heat and power (CHP) and distributed energy systems. For example, projects sponsored separately by the World Bank and the Asian Development Bank assessed China's district-heating network in northern part of the country from various aspects including the transition from the flat-rate heat billing system to a cost-based and consumption-based billing system, implementing heat metering, use of energy-efficient boilers (such as circulating fluidized-bed boilers), replacing old and inefficient heat exchangers, insulating heating pipelines, implementing sensors and controls at the heating supply side and the customer side, and improving building energy efficiency. Other projects which were funded separately by the Asia-Pacific Partnership on Clean Development and Climate and the U.S. Trade and Development Agency evaluated the potential and the benefits of CHP and clean distributed generation (DG) in China through modeling analysis and determining their technical, policy, and financial impacts. In the project *Accelerate Distributed Generation - Combined Heat and Power Applications in China* sponsored by the Asia-Pacific Partnership on Clean Development and Climate, the research team found that CHP systems in China was mostly coal-based and were often equipped with old, inefficient coal boilers and heating loops. The estimated average of district heating boiler efficiency by the project was 60 to 65% with an estimated heat loss from district heating pipelines of 25 to 50%. Due to low efficiency and high heat losses of the existing CHP systems, the potential benefits of energy savings and greenhouse gas emissions reduction of the applications were low. However, the project found that significant emission reduction could be achieved if customer-site CHPs at individual industrial facilities and commercial/residential sites was promoted (WADE, 2010).

The LBNL's review found that most assessments are either completed 5-6 years ago or do not have a strong focus on small-scale industrial coal-fired boilers in China. Given China's ambitious carbon emission reduction targets and the country's urgent needs to improve air quality, a study focusing on assessing various solutions to addressing China's industrial coal-fired boilers including their technical and economic potentials is necessary.

4. Comprehensive Overview of China's Coal-Fired Industrial Boilers

Characteristics of Industrial Boilers in China

A boiler is a common but critical piece of equipment in energy conversion systems. Boilers are widely used in power plants, manufacturing facilities, as well as in buildings. Compared to other end-use boilers, industrial boilers are predominant, are adopted across manufacturing sectors and systems, and are operated in a dispersed manner in China. Among industrial boilers in the country, the majority is coal-fired. As of the end of 2012, there are 467,000 registered coal-fired industrial boilers in China with a total annual capacity of producing 1.78 million tons of steam (MIIT, 2014).

China's industrial boilers are characterized as small in size with average capacity of about 3.8 tons/hour. Raw coal is the main fuel consumed by industrial boilers in China. Compared with coal used for large power plants, however, the quality of coal used in industrial boilers is much lower and has high ash and sulfur content. Very often, boiler operators choose to use raw coal, instead of washed coal which has lower air pollutant emissions but higher cost. As reported by the China's Energy Research Institute (ERI, 2013), coal represents about 80% of the total energy input to industrial boilers and oil contributes another 15%. The use of natural gas and biomass in industrial boilers is very limited in China. Key information about China's industrial boilers is summarized in Figure 2.

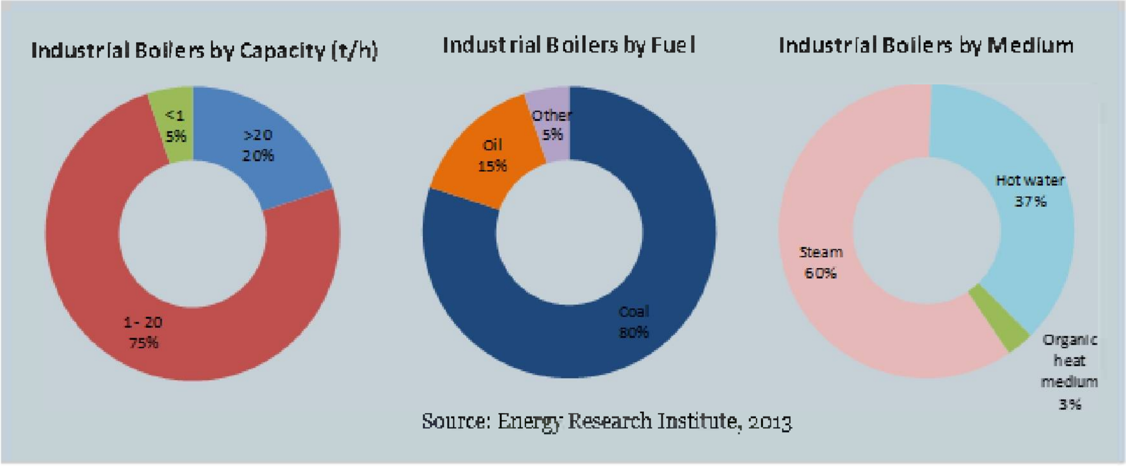

Figure 2. China's Industrial Boilers by Capacity, Fuel, and Medium
Source: ERI, 2013.

Operating conditions of industrial boilers in China are significantly below optimal. A larger number of industrial boilers are quite old, manufactured in 1980s and have low efficiency. These boilers are typically operated manually without automation or intelligent controls. As a result, overall energy efficiency of coal-fired industrial boilers in China is relatively low, about 15% lower than the international advanced level (Gao, 2013).

China's industrial boiler systems consume about 700 million tons of coal annually. These systems account for 18% of China's total coal consumption with CO_2 emissions being estimated to be approximately 1.3 Gigatons (Gt) annually (MIIT, 2014; Dechert, 2015). In addition to becoming one of the major sources of China's GHG emissions, the country's coal-fired industrial boilers have been a significant contributor to China's worsening air pollution. A large number of small industrial boilers often have not implemented adequate pollution control measures, such as dust controls, desulfurization, or de-NOx treatment, making these boilers key sources of local pollution in China. According to the Chinese government (MIIT, 2014), annual soot emissions, sulfur dioxide (SO_2) emissions, and nitrogen oxides (NOx) emissions from China's coal-fired industrial boilers account for 33%, 27%, and 9% of the national total emissions, respectively. In recent years, there has been a wide range of prolonged severe fog and haze, which is closely related to the regional high intensity and low-altitude emissions from coal-fired industrial boilers (NDRC, 2014; Gao, 2013). The large number of small industrial boiler coupled with their dispersed distribution pose a significant challenge for monitoring and enforcing environmental regulations.

Potential Resources for Switching Away from Coal

Natural Gas

Although coal is the dominant fuel used by industrial boilers to produce heat and steam for industrial operations, China has cleaner resources - natural gas and biomass - which can be used instead of coal. Natural gas is the primary fuel-switching option. China's government is increasing natural gas use by seeking additional supply and building more pipelines with the aim to increase the share of natural gas in China's primary energy consumption from 6% in 2013 to 8% by 2015 and to 10% by 2020 (State Council, 2014). In 2012 China consumed about 147 billion cubic meters (bcm) of natural gas, which was a 12% increase from 2011. Industry is the main user of natural gas, representing about 48% of the total share in 2011. Other sectors including power, residential, and transportation sectors have also increased the use of natural gas.

There are some recent changes in the natural gas regulations or market in China that could expand the horizon for a wider use of natural gas. For example, the Chinese government has made attempts to reform industrial gas pricing. China's National Development & Reform Commission (NDRC) has urged large natural gas users to negotiate gas prices directly with suppliers, instead of using government guide prices. NDRC has also announced that they will merge the two tiers of natural gas prices for non-residential users by raising the lower band (the "existing supply") and significantly cutting the higher band (the "incremental tier") that is linked to imported fuel oil prices. The net impact of this change is an overall 5% reduction in natural gas prices for non-residential users. Further, China is developing a domestic gas-trading hub to facilitate natural gas spot trades. In addition, falling liquefied natural gas (LNG) costs abroad, high domestic gas prices in China, and underutilized LNG terminals have led China's independent players to request state-owned LNG importers to import LNG on their behalf, accommodate third-party cargoes, or even grant them direct access to state-owned importers' receiving terminals (Platts, 2015).

In 2012, China produced 107 billion cubic meters (bcm) of natural gas (including coal-bed methane). Output from four provinces - Shaanxi, Inner Mongolia, Xinjiang, and Sichuan – accounted for 75% of China's total natural gas production (as shown in Figure 3). The Chinese government is planning to increase natural gas production to 155 bcm by the end of 2015, to support meeting its goals of reducing coal consumption and air pollution (State Council, 2014). As the country's largest natural gas company, the China National Petroleum Corporation (CNPC) produces about 73% of China's total natural gas production (U.S. EIA, 2015). Another national natural gas company, China National Offshore Oil Corporation (CNOOC), focuses its natural gas business on liquefied natural gas (LNG) and at the same time pursues offshore natural gas development. The company has developed the first three LNG import terminals in China.

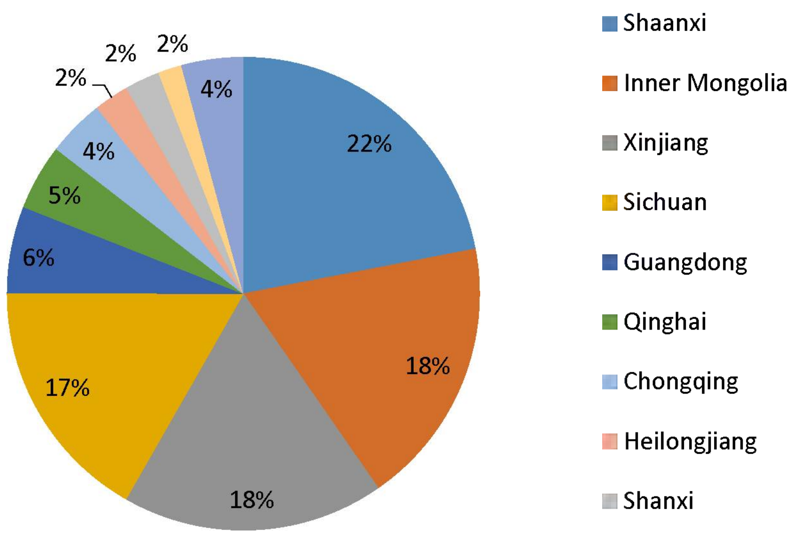

Figure 3. Natural Gas Producing Provinces in China in 2012
Source: NBS, 2013
Note: includes natural gas and coal-bed methane

China's estimated recoverable natural gas reserve is less than 2% of the world total. Due to the lack of domestic gas supply, in merely five years from 2007 to 2012, China's imports of natural gas grew almost 10 fold from 4 billion m^3 to 43 billion m^3, with the import dependency rate growing from 2% to 27% (National Business Daily, 2013). Imports and infrastructure for imports of LNG and pipeline gas have been developed rapidly. By 2012, net import of natural gas totaled to 40 bcm, or close to 30% of total natural gas consumption (NBS, 2013). This share increased to 32% in 2013, or about 5 times higher than the 2006 level. China relies on four strategic corridors for its natural gas import – pipelines from Central Asia, Myanmar, Russia, and imported liquefied natural gas (mainly from Qatar and Australia) that will provide around 102 bcm of natural gas in 2015 and at least 169 bcm/year in 2020 due to the rapid increase of domestic demand for natural gas (Dong, 2015). The international oil and natural gas prices have remained low in the past couple of years. The price outlook of natural gas that China imports may stay low for a while, which could help China increase the country's natural gas imports. Despite of possible increase of imported natural gas, however, energy security from depending on foreign natural gas supply would remain an issue if China increases the share of natural gas significantly in its energy mix.

Data on China's energy supply capacity compiled by the U.S. Energy Information Administration (USEIA, 2015) indicates that at the end of 2012, China had more than 50,000 kilometers of natural gas pipelines. The West-to-East Gas Transmission Pipeline was first constructed in 2004 to supply gas from China's western provinces to meet the growing demand for natural gas in the nation's east and southern regions. CNPC is the key operator of the West-to-East Pipeline. The first phase linked western provinces in China with eastern regions and ends in Shanghai. The second phase, which was completed in 2011, connects the Central Asian Gas Pipeline at the border with Kazakhstan to transport gas to China's southeastern regions. CNPC is now in the process of building the third pipeline connecting the Central Asian gas production to Fujian and Guangdong provinces. In addition to the Central Asian Gas Pipeline, which transports natural gas from Turkmenistan, Uzbekistan, and Kazakhstan to China, CNPC signed an agreement with Myanmar in 2008 to transport gas from offshore Myanmar to China's Yunnan and Guangxi Provinces. Most recently, China finalized an agreement with Russia to purchase and transport natural gas from eastern Russia through a yet-to-be-built pipeline. Valued at USD$400 billion, the pipeline is expected to be in operation in 2018. China's natural gas pipelines are shown in Figure 4.

Figure 4. Key Oil and Natural Gas Pipelines in China
Source: U.S. EIA, 2015.

As China increases the share of natural gas in the country's energy mix through increasing domestic production and imports, the government has been making adjustments in China's natural gas prices. The goal is to make the pricing system more transparent, to reflect and respond to international market pricing fluctuations, and to make natural gas competitive with other fuels. In 2011, the Chinese government launched a pilot program of reforming natural gas prices in Guangdong and Guangxi provinces. The pilot linked the natural gas prices for non-residential users to the price of imported oil and liquefied petroleum gas (LPG). In 2013, the pilot was expanded to the rest of the country. The price of natural gas was increased about 15% on average for non-residential customers, including fertilizer producers. In 2013, the Chinese government differentiated city-gate gas pricing for non-residential users into two pricing levels: a

Stock Price and an Incremental Price. The Stock Price is based on gas supply going into each province recorded in 2012, using the consumption volume of 112 billion cubic meters as the baseline. The incremental supply above that had a separate tier Incremental Price which was linked to imported fuel oil and LPG prices and set at a much higher level than the Stock Price. The government created the tiered gas pricing to encourage energy savings so that end-users who raised their gas consumption would experience a higher price. This price reform was continued with NDRC merging the two price bands into one Maximum Price in April 2015 by raising city-gate prices for existing supply and lowering prices for the incremental supply tier (due to the lowered international oil and LPG prices). This has led to reduced overall natural gas prices from using the previous two-tiered pricing (Platts, 2015).

Biomass

Biomass is another alternative resource that can be considered for fuel switching in China's industrial boilers. In 2010, biomass supplied 24 million tons of coal equivalent (Mtce) of energy, meeting about 1% of China's primary energy needs (NEA, 2012b). Although the Chinese government has launched demonstration programs that use biomass boilers to provide heat, biomass is primarily used for increasing the nation's installed capacity of biomass-generated electricity from 5.5 GW in 2010 to 13 GW by 2015 (State Council, 2013). From the scale of economy perspective, developing large-scale power generation from biomass is more efficient than using it in smaller scale industrial boilers. Table 1 shows the production levels and respective shares of total biomass output of various types of biomass energy in China.

Table 1. Current Status and Development Targets of Biomass in China

Type of Biomass Energy	Energy Production in 2010 (Mtce/year)	Current Share of Total Production	Targeted Production in 2015 (Mtce/year)
Biomass power generation	10.2	42%	24.3
Household biogas projects	9.3	39%	15
Large-scale biogas projects	0.7	3%	2
Biomass-based briquettes	1.5	6%	5
Biomass ethanol	1.6	7%	3.5
Biodiesel	0.7	3%	1.5
Total	24	100%	51.3

Source: NEA, 2012b.

Boiler-Related Policies and Standards

Relevant Policies

Since 2007, a series of policy documents related to industrial boilers including a national *Boiler Action Plan* have been issued by various Chinese Ministries (MIIT, 2014). These policy directives set specific targets and requirements for reducing energy use and controlling pollution from coal-fired industrial boilers. These policies also encourage solutions such as fuel switching from coal to alternative fuels and developing natural gas based distributed energy (DE) and combined heat and power (CHP) as alternatives to coal-fired boilers. Table 2 summarizes the relevant polices. Appendix 3 provides more details on these policies.

Table 2. Summary of Relevant Policies Related to Industrial Boilers in China

Year	National Policy	Issuing Agencies	Key Points Related to Industrial Boilers, Fuel Switch, CHP, DE
2007	*The Energy Conservation Law (Revised)*	People's Congress	• Encourages industrial facilities to adopt CHP and waste-heat recovery. • Encourages utility companies to make arrangements for "clean, high efficient, and eligible CHP power-generating units to be connected to the grid."
2008	*The Circular Economy Promotion Law of China*	People's Congress	Promotes the capture of waste heat, waste gas, and underutilized by-product
2010	*China's 2010 CHP Development Planning and 2020 Development Plan*		Establishes a goal to increase CHP capacity by more than 50% from the level of 2010 and reach 200 GW by 2020
2011	*Guiding Opinions on the Development of Natural Gas-Based Distributed Energy*	NDRC, MOF, MOHURD, and NEA	• Establishes 1,000 natural gas distributed energy projects by 2015 • Develops 10 demonstration zones to showcase different applications by 2015 • Set a goal that by 2020, total installed capacity of natural gas based distributed energy will be 50 GW
2012	*Twelfth Five-Year Plan on Air Pollution Prevention and Control in Key Regions*	State Council	• Phases out small industrial coal-fired boilers (under 10 tons/hr) • Increases combined heat and power • Establishes district heating networks at industrial parks
2013	*Atmospheric Pollution Prevention Action Plan*	State Council	• Promotes comprehensive retrofit of coal-fired boilers • Prohibits construction of new coal-fired boilers under 20 ton/hr in key cities • Promotes replacing coal with natural gas in key regions • Requires units under 20 tons/hr to install desulfurization devices • Decreases the share of coal in total energy use below 65% by 2017
2013	*Interim Measures on Managing Electricity Generation from Distributed Energy*	NDRC	Removes some of the grid-interconnection barriers in distributed energy projects

2014	*Amendment to China's Environmental Protection Law*	People's Congress	- Establishes daily fines for pollution violations - Incorporates environmental performance into the job performance reviews of local government officials - Gives non-governmental organizations the right to sue polluters in court
	Biomass Boiler Demonstration Project,	NEA, MEP	Develops 120 biomass boiler projects by 2015 which will supply heat for more than 6 million square meters of residential heating areas and supply more than 1,800 tons of steam per hour in industrial sector
	Guidelines for Implementing Natural Gas-Based Distributed Energy Demonstration Projects.	NDRC, MOHURD, and NEA	- Requires local provinces to develop distributed energy development plans - Establishes application and selection procedures for demonstration projects - Develops relevant incentives, standards, and regulations
	Comprehensive Implementation Plan of Improving Coal-Fired Boiler Energy-Saving and Environmental Protection Performance (Boiler Action Plan)	NDRC, MIIT, MEP, AQSIQ, MOF, NEA, NGOA	- Phases out small coal-fired boilers with an aggregated capacity of 400,000 tons (of steam production per hour) by 2018 - Promotes 500,000 high efficient boilers - Increases the goal for the market share of high-efficient coal-fired boilers from the current 5% to 40% by 2018 - Increases boiler efficiency by 6% from the 2013 level - Increases pollution control of boilers
	U.S. – China Joint Statement on Climate Change	Chinese Government	- Sets a goal to peak CO_2 emissions by 2030 or earlier - Sets a goal to increase the share of non-fossil energy sources to 20% by 2030

Note: AQSIQ: General Administration of Quality Supervision, Inspection and Quarantine; MEP: Ministry of Environmental Protection; MIIT: Ministry of Industry and Information Technology; MOF: Ministry of Finance; MOHURD: Ministry of Housing and Urban-Rural Development; NDRC: National Development and Reform Commission; NEA: National Energy Administration; NGOA: National Government Offices Administration

Relevant standards

In October 2009, the Chinese government published the national standard governing industrial boiler energy efficiency, *the Minimum Allowable Values of Energy Efficiency and Energy Efficiency Grades of Industrial Boilers* (GB 24500-2009), which took effective on September 1, 2010 (AQSIQ and SAC, 2009). The standard sets both mandatory energy efficiency values ("the minimum allowable values of energy efficiency") and recommended energy efficiency values ("the evaluating values of energy efficiency") for industrial boilers. The standard applies to boilers that use coal, oil, and natural gas. Coal types include bituminous, lean, anthracite, and lignite coal while oil types include heavy oil and light oil. Boilers that use coal as fuel input are further grouped into stoker boilers, chain-grate stoker boilers, and fluidized bed boilers. By steam generation capacity, the standard applies to a smaller type of boiler (with a steam generation capacity between 6 tonnes/hr and 20 tonnes/hr) and a larger boiler (with a steam generation capacity larger than 20 tonnes/hr).

Three levels of energy efficiency values are provided in the standard. The mandatory energy efficiency value is the third level (the lowest) of energy efficiency and the recommended energy efficiency value is the second level of energy efficiency. Level 1 is the highest level of energy efficiency. For example, for a chain-grate stoker boiler that uses bituminous coal (with a lower heating value higher than 21,000 kJ/kg), the mandatory energy efficiency value for a smaller boiler (with a steam generation capacity between 6 tonnes/hr and 20 tonnes/hr) is 82%. The mandatory energy efficiency value for a larger boiler (> 20 tonnes/hr) is 83%. This national standard does not cover boilers that use biomass or pulverized coal. The standard sets the energy efficiency values for boilers under rated capacity. But it does not differentiate energy efficiency values for boilers in various working conditions and different use stages.

China also established testing requirements for boilers. The *Thermal Performance Test Code for Industrial Boilers* (GB 10180-1988) was issued in 1988, which providing the mandatory procedures for testing the thermal performances of the industrial boilers. The *Energy Efficiency Test and Evaluation Regulation for Industrial Boilers* (TSG G0003-2010), established in 2010, sets the test procedures and technical regulations for testing energy efficiency levels of industrial boilers. These testing protocols set the foundation and necessary conditions for improving overall operation including energy efficiency performance of industrial boilers.

In addition, China recently established a national standard regulating boiler emissions. China's Ministry of Environmental Production (MEP) issued the revised *Emission Standard of Air Pollutants for Boilers* (GB 13271-2014) on May 16, 2014, which is the newest revision of GB 13271, after its first publication in 1983 and subsequent revisions in 1991, 1999, and 2001. This newly revised standard prescribes the maximum allowable emission concentration values for particulate matter, sulfur dioxide, nitrogen oxides, mercury and its compounds as well as limiting values of flue gas opacity. The standard covers steam boilers using coal, oil, and natural gas that are no larger than 65 tonnes/hour, hot water boilers and organic fluid boilers of all capacities, and chain-grate and stoker boilers of all capacities. Boilers that uses other types of fuels, including briquettes, coal-water slurry, gangue, petroleum coke, oil shale, and biomass are required to meet the same emission standards as coal-fired boilers. Boilers that use municipal wastes and hazardous wastes are not covered under this standard.

Compared to previous versions, this standard added the emission values of nitrogen oxides and mercury and its compounds for coal-fired boilers. It also established "special limitation for air pollutants" for key regions in China. Compared to previous versions, the new version eliminated the prescription that boilers with different functions or capacities have different emission limiting values and has more rigorous emission requirements for each of the air pollutants.

New boilers were required to meet this new emission standard by July 1, 2014. Existing boilers that are larger than 10 tonnes/hour and hot water boilers that are more than 7 MW are required to meet the emission requirements by October 1, 2015. Smaller existing boilers are required to meet the standard by July 1, 2016.

Local governments are given more authority on overseeing industrial boilers. Local regulators can establish local standards regulating pollutants that are not included in the national standard. They can also prescribe even more stringent emission standards than the national requirements. In addition to regulating emissions from existing boilers, the standard also enables local environmental regulators to approve new boiler projects, evaluate environmental impacts of boiler construction, and regulate environmental protection devices (MEP, 2014).

5. Survey Information of Pilot Cities: Ningbo and Xi'an

Ningbo

Economic and Industrial Structure

Ningbo is located on the east coastline in China's Zhejiang Province. Ningbo is a prominent city that has been designated by the Chinese central government as a pilot for several important energy and environment related initiatives. For example, Ningbo has been selected as a pilot city for the National New Urbanization Pilot, National Low Carbon City Pilot, and National Smart City Pilot.

According to government statistics, the population of Ningbo is 5.8 million people as of 2014 (NBS, 2014; NEITC, 2014b). Ningbo's gross domestic product (GDP) and per capita GDP was 712.89 billion RMB and 93,176 RMB (approximately $15,046), respectively, in 2013. Primary, secondary, and tertiary added value were 28 billion RMB, 374 billion RMB, and 311 billion RMB, each accounting for 4%, 45%, and 40% of the city's GDP, respectively.

Ningbo is a relatively industrialized city. There are nearly 125,000 industrial enterprises and 20 special development zones that are above provincial level, six of which are multipurpose development parks and seven of which are industrial parks (NBDRC 2015a). The city is planning to develop its industrial parks into industrial eco-parks and to encourage these development zones to utilize central heating, central gas, and unified processing for sewage and garbage (NKDALGO, 2014).

Key industries in Ningbo include petroleum processing, chemical materials, power generation, motor manufacturing, general equipment, non-ferrous metals, and ferrous metal industries. These industries accounted for 12.4%, 11%, 6.9%, 5.8%, 5.5%, 4.4% and 4.2% of production value, respectively, in 2013 (NBDRC 2015a). The city plans to focus on the development of special industry clusters in new materials, port-surrounding petrochemical, textile, smart appliances, and equipment manufacturing.

However, restructuring Ningbo's industries is not an easy task because the development of Ningbo's high technology industries and strategic emerging sectors is slower than the development of its energy-intensive industries. In 2013, the city's high technology industries and strategic emerging industries value added increased by merely 6.5% and 6.2%, respectively, which is below the average growth rate of city's above-scale industry by 1.5% and 1.8% respectively. The growth of these industries was also significantly lower than the growth rate of the ferrous metal (602.9%), petroleum (109.2%), electric power (43.0%), and motor manufacturing (37.0%) industries (NEITC, 2014a).

Energy Supply and Price

More than 95% of Zhejiang Province's primary energy supply is imported. In recent years, importing LNG into Ningbo's port and using LNG pipelines has been Zhejiang Province's approach for reducing pollution, particularly particulate matter 2.5 ($PM_{2.5}$) emissions (NEEIQBP, 2014).

Ningbo is connected to the Zhejiang provincial natural gas pipeline, *Hangyong Pipeline*. As of 2013, Ningbo had a gas pipeline network of 5,088 kilometers. However, the city's natural gas supply network mainly serves the central district and suburban areas in Yuyao and Cixi while three southern counties and many medium and small sized towns in Ningbo are not covered (NEIC, 2014b).

In Ningbo, LNG for residential use is 12 RMB/m^3 and pipeline natural gas for residential use is 2.8 RMB/m^3 while the liquefied petroleum gas price for non-residential use is 16 RMB/m^3 and the pipeline gas price for non-residential end-use is around 4.3 RMB/m^3 (or 3.04 RMB/m^3 at the city gate) (NEITC, 2014b).

Energy Consumption and Environmental Impact

Citywide energy consumption in Ningbo increased from 35.46 Mtce in 2010 to 41.88 Mtce in 2014 (NBDRC, 2012; Qianjiang Evening News, 2015). In 2012, energy consumption in the industry sector accounted for approximately 75% of Ningbo's total energy consumption, which is about 15% higher than national average (NBDRC 2015a). Use of coal and petroleum products accounted for 71% and 25% of total energy consumption, respectively. Secondary industry, including both the industry sector and construction, contributed to 74% of Ningbo's energy-related GHG in 2010, as illustrated in Figure 5. In 2013, Ningbo emitted 136,773 tonnes of sulfur dioxide (SO_2) and 240,827 tonnes of nitrogen oxides (NOx). Absolute emissions of both pollutants have been decreasing over the past few years (NCG, 2014b).

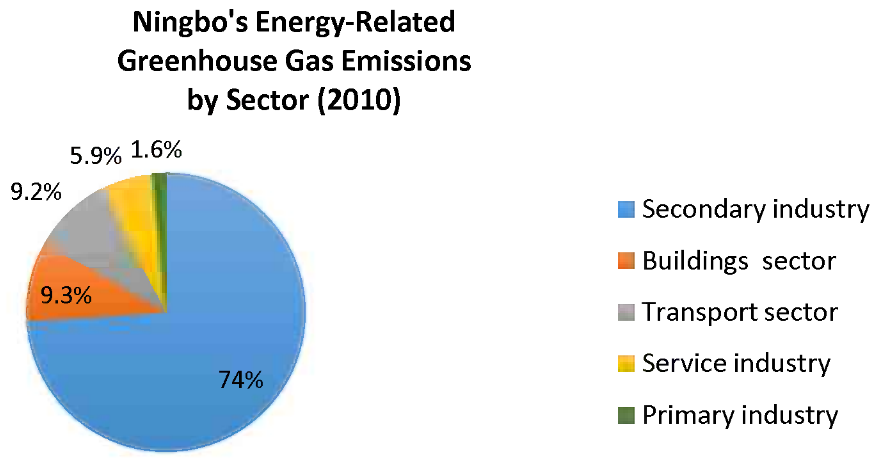

Figure 5. Ningbo's Energy-Related Greenhouse Gas Emissions by Sector (2010)[4]
Source: NBDRC, 2012.

Energy and Emissions Targets

Ningbo's government has set a series of targets to reduce energy use, control coal consumption, and minimize air pollution in the city. The city is expected to reduce energy intensity by 18.5% from the 2010 level by 2015, with a potential energy saving of over 5 Mtce (NBDRC, 2012). By 2017, the energy intensity of Ningbo's industrial sector is expected to be 15% lower than that of 2012 (NCG, 2014a). In addition, Ningbo plans to implement coal control measures in order to

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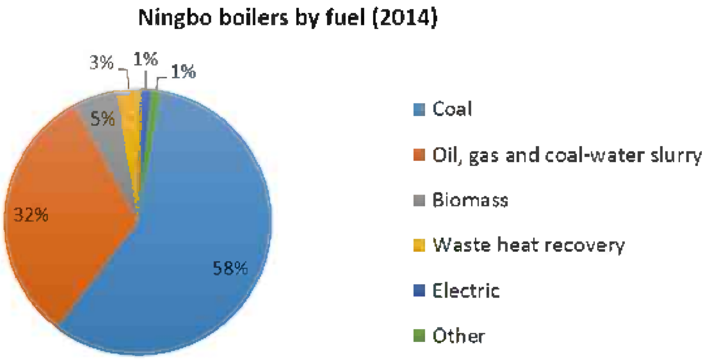
[4] In China, primary industry refers to agriculture, forestry, animal husbandry and fishery industries while secondary industry refers to mining and quarrying, manufacturing, production and supply of electricity, water and gas, and building construction

reduce the share of coal in the city's energy mix from 67% in 2010 to 57% in 2015 (NBDRC, 2012).

Ningbo's emissions targets for 2015 are to decrease COD, ammonia nitrogen, SO_2 and NOx emissions by 13.2%, 13.0%, 18.9% and 31.9%, respectively (NPGO, 2012). By 2017, Ningbo's air quality is expected to improve; the number of days with good air quality are expected to increase, fine particulate matter ($PM_{2.5}$) is expected to be at least 18% below the average pollution levels in 2013 (NCG, 2014a). To reach these targets, the city plans to accelerate the desulfurization of heating power plants and major metallurgy enterprises and the de-nitrification of coal-fired power plants. Ningbo will implement de-nitrification for the coal-fired plants to reach a denitrification rate of 70% and will enhance desulfurization equipment management to reach a desulfurization rate of over 90%. Additionally, the city will also provide centralized heating from large power plants and eliminate small heating power plants and small boilers (NBDRC, 2012).

Boiler Characteristics in Ningbo

As of October 2014, Ningbo has a total of 3,444 boilers for industrial and household use. More than half of the boilers are coal-fired (57.6% of the total). Boilers in Ningbo are widely spread and have relatively low capacities. Most of the boilers have a capacity of less than 4 t/h. Boilers with capacity of 1 t/h or less, capacity of 1-4 t/h, and capacity of 4 t/h or more account for 48.30%, 43.80% and 7.90% of all boilers, respectively (NCQTSB, 2014). Figure 6 shows the types of boilers in Ningbo.



3,444

industrial boilers and household boilers in 2014

Boiler capacity (t/h)	Percentage
≤ 1	48%
1-4	44%
≥ 4	8%

Figure 6. Ningbo Boilers by Fuel (2014)
Sources: NCQTSB, 2014; NBDRC, 2015b.

According to the Ningbo government, there are 1,898 boilers that use highly polluting fuels of which 1,423 are industrial boilers and the remaining are used for other purposes. About 88% of these identified industrial boilers are coal-fired while the remaining 12% of the industrial boilers are oil-fired. Most of these industrial boilers (more than 97%) have a capacity below 10 t/h (NBDRC, 2015b). the Ningbo government has been phasing out coal-fired boilers in the designated prohibition zones (mainly the built-up urban areas). As of October of 2014, Ningbo has phased out over 600 coal-fired boilers and has added 162 gas-fired boilers and 87 biomass boilers (NCQTSB, 2014).

Local Policies

The Ningbo government issued the Ningbo Air Pollution Prevention Action Plan (2014-2017), which prohibits burning highly polluting fuels or non-compressed biomass in new boilers that are 20 t/h or smaller within the built-up urban areas and eliminates and retrofits (fuel switch) boilers of 10t/h or less outside prohibition zones (NCG, 2014a). By the end of 2017, Ningbo is expected to eliminate all industrial furnaces and boilers using polluting fuels outside of the prohibition zones and complete heat supply network construction for industrial parks. Ningbo's Municipal Finance Bureau created an incentive policy to support energy efficiency improvements and fuel switching for boilers (NMFB, 2011). The government also issued policies prohibiting the sale and use of highly polluting fuels in the city (NCG, 2011a, 2011b, 2013). The highly polluting fuels refer to coal, heavy oil, and biomass that are directly combusted and other such highly polluting fuels. Instead of using these polluting fuels, use of natural gas, electricity, and other clean energy fuels or centralized heating are encouraged (Deng, 2011).

Xi'an

Economic and Industrial Structure

Xi'an is the capital city of Shaanxi Province, located in central China. Both Shannxi and Xi'an are one of the pilots selected by the Chinese central government for the National Low Carbon Pilot. The population of Xi'an was 8 million as of 2014. Xi'an's gross domestic product (GDP) was 488 billion RMB, accounting for 31% of Shaanxi Province's GDP and per capita GDP was 57,105 RMB (approximately $9,210) in 2013 (NBS, 2014). In 2013, the primary, secondary, and tertiary industries contributed 4%, 43%, and 52% of Xi'an's GDP, respectively. By 2015, the city total industrial value added is expected to grow from 148.5 billion RMB in 2013 to 200 billion RMB (IPRD, 2014).

Currently, Xi'an has 18 industrial parks of which eight are provincial industrial parks, two are city industrial parks, and the other eight are industrial parks administered by districts and counties. A total of 1,778 companies are located in the industrial parks.

Energy Supply

Xi'an is an energy-importing city. Imported energy accounts for 97% of Xi'an's energy supply. Natural gas is mainly provided by the Shaanxi Natural Gas Company through the Jiangxi Pipeline and Guanzhong Circle while coal is supplied by regions such as Tongchuan, Binchang, Baishui, Hancheng, Yan'an, Yulin and Shanxin. In 2013, pipelined natural gas usage in Xi'an was 1.56 billion m^3, accounting for 51.85% of the province's total natural gas consumption (XDRC, 2014).

Currently, the annual natural gas supply allocated can meet the demand in Xi'an generally, but spike use during peak periods can cause gas supply tension, which is mainly due to the fact that daily and hourly natural gas supply capacity cannot meet natural gas demand during the peak use and emergency peaking adjustment capacity is insufficient. In 2013, Xi'an's peak supply was over 9 million m^3 daily and the variation between the peak and the valley was more than 7 million m^3 per day (XDRC, 2014).

Energy Consumption and Environmental Impact

Citywide energy consumption in Xi'an was 26 Mtce in 2013, which was primarily for industrial processes, accounting for 73% of total primary energy use. Coal is the major energy source, representing about 45% of total primary energy use in 2013 (Liu, 2015). Coal prices in Xi'an have been decreasing. In January 2013, the field price of 5,500 cal soft coal in Xi'an was 615-620 RMB per tonne. This decreased to 520-525 RMB per tonne by January 2014 and has further decreased to 370-385 RMB per tonne in January 2015 (Liu, 2015). For natural gas, the residential price is currently 1.98 RMB/m^3 while the non-residential gas price averages 2.30 RMB/m^3 at the city gate (XDRC, 2014). The price of biomass is higher than that of coal and varies largely due to transportation costs. The price of biomass pellet fuel is 800-1000 RMB per tonne and the price of biomass press block is 550-750 RMB per tonne (Liu, 2015).

Industrial pollution made up a large proportion of the city's total emissions of SO_2, NOx, and smoke and dust emissions. Figure 7 shows SO_2, NOx and soot and dust emissions from 2011 to 2013 and the industrial contribution to these emissions (XASEIT- TC, 2015).

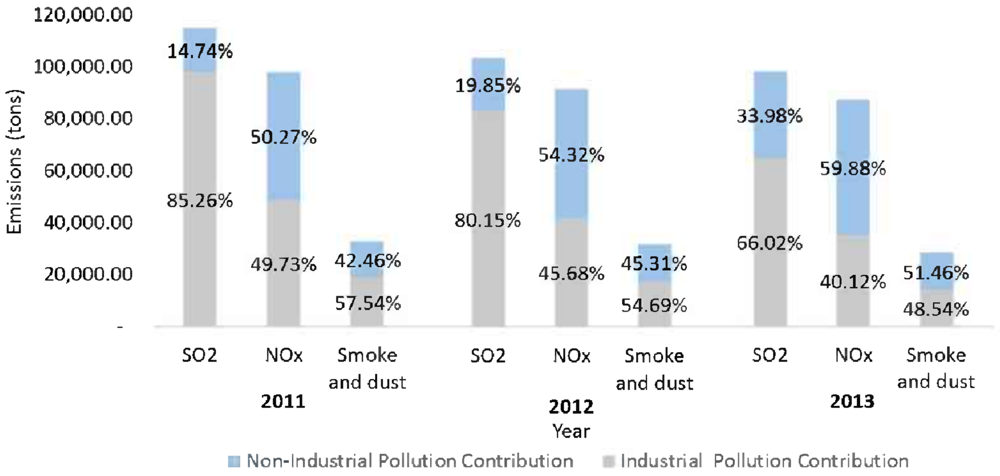


Figure 7. Industry Contribution to Air Pollutant Emissions in Xi'an (2011-2013)
Source: XASEIT-TC, 2015.

The main sources of these pollutants were coal and biomass combustion, vehicle emissions, electric power and heating production, and production of nonmetallic minerals manufacturing, the paper industry, and other industries. Industrial boilers contributed 34,000 tons of SO_2, 30,000 tons of NOx, and 10.5 million tons of CO_2 in 2014 in Xi'an (XDRC, 2014).

Energy and Emissions Targets

The Xi'an government has set a series of energy targets through 2020. Table 3 shows the energy targets set in Xi'an for 2015, 2017, and 2020. Xi'an is expected to reduce the share of coal use in total energy consumption to 20% by 2020 while increasing the shares of natural gas and renewable energy to 17% and 18%, respectively, by 2020.

Table 3. Xi'an Energy Targets

Year	2015	2017	2020
Total Energy Consumption (Mtce)	≤ 30	≤ 34	≤ 40
Total Coal Consumption (million tonnes)	≤ 14	≤ 12	≤ 11

Share of Coal Use	≤ 33%	≤ 26%	≤ 20%
Share of Natural Gas	≥ 12%	≥ 16.5%	≥ 17%
Share of renewable energy	≥ 11%	≥ 15%	≥ 18%
Energy Intensity (tce/10,000 RMB)	≤ 0.529	≤ 0.496	≤ 0.452

Source: XDRC, 2014.

Boiler Characteristics in Xi'an

In 2014, industrial facilities in Xi'an operated 6,903 industrial boilers consuming approximately 4 Mtce of coal and producing 34,000 tonnes of SO_2 (33% of the city's total SO_2 emissions) and 30,000 tonnes of NOx, respectively (XASEIT- TC, 2015). A majority of boilers in Xi'an are small to mid-sized. Xi'an's industrial boilers use many types of fuels. The most common fuel type was coal (Figure 8). Among the coal-fired boilers, the most common type of coal was bituminous coal. Biomass fuels used in boilers included rice chaff and wood (BII, 2014). Currently, gas-fired boilers are mainly used in hospitals and units with small heating areas for winter heating and are seldom used in industrial operations. Most of the gas-fired boilers are 2 to 15 t/h with high heating efficiency and are in good operational condition (XDRC, 2014).

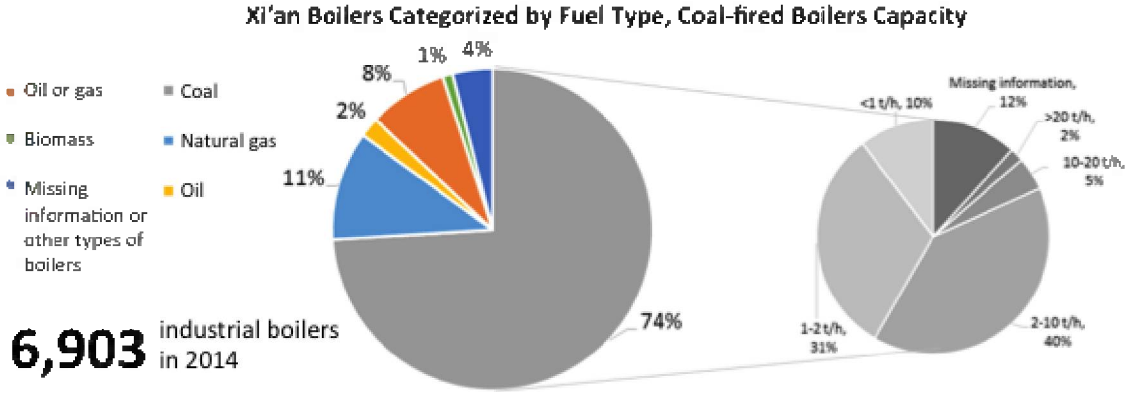


Figure 8. Industrial Boilers in Xi'an by Fuel and Capacity
Source: BII, 2014.

Local Policies

At the provincial level, the *Shaanxi Low Carbon Action Plan for Energy Savings and Emissions Reduction (2014-2015)* includes policies on industry restructuring and promotion of coal boiler retrofits that aims to eliminate a total capacity of 8,273 t/h of outdated steam boilers (XYDRC, 2014). To support the effort, Shaanxi plans to develop more effective policies, which includes an energy consumption cap on energy-intensive industries, punitive energy prices for energy-intensive enterprises, and differential pricing for energy-intensive industries. Monitoring systems will be strengthened through more rigorous assessment of targets and energy use early warning systems. Facilities that do not meet emission standards will be shut down for retrofitting (XYDRC, 2014).

The *Notice on the Launch of Industrial Boiler Energy Conservation and Retrofit Demonstration Promotion* issued by the Shaanxi Province Industry and Information Technology Commission outlines a multi-stage plan to be carried out from 2012-2015 to retrofit and reduce emissions through launching five pilot projects. The target is for efficiency of industrial furnaces and boilers to improve by 2 and 5%, respectively, from that of 2010 (IITDSP, 2012).

At the city level, the *Notice on Further Enhancing Energy Saving and Emissions Reduction in Xi'an* (2011) included measures to implement key projects to improve boiler efficiency. The *Xi'an Combined Heat and Power Plan for 2010-2020* planned to carry out 13 combined heat and power (CHP) projects and four heat supply network projects using waste heat from industrial processes. Currently, heating in Xi'an is provided primarily by distributed, small-scale boilers which produce a large amount of SO_2 and other emissions (XEN, 2008).

The Xi'an government is implementing a phasing-out strategy to eliminate inefficient and high-polluting boilers. Specifically with regards to the city's heat supply, coal-fired boilers under 20 t/h will be eliminated and the proportion of large-tonnage coal-based heating boilers will increase. For districts where the urban central heating pipeline network cannot meet heating needs, the city government encourages the use of gas boilers and boilers that burn clean energy. By the end of 2013, the Xi'an government had phased out 593 coal-fired boilers and additional 350 boilers were to be eliminated in 2014 (XDRC, 2014).

6. Techno-Economic Assessment of Alternatives to Improving Energy Efficiency and Fuel Switching of Coal-Fired Boilers

In collaboration with the Chinese expert team, the LBNL research team conducted a comprehensive techno-economic analysis to assess the cost-effectiveness of various solutions to coal-fired industrial boilers. The analysis utilized case study information from Ningbo and Xi'an and focused on three options. According to national and local government mandates, coal-fired boilers with a steam production capacity smaller than 20 tonnes per hour (t/h) need to be eliminated while coal-fired boilers with a steam production capacity equal or larger than 20 t/h must be retrofitted to meet the government requirements for efficiency improvement and pollution reduction. Thus, taking into account these requirements currently enforced by the national and governments of Ningbo and Xi'an, this analysis assessed three options: (1) fuel switching to replace coal with natural gas, biomass, oil, and electricity for 10 t/h boilers; (2) retrofitting 20 t/h boilers through a series of efficiency improvement measures; (3) developing community-scale systems to replace scattered boilers operated by individual facilities. Table 4 summarizes the key parameters used in the techno-economic analysis.

Table 4. Key Parameters of Techno-Economic Analysis

Parameter	Ningbo	Xi'an
Coal price*	400 RMB/tonne	371 RMB/tonne
Natural gas price*	3.04 RMB/m^3	2.28 RMB/m^3
Electricity price*	0.90 RMB/kWh	0.85 RMB/kWh
Heavy oil price*	4,250 RMB/tonne	
Biomass pellet fuel price*	1,000 RMB/tonne	
Discount rate	10%	
Boiler lifetime**	15 years	
Lifetime of distributed combined heat and power** (CHP) system	25 years	
Cost of emission regulation compliance***	CO_2: 34.94 RMB/ton, SO_2: 2.5 RMB/kg, NOx: 5.0 RMB/kg, Flue Dust: 0.05 RMB/kg	

*Coal prices are based on the weighted average coal price of December 2014 to May 2015 that considers seasonal price variation due to the changing demand for coal in different seasons (China Coal Market Portal, 2015). Natural gas prices are at the city gate. In a comparison, average U.S. industrial natural price between September 2014 and February 2015 was equivalent to 1.08 RMB/m^3 (U.S. EIA, 2015). Prices for heavy oil and biomass, which have little variation between Ningbo and Xi'an, were from the Chinese experts interviewed by the LBNL team. Electricity prices are based on average electricity rates charged for industrial customer group of 1-10 KV (NBDRC, 2015c; SPPB, 2015).

**Information on the boiler and CHP lifetime is acquired from interviews with the Chinese expert team by the LBNL team. The number of years is average lifetime of various types of systems.

***Cost of industrial facilities controlling boiler emissions to comply with government pollution control mandates. Information on pollutants other than CO_2 based on the interview with Xi'an industrial facilities. For CO_2, the unit cost is the average value of monthly trading prices of seven local cap-and-trade pilots in China during a one-year period from June 2014 through May 2015 (Carbon Trading Portal, 2015).

A proper discount rate has to be applied for conducting an economic analysis and it is needed in this assessment to annualize the cost into the future years for a lifetime of a project or technology. No precise values are available in determining the discount rate. Practitioners must rely on making the most reasonable assumptions and/or estimate. A report issued by the Asian

Development Bank provides a solid reference on the choice of an appropriate social discount rate for cost-benefit analysis of public projects or projects related to climate abatement in developing countries (Zhuang, et al., 2007). According to the report, social discount rate in China is about 8% for short and medium term projects and below 8% for long-term projects. LBNL's interview with an expert at the International Financing Corporation (IFC) indicated that project assessment in China normally uses a discount rate of 12% for typical investment projects while a discount rate of 10% was applied to a recent World Bank's assessment of city district heating projects related to boilers in Hebei, China (personal communication, 2015). In the assessment documented in this report, we used a discount rate of 10% given that our assessment is more similar to the World Bank case.

Option 1: Fuel switching by replacing coal-fired boilers with boilers fueled by natural gas, biomass, oil, and electricity

Investment Costs of Industrial Boilers

Surveys in Ningbo and Xi'an found that chain-grate stoker boilers accounts for a majority of the small coal-fired boilers. The first option therefore focused on comparing the economic feasibility of replacing a small-sized coal-fired boiler (10 t/h capacity under this option) with a comparable boiler that uses other resources including natural gas, heavy oil, biomass, and electricity. For boilers at the size of 10 t/h, the analysis assumed that each boiler system would produce 30,000 tons of saturated steam per year at 1.0 megapascal (MPa) based on the typical boiler operation schedule at the investigated facilities. Table 5 lists the information on the investment costs of five types of boilers, which was obtained from the Chinese experts interviewed by the LBNL research team.

Table 5. Investment Costs for Different Types of Boiler

(Unit: 10,000 RMB)

Boiler Type	Design Cost	Construction Cost (CC)	Equipment Cost (EC)	Thermal Control Cost (TCC)	Installation and Commissioning (IC)	Total	Notes
Coal-fired chain-grate stoker boiler	10	50	80	15	20	175	• CC: boiler house, pile foundation, and chimney stacks • EC: boiler, dust-removal system, pumps, fans, water treatment, desulfurization tower, coal belt, slag eliminator, and insulation • TCC: thermal, electrical, and auto-control systems • IC: installation costs, utilities costs (water and electricity)
Heavy oil boiler	10	40	85	10	20	165	• CC: boiler house, foundation, and chimney stacks • EC: boiler, dust-removal system, pumps, fans, water treatment, desulfurization tower, coal belt, slag eliminator, and insulation • TCC: thermal, electrical, and auto-control systems • IC: installation costs, utilities costs (water and electricity).
Natural gas boiler	10	40	80	10	15	155	• CC: boiler house • EC: boiler, pumps, fans, water treatment, and insulation • TCC: thermal, electrical, and auto-control systems • IC: installation costs and utilities costs (water and electricity)
Biomass boiler	10	50	75	15	20	170	• CC: boiler house, foundation, and chimney stacks • EC: boiler, dust-removal system, pumps, fans, water treatment, feed belt, slag eliminator, and insulation • TCC: thermal, electrical, and auto-control systems • IC: installation costs, utilities costs (water and electricity)
Electric boiler	10	30	80	10	15	145	• CC: boiler house • EC: boiler, pumps, water treatment, fans, and insulation • TCC: thermal, electrical, and auto-control systems • IC: installation costs, utilities costs (water and electricity)

Operational Costs of Consuming Different Boiler Fuels

Table 6 provides parameters used to calculate boiler operation costs while Table 7 shows the operational costs of consuming different boiler fuels both using Xi'an as the case. The chain-grate stoker boiler has the lowest operational cost, followed by the natural gas-fired boiler, the biomass boiler, and the heavy oil boiler, respectively, while the electric boiler has the highest operational cost. If the operational cost of producing per unit of steam using coal is set at 1, the ratio of using natural gas, biomass, oil, and electricity is 1:2.38:2.92:3.95:8.09. Compared to coal-fired boilers, there is a significant difference in the operational costs of using alternative boiler fuels.

Table 6. Parameters and Values Related to Boiler Operations in Xi'an

Boiler Operational Parameters	Chain-grate stoker boiler	Heavy oil boiler	Natural gas boiler	Biomass boiler	Electric boiler
Boiler designed thermal efficiency (%)	82	92	95	88	95
Boiler actual thermal efficiency (%)	70	85	88	80	90
Lower calorific value Natural gas (MJ/m^3) Coal, heavy oil, biomass (MJ/kg) Electricity (MJ/kWh)	22.53	40.19	34.47	13.98	3.60
Electricity consumed by non-electric boilers in per tonne of steam (kWh)	15.3	5	3	10.45	0
Number of boiler operating personnel (including management, operation, and maintenance)	6	3	2	4	2
Annual labor cost (based on 40,000 RMB per worker)	24	12	8	16	8
Fuel price Natural gas (RMB/m^3) Coal, heavy oil, biomass (RMB/t) Electricity (RMB/kWh)	371	4250	2.28	1000	0.85
Fuel consumption per tonne of steam Natural gas (m^3/steam tonne) Coal, heavy oil, biomass (kg/steam tonne) Electricity (kWh/steam tonne)	148.61	68.61	77.27	209.56	724.18

Note: Thermal enthalpy per tonne of steam (pressure: 1.0 MPaG, temperature: 184°C, saturated steam): 2,779.7 MJ; thermal enthalpy per tonne of feed water (feed water temperature: 104°C): 435.95 MJ; steam thermal enthalpy – feed water thermal enthalpy: 2,343.75 MJ; water consumption of producing per tonne of steam: 1.2 tonnes

Table 7. Boiler Operational Costs in Xi'an

Boiler Operational Cost Parameters	Chain-grate stoker coal boiler	Heavy oil boiler	Natural gas boiler	Biomass boiler	Electric boiler
Fuel consumption cost per tonne of steam (RMB/steam tonne, including taxes)	55.13	291.58	176.17	209.56	615.56
Electricity cost for non-electric boilers in per tonne of steam (based on 0.85 RMB/kWh)	13.0	4.3	2.6	8.9	0
Water cost per tonne of steam produced (based on 1.8 RMB/tonne)	2.16	2.16	2.16	2.16	2.16
Cost of desulfurization per tonne of steam produced (RMB)	1.8	2.1	0	0	0
Labor cost per tonne of steam produced (RMB)	3.44	1.66	1.09	2.29	1.14
Maintenance cost per tonne of steam produced (RMB)	1.1	1.1	1.1	1.1	1.1
Total cost per tonne of steam produced (RMB) (before excluding self-use steam in deaerator)	76.63	302.90	183.12	224.0	619.96

Total cost per tonne of steam produced (RMB) (after excluding self-use steam in deaerator)	80.66	318.85	192.76	235.78	652.59
Annual total operational costs (10,000 RMB) (assuming steam production of 30,000 tonne/yr)	241.99	956.54	578.28	707.35	1957.76

Cost Comparison of Using Different Boiler Fuels

The analysis above indicates that coal-fired boilers have relatively high capital cost to build but low operational cost to run. Natural gas, heavy oil, and electric boilers all have relatively low capital costs but higher operational costs. For easier comparison, this analysis used the method of equivalent annual cost (EAC)[5] to compare the annualized costs of using different boiler fuels. Annualized costs of boilers include annualized capital costs and annual operational costs. Annualized capital cost (F) is calculated as:

$$F = Investment\ Cost\ \times \frac{d}{1-(1+d)^{-n}}$$

where:
d: discount rate
n: lifetime of boiler equipment

Operational cost (O) is calculated as:

$$O = fuel\ cost + water\ cost + electricity\ cost + labor\ cost + maintenance\ cost + desulfurization\ cost$$

Figure 9 compares the fixed investment and operational costs of using different boiler fuels for the case of Xi'an. Given that there are differences in coal, natural gas, and electricity prices in Ningbo and Xi'an, Figure 9 also compares the operational costs of a coal-fired boiler, natural gas-boiler, and electric boiler in the two cities.

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[5] Equivalent annual cost (EAC) is the cost per year of owning and operating an asset over its entire lifespan.

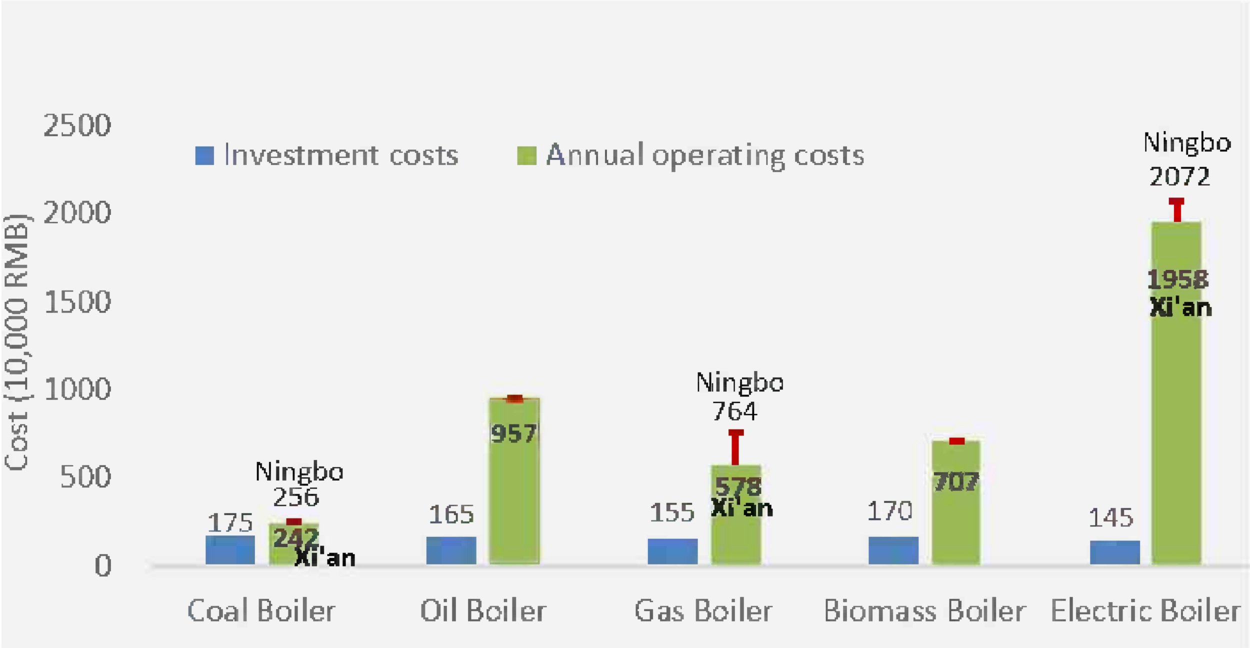

Figure 9. Boiler Cost Comparison of Using Different Fuels

Key conclusions from Figure 9 include:

- Among the studied fuel switching options, the fixed cost of these units does not differ much but operational costs differ significantly due to distinctive fuel prices, which are much higher than fixed equipment costs. Annual operational costs of coal-fired boilers are significantly lower than other types of boilers.
- Natural gas can be a viable option for fuel switching if its price can be kept competitive. For Xi'an, due to relatively lower natural gas price, the operational cost of natural gas-fired boilers are lower than biomass, heavy oil, and electric boilers. For Ningbo, however, due to its relatively high natural gas price, the operational cost of natural gas-fired boilers is higher than biomass, but lower than oil and electric boilers.
- If simply converting chain-grate stoker boilers to natural gas-fired boilers, the operation costs in Xi'an and Ningbo would increase by 139% and 198%, respectively. Thus, the current high natural gas price is the most important barrier to replacing coal with natural gas in small industrial coal-fired boilers.
- Electric boilers are the most costly option mainly due to the energy conversion losses (from thermal energy to electricity, and then from electricity to thermal energy) and higher electricity prices for industrial customers in China.
- Although electric boilers are not an economical option for a complete replacement of coal-fired boilers based on the current higher electricity rates for industrial customers, they can be used as a supplementary energy storage option that can supply or store heat during electricity grid off-peak hours when electricity is inexpensive and the use of excess power (from sources like wind) is desirable. Using Xi'an as an example, for instance, if the electricity price went down to below 0.1 RMB/kWh and 0.25 RMB/kWh, using an electric boiler would be more economical than operating a coal-fired boiler and

a natural gas-fueled boiler, respectively. Table 8 shows the electricity rates in Ningbo and Xi'an, at which using an electric boiler becomes economical comparing with operating boilers of burning other fuels.

- Biomass could be a good fuel switching option but the Chinese government's focus on promoting biomass-based electrification can make it hard to bring industrial use of biomass boilers to scale.

Table 8. Electricity Prices to Make Electricity Competitive to Other Boiler Fuels

Unit: (RMB/kWh)

City	Coal-fired chain-grate stoker boiler	Heavy oil boiler	Natural gas boiler	Biomass boiler
Ningbo	0.11	0.41	0.33	0.30
Xi'an	0.10	0.41	0.25	0.30

Environmental Impacts of Using Different Boiler Fuels

This project analyzed the environmental protection impacts of replacing coal with other fuels for boilers. A calculation of net emissions reduction was made to evaluate the environmental protection impact of switching to alternative fuels. The amount of net emissions reduction refers to the difference in emissions reduction from coal replacement and emissions from using alternative fuels. Take the natural gas-fired boilers for example, the net emissions reduction of switching to natural gas is derived from the emissions reduction from reduced coal use in replacing coal-fired boilers minus the emissions from natural gas-fired boilers. Calculation of the electricity boilers is different. In this assessment, we assume that emissions from using electric boilers are zero.[6] Therefore, in this analysis, net emissions reduction from switching coal to electricity is only the emissions reduction from the avoided coal use from coal replacement. By dividing the cost of alternative fuel boilers (capital cost plus operational cost) with net emission reduction, the economic efficiency of pollution reduction of different alternative fuels, i.e., cost per unit of emission reduction (in the unit of 10,000 RMB per kg/tonne emission reduction) can be calculated.

Figure 10 illustrates the economic efficiency of pollution reduction of replacing coal with other alternative fuels for the case of Xi'an. The economic efficiency of pollution reduction of natural gas-fired and electricity boilers in Ningbo is compared against that in Xi'an in Figure 10 due to the difference of natural gas and electricity prices in the two cities.

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[6] When evaluating emissions, one should consider of the life-cycle effect of consuming any fuels. For example, emissions from the use of electricity are significant from a life-cycle perspective if coal is used to produce the power. In this assessment, however, the boundary of evaluating emissions was set at the end-use stage.

	Natural Gas Boiler	Heavy-oil Boiler	Biomass Boiler	Electric Boiler
🟦 SO2	6.1	9.8	7.5	19.8
🟥 NOX	19.3	25.9	22.1	52.3
🟩 CO2	0.12	0.45	0.32	0.22

Figure 10. Cost-Effectiveness of Emissions Reduction of Boiler Fuel Switching

As shown in Figure 10, natural gas-fired boilers have a better cost efficiency compared to other alternative fuels. For the same fuel, the lower the fuel price, the higher the cost-efficiency of pollution reduction. For example, Xi'an has lower natural gas price than Ningbo; thus, the cost efficiency of using natural gas to replace coal to reduce pollution is much better than Ningbo (indicated in the single vertical line in Figure 10). In addition, Xi'an also showed better cost-efficiency of CO_2 reduction of using natural gas compared to other alternative fuels. Therefore, lower natural gas price is beneficial to promote natural gas boilers, reduce pollution, and reduces CO_2 emissions. Figure 10 also shows that electric boilers are quite low in cost-efficiency of pollution reduction especially for SO_2 and NOx due to their high operation costs even though they do not directly emit pollution.[7]

Prices of Coal vs. Natural Gas

The above analysis showed the importance of fuel prices; thus, it is necessary to construct a price breakeven line between coal and natural gas. Figure 11 illustrates the price breakeven line of producing one tonne of steam at the same cost, using coal or natural gas. Each point on a breakeven line represents the corresponding coal and natural gas prices to make their costs equal. The price breakeven value is calculated from:

$$q_{col} \times h_{col} \times r_{col} = q_{gas} \times h_{gas} \times r_{gas}$$

$$q_{col} \times p_{col} = q_{gas} \times p_{gas}$$

Where: q_{col}: coal consumption per unit of steam produced (kg); h_{col}: lower calorific value of coal (MJ/kg); r_{col}: coal-fired boiler thermal efficiency; p_{col}: coal price; q_{gas}: natural gas

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[7] This analysis does not consider source pollution from electricity generation; rather, it only considers pollution at the end-use.

consumption per unit of steam produced (m^3); h_{gas}: lower calorific value of coal (MJ/ m^3); r_{gas}: natural gas boiler thermal efficiency; p_{gas}: natural gas price.

When the ratio between coal price and gas price is 0.5199, the costs of generating the same amount of steam are the same (i.e., the breakeven point). When the ratio between coal and natural gas price is above the breakeven line (i.e., the red area shown in Fig. 11), natural-gas boilers are more economical and when the ratio is below the breakeven line (the grey area in Fig. 11), coal-fired boilers are more economical. The two dots in Figure 11 represented the existing ratio in Xi'an and Ningbo, respectively, both indicates that natural-gas boilers are less economical than coal-fired boilers in terms of costs. But comparing between the two cities, Xi'an is closer to the breakeven line, indicating that compared to the situation in Ningbo, costs of using coal vs. natural gas are closer to each other in Xi'an.

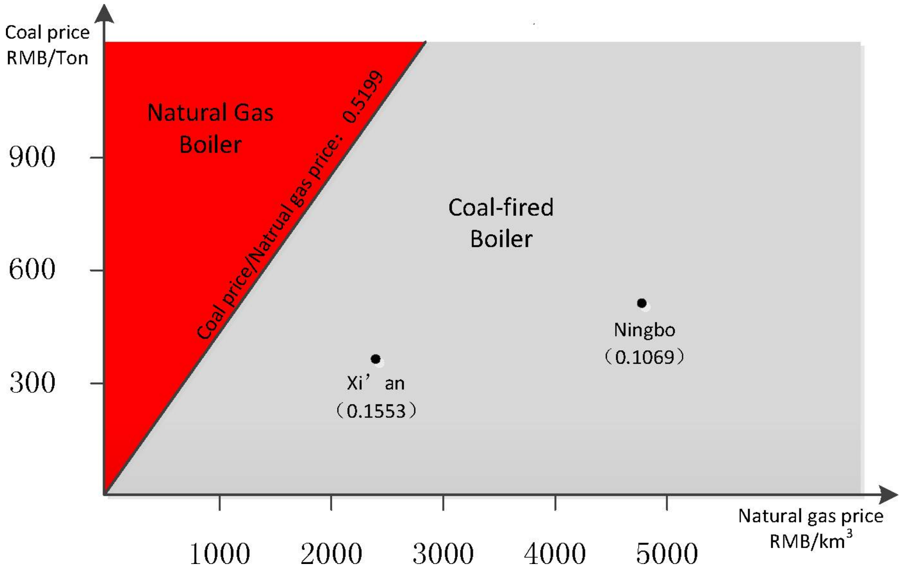

Figure 11. Breakeven Line of Coal and Natural Gas Price

Option 2: Retrofitting existing boilers to improve energy efficiency

As an important measure to combat China's worsening air pollution, the Chinese government has mandated the phase-out of small boilers and requires enterprises to conduct retrofits on coal-fired boilers that are not on the phase-out list (e.g., coal-fired boilers with a capacity of 20 tonnes/hr or larger). This section focuses on assessing the cost-effectiveness of retrofitting coal-fired boilers of 20 tonnes/hr using the information from Xi'an and Ningbo.

Thermal Efficiency Specifications for Industrial Boilers

The national standard *Monitoring and Testing for Energy Saving of Coal-Fired Industrial Boilers* (GB/T 15317 – 2009) applies to industrial steam boilers in the capacity range of 0.7 MW (1 tonne/hr) to 24.5 MW (35 tonne/hr), and industrial hot water boilers with a rated heat supply capacity no less than 2.5 GJ/hour. Table 9 to Table 12 provide key energy-saving indicators of industrial boilers specified by the standard (AQSIQ and SAC, 2010).

Table 9. Thermal Efficiency Evaluation Indicators

Rated Thermal Power Q (MW) [Steam Production D (GJ/h)]	Thermal efficiency η (%)
0.7 ≤Q＜1.4（2.5≤D＜5）	≥65
1.4 ≤Q＜2.8（5≤D＜10）	≥68
2.8 ≤Q＜4.2（10≤D＜15）	≥70
4.2 ≤Q＜7（15≤D＜25）	≥73
7 ≤Q＜14（25≤D＜50）	≥76
Q≥14（D≥50）	≥78

Table 10. Exhaust Temperature Evaluation Indicators

Rated Thermal Power Q (MW) [Steam Production D (GJ/h)]	0.7≤Q＜1.4 （2.5≤D＜5）	1.4≤Q＜2.8 （5≤D＜10）	2.8≤Q＜4.2 （10≤D＜15）	4.2≤Q＜7 （15≤D＜25）	Q≥14 （D≥50）
Exhaust Temperature (°C)	≤230	≤200	≤180	≤170	≤150

Table 11. Exhaust Excess Air Index Evaluation Indicators

Rated Thermal Power Q (MW) [Steam Production D (GJ/h)]	0.7≤Q＜1.4 （2.5≤D＜5）	1.4≤Q＜2.8 （5≤D＜10）	2.8≤Q＜4.2 （10≤D＜15）	4.2≤Q＜7 （15≤D＜25）	Q≥14 （D≥50）
Exhaust Excess Air Index	≤2.2	≤2.2	≤2.2	≤2.0	≤2.0

Table 12. Ash Carbon Content Evaluation Indicators

Rated Thermal Power Q (MW) [Steam Production D (GJ/h)]	0.7≤Q＜1.4 （2.5≤D＜5）	1.4≤Q＜2.8 （5≤D＜10）	2.8≤Q＜4.2 （10≤D＜15）	4.2≤Q＜7 （15≤D＜25）	Q≥14 （D≥50）
Allowable Carbon In Ash (%)	≤15	≤15	≤15	≤12	≤12
Note: Using anthracite, the indicators can increase up to 20%.					

Thermal Performance Testing of Industrial Boilers

In 2014, the Xi'an Institute of Special Equipment Inspection and Testing conducted an inspection on boiler operation conditions and energy efficiency performance testing for 72 industrial boilers. The LBNL team used the 2014 testing results of boilers in a brewing facility in Xi'an to analyze their operation performance and evaluate the cost-effectiveness of taking potential energy-saving measures. Table 13 shows the basic status of the assessed boilers. Table 14 provides the testing results of the boilers.

Table 13. Basic Conditions of Assessed Boilers

Steam Type	Saturated Steam	Rated thermal efficiency	77.70%
Rated Output	20,000 kg/h	Designed fuel	Bituminous coal
Rated Pressure	1.25 MPa	Outlet steam temperature	Saturated
Rated Exhaust Temperature	175.00°C	Economizer	Yes
Combustion Type	Stoker	Air Preheater	Yes
Combustion Equipment	Coal-fired chain-grate stoker	Inlet feedwater temperature	105°C

Table 14. Boiler Operation Testing Results

#	Category	Unit	Data Source	Test Result	Best performance data of surveyed enterprises in Xi'an
1	Excess air index		Testing data	3.02	1.88
2	Boiler exhaust gas temperature	°C	Testing data	210.31	Industrial boiler performance evaluation indicator: 150°C
3	Exhaust O_2 content	%	Testing data	14.04	
4	Exhaust CO content	%	Testing data	0.0142	
5	Inlet air temperature	°C	Testing data	32.41	
6	Fly ash combustible content	%	Testing data	11.25	
7	Unburned combustible in sifting	%	Laboratory data	39.46	
8	Slag combustible content	%	Laboratory data	12.25	
9	Fuel lower heating value	kJ/kg	Testing data	21300.00	
10	Fuel ash content	%	Testing data	20.93	
11	Boiler output	kg/h	Testing data	13000.00	
12	Percentage of slag in total ash content (by weight)	%	Testing data	80.00	
13	Exhaust heat loss	%	Calculated	19.00	12.68%
14	Heat loss due to unburned gases	%	Calculated	0.20	0.20%
15	Heat loss due to unburned carbon in refuse	%	Calculated	5.27	3.82%
16	Radiation heat loss	%	Calculated	2.00	1.3%
17	Heat loss due to sensible heat in slag	%	Calculated	0.50	0.31%
18	Testing efficiency	%	Calculated	73.03	Industrial boiler performance evaluation indicator: 78%

Notes: Testing results are based on 65% of the rated boiler output

The testing results show that heat losses of the assessed boiler are mainly in four areas including relatively high excess air index, high exhaust temperatures, heat loss due to unburned carbon in refuse, and radiation heat loss.

Efficiency Retrofit Measures for Industrial Boilers

Our boiler analysis assessed nine types of energy-saving retrofit measures that are either listed in the "National Key Energy-Saving Technology Promotion Catalogues" published by the National Development of Reform Commission (NDRC) or based on the recommendations by the experts in the field (Du, 2012; UNIDO, 2014). Table 15 describes these measures.

Table 15. Energy-saving Retrofit Measures for Industrial Chain-Grate Boilers

Retrofit Measures	Technology Description	Notes
Exhaust gas waste heat recovery technology	Preheat boiler inlet air temperature or boiler feedwater temperature using exhaust gas through air preheater or economizer to improve combustion efficiency. Normally for every 10°C decrease in exhaust temperature (ensuring exhaust gas temperature is above dew point), boiler efficiency can improve 0.5% - 0.6%.	
Condensate water recovery	Condensate heat recovery can reduce boiler blowdown rate, reduce boiler blowdown heat loss, and improve boiler thermal efficiency. It can reduce water-softening treatment and improve cost savings.	
Boiler water treatment anti-corrosion/ scaling energy-saving technology	Timely treatment of carbonate fouling inside boiler and the pipes to improve water flow rate and heat conduction and ensure boiler operation safety.	The No. 45 listed in the first catalogue of China's energy-saving technologies (published in 2008)
Boiler intelligent soot blowing optimization and online coking warming system	Built on the existing online monitoring of boiler pollution, the intelligent soot blowing operational mode combines open-loop operation with close-loop feedback monitoring to reduce steam use for soot blowing, reduce exhaust gas temperature, and improve boiler efficiency.	The No. 5 listed in the second catalogue of China's energy-saving technologies (published in 2009)
Compound combustion technology for chain-grate stoker boilers	Combining chain-grate stoker with pulverized coal, ignite pulverized coal using the flame on stoker and increase combustion temperature using the high temperature flame from pulverized coal combustion to provide heat source to the coal layers on the stoker and to ensure smooth combustion of coal that is difficult to burn.	
Insulation optimization of steam piping, valves, fittings, and vessels	Based on boiler surface temperature and monitoring exhaust gas temperature, analyze seals and insulation of boiler surface, repair poor seals and broken insulation, and strengthen regular inspection of auxiliary piping, feedwater system, and blowdown system to reduce boiler combustion heat loss and save fuels.	
Excess air management	When excess air index is too high, it will lead to imbalanced mixture of coal and air, resulting to reduced temperature of average furnace temperature, affecting combustion conditions, increasing exhaust, and generating more thermal energy through exhaust, i.e., increasing exhaust gas heat loss. When excess air index is too low, fuels cannot be combusted sufficiently and energy cannot be optimally utilized. Excess air management ensures the conditions of sufficient oxygen for fuel use and complete combustion, as well as cost-effective use of fuels.	
Pollution treatment and heat recovery	Boiler blowdown recovery through surface heating and recovers the heat from boiler feedwater side to improve feedwater temperature, reduce fuel use, and improve boiler output.	
Flash steam recovery	Use a flesh tank system to recover condensate and flash steam	

Table 16 lists the parameters related to the cost-effectiveness analysis of these measures. Assumptions include: (1) baseline efficiency of assessed boilers (i.e., 20 t/h) is based on the actual testing result of thermal efficiency (73.03%) of boilers in Xi'an, (2) boiler output is assumed to be 50,000 tonnes of saturated steam per year at 1 MPa pressure for a boiler at the size of 20 t/h, and (3) the techno-economic analysis is only conducted to compare individual measures and does not consider the synergies of adopting multiple measures simultaneously. The analysis is based on the operation information of industrial boilers in a brewing facility in Xi'an (as discussed above).

Table 16. Economic Analysis of Different Energy-Saving Measures

Measure Type	Key equipment	Thermal efficiency improvement (%)	Equipment lifetime (years)	Equipment installed cost (10,000 RMB)	Equipment annual operational cost (10,000 RMB)	Adoption status in Xi'an*	Notes
Exhaust gas waste heat recovery	Economizer, air preheaters	4—5%	15	70	-	Adopted	Reduce exhaust temperature from 200 ° C to 130 ° C
Condensate recovery	Condensate recovery and utilization device	5—6%	12	50	6	Adopted	Calculated based on 60° C temperature difference between condensate and feedwater temperature
Boiler water treatment anti-corrosion/ scaling energy-saving technology	Alkali boiling with acid washing	1.2—3%	2.5	7	-	Not adopted yet	Water scale thickness assumed to be 1mm
Boiler intelligent soot blowing optimization and online coking warming system	Soot blower and control & monitoring equipment	2—3%	12	35	5	Not adopted yet	Boiler fouling thickness assumed to be 1mm
Compound combustion technology for chain-grate boilers	Fan pulverized system	6%-8%	15	50	10	Not adopted yet	Assume 20% coal to pulverized coal rate, and system power consumption is 26.47 kWh/t
Insulation optimization of steam piping, valves, fittings, and vessels	Pipes, valves, fittings, and vessels	0.75-1.5%	10	20	-	Not adopted yet	—
Excess air management	—	1.5-3%	0.5	0.8	-	Not adopted yet	—
Pollution treatment and heat recovery	Heat exchanger	1.9%	10	35	-	Not adopted yet	—
Flash steam recovery	Flash steam vessel heat exchanger	2.2%	10	45	5	Not adopted yet	—

*Adoption status only indicates whether a measure has been adopted in industrial boilers in Xi'an. Actual adoption rates for various measures are not available.

The annualized investment cost of technical retrofit measures (F) is calculated as:

$$F = Investment\ Cost \times \frac{d}{1-(1+d)^{-n}}$$

where:
d: discount rate (10%)

n: lifetime of energy efficiency equipment (varying)

The cost of saved energy, or CSE, is calculated as:

$$CSE = \frac{F + O - p \times \Delta E - S}{\Delta E}$$

where:
F: annualized capital cost of retrofit measures
O: annual operational cost associated with the retrofit measures/equipment
S: annualized incentive on technical retrofits
ΔE: annual energy saved from technical retrofits
P: coal price

The net cost[8] per unit of energy saved (y axis) and the energy saving potential (x axis) are calculated to create an energy saving cost curve for various retrofit measures to determine these measures' economic and technical potential for energy efficiency improvement. The area below the x axis indicates that cost-savings are greater than investment costs over the lifetime of the technology while the area above the x axis indicates cost-savings are smaller than the investment cost. To understand how fuel prices affect the cost-effectiveness of these measures, two cost curves under different coal prices are constructed (i.e., Ningbo vs. Xi'an). Figure 12 displays the cost curve for each city. Of the nine energy efficiency measures, five and six are cost effective in Xi'an and Ningbo, respectively. The assessment shows that fuel prices play an important role in affecting the economic potential of these measures. Compared the results of the two cities, adopting these measures could create more cost savings in Ningbo than in Xi'an due to its relatively higher coal prices.

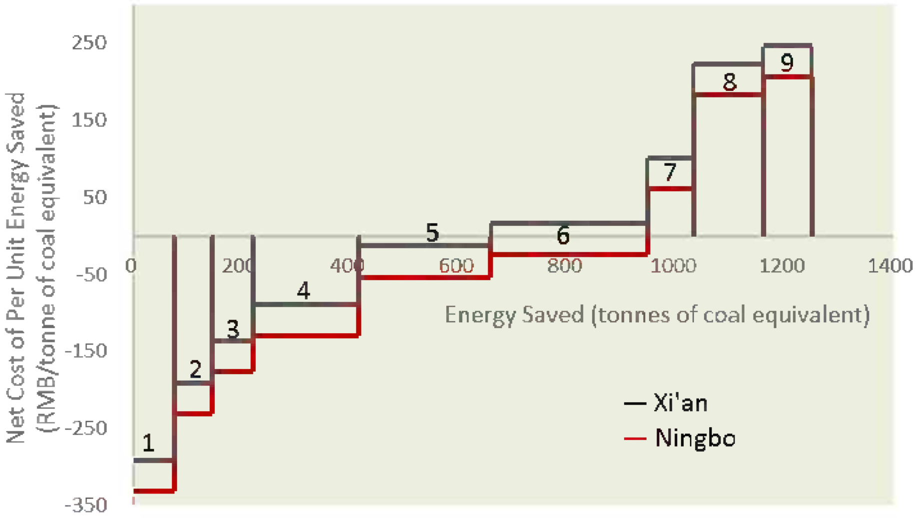

Figure 12. Cost of Energy Conservation of Energy-Saving Retrofit Measures for Boilers

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[8] Net cost-saving is derived from adding the annual avoided operating cost of saved energy due to efficiency gains to the incentives received for pursuing the retrofit, then subtracting the annualized investment cost.

Notes: 1. Excess air management; 2. Boiler water treatment anti-corrosion/ scaling energy-saving technology; 3. Insulation optimization of steam piping, valves, fittings, and vessels; 4. Exhaust gas waste heat recovery; 5. Condensate recovery; 6. Compound combustion technology for chain-grate boilers; 7. Boiler blowdown treatment and heat recovery; 8. Boiler intelligent soot blowing optimization and online coking warming system; 9. Flash steam recovery

In addition to the measures assessed, there are other energy efficiency options that can be adopted but are not included in this analysis due to data shortage or lack of commercialization in China. Examples of additional solutions include improvement of operation management practices, efficient burners, automated combustion control, intelligent boiler cleaning systems with sensors and software, and boiler imaging and temperature measurement technology[9]. The analysis shows that implementing energy-saving measures is often cost-effective. However, in practice, due to technical, informational, financing, and market barriers, these cost-effective measures have not been widely adopted. One of the following sections will discuss these barriers.

Option 3: Eliminate scattered boilers and build a community-scale system to serve the aggregated demand

Chinese cities are in the process of phasing out small coal-fired boilers. This provides an opportunity for cities to design comprehensive plans and compliance strategies to optimize resource use and effectively meet both of the energy and environmental targets. While the small coal-fired boilers are required to be closed, the demand for heat and steam in industrial facilities still exists and must be met. It is important for cities including Ningbo and Xi'an to decide what options to use, i.e., whether to let facilities replace coal boilers with small boilers using alternative fuels (either natural gas-based or other cleaner fuels), or to make a bolder move by developing community-scale systems that could meet the aggregated industrial heat and steam loads of scattered units installed and operated separately by individual facilities.

A distributed energy service center such as a community-scale system is a new strategy to use distributed energy to meet the demands of heat and steam of multiple neighboring companies (in an industrial park setting, for example). In order to reduce air pollution and increase energy efficiency, the Chinese government has been promoting large-scale urban district heating systems by eliminating small, scattered coal-fired boilers. In industry, however, due to the differentiated demand for heat and steam load across industrial users, it is difficult to rely on a large-scale, centralized service. Distributed energy centers not only can meet differentiated demands of industrial users but can also achieve higher resource utilization efficiency that cannot be achieved by scattered boilers. A distributed energy center can use more efficient technologies (such as combined heat and power, CHP) that are not always cost-effective if used at a very small scales. Replacing a number of dispersed boilers with a single community-scale system could also significantly reduce the cost of controlling and monitoring emissions from scattered sources. In addition, a CHP distributed energy system that is capable of producing heat/steam/electricity can become a flexible peaker unit and supply much needed grid support during the electricity grid's peak while at the same time meeting industrial facilities' demand for heat and steam. For example, the U.S. Food and Drug Administration (FDA) collaborated with

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[9] Information about these advanced solutions can be viewed at: http://www.geautomation.com/news/ge-fanuc-intelligent-platforms-announces-optimized-boiler-control-solutions-based-on-proficy-process-systems/n2649; http://www.diamondpower.com/ProductService.aspx; http://www.nrel.gov/docs/fy04osti/33470.pdf

the private sector to build a distributed energy service center in FDA's White Oak Research Center, not only meeting the entire facility's energy demand with a CHP system, but also providing high-value added grid support during grid peak hours by increasing the share of CHP's power generation to maximize project investment return (Honeywell, 2012).

The LBNL team assessed the case of replacing scattered natural gas boilers in five industrial facilities within a 10-kilometer diameter[10] in Xi'an's Lintong District with a potential community-scale system that can serve the aggregate steam and heat loads of the existing facilities. Boiler conditions and the steam/hot water demand of the five facilities are presented in Table 17.

Table 17. Types and Operation Conditions of Industrial Boilers in Five Companies

	Xi'an Standard Industries	Yinqiao Dairy	Yili Group	Xi'an Bangqi Food Oil Company	Shangu Power	
Boiler Type	Natural gas boiler	Natural gas boiler	Chain-grate coal-fired boiler	Chain-grate coal-fired boiler	Natural gas boiler	Natural gas boiler
Number of boiler and capacity (steam tonnes x number of boilers)	10×2	10×3	20×1	20×3	6×2	20×1
Boiler operational thermal efficiency	88	88	75	75	86	90
Thermal medium needed	Hot water	Steam	Hot water	Steam	Hot water	Hot water
Thermal enthalpy per tonne of steam (MJ/tonne) (1.0 MPaG, 184°C, saturated steam) Thermal enthalpy per unit of hot water (MJ/tonne) (<1.0 MPaG, 120°C)	504.09	2779.7	504.09	2779.7	504.09	504.09
Thermal enthalpy of feedwater (MJ/tonne) (steam feedwater temperature 104°C; hot water feedwater temperature 60°C)	251.67	435.95	251.67	435.95	251.67	251.67
Annual steam or hot water demand (10,000 tonnes)	1	10	2	25	0.8	2
Lower Heating Value Natural gas ($MJ \cdot m^{-3}$) Coal ($MJ \cdot kg^{-1}$)	34.469	34.469	22.53	22.53	34.469	34.469
Annual thermal enthalpy demand of steam or hot water (GJ)	2524.20	234375.00	5048.40	585937.50	2019.36	5048.40

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[10] Serving loads within an effective geographical range is desirable for a community-scale system so that heat losses from delivering steam/heat from the system to loads can be minimized.

Fuel consumption Natural gas (km^3) Coal (tonne)	83.22	7726.80	298.77	34675.99	68.12	162.74

This analysis assessed three types of community-scale systems: a natural gas-based CHP, a large coal-fired boiler, and a large natural gas-based boiler that serve the aggregated heat and steam loads of five companies in close proximity. The assessment was to compare these three types of community-scale systems with dispersed natural gas boilers[11] that are operated individually by the five companies in Xi'an. Due to the limits the Chinese government has put on coal-fired power generation units (i.e., it is difficult for units below 200 MW to be approved), this analysis did not consider distributed coal-fired CHP systems.

In this assessment, a community-scale boiler system consists of three coal-fired or natural gas-fired boilers (each 35 tonnes/hr) or a CHP system with two gas turbines (e.g., Taurus 60 made by Solar Turbine) and a natural gas-based boiler (30 tonnes/hr). These configurations are capable of producing the same amount of heat/steam that meets the demand of the five companies. For ease of comparison, this analysis assessed the cost-effectiveness of different types of community-scale systems through comparing their costs which include annualized system capital costs and annual costs associated with operating these systems.

The system annualized capital cost (F) is calculated as:

$$F = Investment\ Cost\ \times \frac{d}{1-(1+d)^{-n}}$$

where:
d: discount rate
n: lifetime of the system

This analysis assumed that the lifetime of a natural gas-based CHP system is 25 years while the lifetime of coal-fired or natural gas-fired boilers is 15 years, and the discount rate is 10%. Table 18 provides key parameters for comparing different types of community-scale systems using information from the five facilities in Xi'an.

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[11] Natural gas boilers are chosen because small coal-fired boilers are prohibited by the government policy.

Table 18. Parameters Used for Comparing Different Community-Scale Systems, Xi'an

Parameters	Natural gas-based community-scale CHP*	Community-scale coal-fired boilers	Community-scale natural gas boilers	Self-operated natural gas boilers by 5 individual facilities
Total equipment investment cost (10,000 RMB)	14000	2400	2100	3600
Annualized investment cost (10,000 RMB)	1542.4	315.5	276.1	473.3
Lower Heating Value of fuels Natural gas (MJ/m^3) Coal (MJ/kg)	34.47	22.53	34.47	34.47
Thermal efficiency	Power generation: 35% Heat supply: 90%	Heat supply: 77%	Heat supply: 90%	Heat supply: 88%
Annual electricity generation (kWh)	6953.4×10^4	—	—	—
Annual self-use of electricity (kWh)	328.7×10^4	510×10^4	100×10^4	306.9×10^4
Electricity price (RMB/ kWh)	0.85	0.85	0.85	0.85
Fuel prices Natural gas (RMB/m^3) Coal (RMB/tonne)	2.28	371	2.28	2.28
Fuel use for power generation Natural gas (km^3) Coal (tonne)	20749.34	—	—	—
Fuel use for heat/steam supply Natural gas (km^3) Coal (tonne)	26914.78	49129.35	26914.78	27526.48
Water consumption (tonne)	35×10^4	40×10^4	35×10^4	38.5×10^4
Water price (RMB/tonne)	1.8	1.8	1.8	1.8
Other costs** (10,000 RMB)	135	200	120	436
Total costs (10,000 RMB)	6976.78	2552.64	6697.66	7515.51

*Relevant CHP information was obtained through personal communication, 2014a

**other costs include labor cost, repair cost, and daily maintenance cost.

This analysis also considered the costs of industrial facilities complying with government pollution control requirements for soot, nitrogen oxides, and sulfur dioxides. Because China is planning to implement a national cap-and-trade program, the cost of CO_2 emissions from coal-fired boilers is also considered in this analysis, based on the average trading prices of seven cap-and-trade pilots in China from June 2014 to May 2015 which was 34.94RMB/ton (Carbon Trading Portal, 2015).

Recent news in China (Sina News, 2015) indicates that the market in China is expecting a further reduction of the natural gas price for non-residential users by 0.40 to 1.00 RMB/m^3 towards the end of this year. This downward price adjustment will certainly help narrow the cost gap between a natural gas-based system and a coal-based system. This analysis therefore also made a cost comparison of the four steam/heat supply options, again using the information in Xi'an as a case and assuming the natural gas price would be reduced by 0.5 RMB/m^3 from its existing level.

Table 19 compares key indicators for the four options and shows the cost comparison results in the case of the five facilities in Xi'an and assuming each option supplying the same amount of heat/steam.

Table 19. Comparison of Community-Scale Systems vs. Scattered Units, Xi'an

Category	**Indicators**	**1. Natural gas-based CHP**	**2. Community-scale coal-fired boilers**	**3. Community -scale natural gas boilers**	**4. Self-operated natural gas boilers by 5 individual facilities**
		Thermal to Electricity Ratio: 3.5: 1			
Equipment	Equipment cost (10,000 RMB)	14000	2400	2100	3600
Fuel	Annual consumption of coal (tonnes) or natural gas (10,000 m^3)	47664.12	48129.4	26914.8	27526.48
Emissions	Soot (tonnes/yr)	13.63	1925.17	7.70	7.87
	CO (tonnes/year)	3.96	88.08	2.23	2.28
	SO_2 (tonnes/year)	30.03	866.33	16.96	17.34
	NOx (tonnes/year)	162.06	437.01	91.51	93.59
Cost (exclude the environmental compliance cost)	Net cost* (10,000 RMB)	6976.78	2552.64	6697.66	7515.51
	% of the cost of option 4: facilities self-operated natural gas boilers	92.8%	33.96%	89.12%	100%
Cost (include environmental compliance cost)	Net cost* (10,000 RMB)	7293.74	3435.33	6876.65	7698.56
	% of the cost of option 4: facilities self-operated natural gas boilers	94.74%	44.62%	89.32%	100%
Cost (with environmental compliance cost and a further reduction of natural gas price by 0.50 RMB/ m^3)	Net cost* (10,000 RMB)	4910.54	3435.33	5530.91	6322.23
	% of the cost of option 4: facilities self-operated natural gas boilers	77.67%	54.34%	87.48%	100%

* Net cost = annualized equipment cost + annual fuel cost – annual revenue from selling electricity produced by CHP

The following conclusions can be drawn from Table 19:

- Although the three types of community-scale system differ in cost, all of them are more economical than five facilities building and operating their individual boilers. From this perspective, replacing separate self-operated boilers with a community-scale system capable of serving the aggregated heat/steam loads of these facilities can be a cost-effective solution.

- A community-scale coal-fired boiler system seems to be the most economical option among all the four supply options studied. If the facilitates' environmental compliance costs are not considered, the cost ratios between community-scale coal-fired boilers, community-scale natural gas boilers, natural gas-based CHP, and facilities operating their self-built natural gas boilers are: 1: 2.62: 2.73: 2.94. However, when considering the environmental compliance costs, the cost ratios change to 1: 2.00: 2.12: 2.24, indicating that the cost advantage of community-scale coal-fired boilers decreases when environmental compliance costs of burning coal is added. More stringent regulations on air pollution and greenhouse gas emissions will increase the cost of using coal.
- Among all community-scale systems assessed in the analysis, the natural gas-based CHP system that is equipped with micro-turbines has the highest cost, which is close to the total cost of five facilities operating their own boilers. The high cost of the system is due to the high equipment cost of micro-turbines in addition to the relatively high natural gas price. Micro-turbines which are the main component of such natural gas-based CHP systems currently have a very limited use in China. With the scale-up of the CHP equipment market, the gradual decline of natural gas prices, and stronger policy support for natural gas-based distributed energy development in China, the economic benefits of natural gas-based CHP systems will be further improved. As Table 19 shows, a further reduction of natural gas prices (e.g., a reduction of 0.50 RMB/m^3 from the current level) can make the CHP system more economical than a community-scale natural gas system and change the cost ratios between community-scale coal-fired boilers, natural gas-based CHP, community-scale natural gas boilers, and facilities operating their own natural gas boilers to: 1:1.43:1.61:1.84.

7. Barriers to Adoption of Energy Efficiency, Fuel Switching, CHP, and Distributed Energy for Industrial Boilers

The techno-economic analysis has shown that retrofitting existing coal-fired boilers, fuel switching from coal to natural gas, and using resources via a community-scale distributed CHP system can be effective alternatives to industrial coal-fired boilers. However, our field investigation visits[12] in Ningbo and Xi'an and our desktop research on challenges revealed that China faces many barriers that can prevent these options from being fully realized. Table 20 lists key barriers to efficiency improvement, to greater use of natural gas, as well as to deployment of CHP and distributed energy (DE).

Table 20. Major Challenges of Adoption of Cost-Effective Solutions for Industrial Boilers

Barriers to Energy Efficiency	Barriers to Fuel Switching	Barriers to CHP and DE
<u>Lack of proper standards</u> • Lack of a proper energy efficiency standards for pulverized coal boilers, small electric boilers, and biomass boilers • Lack of indicators for evaluating boiler performance at the system level • Lack of standardized boiler operation practices, tune-up procedures, and water treatment requirements <u>Lack of proper technologies and steam system-wide solutions</u> • Small market share for energy efficient technologies such as fluidized bed boilers • Boiler design and manufacturing focus more on safety and less on energy performance • Missed opportunities in	<u>Lack of effective planning</u> • Lack of effective strategies, viable plans, and technical support to fill the gap created by mandatory elimination of coal-fired boilers, resulting in lost opportunities to deploy comprehensive solutions <u>Market uncertainty and lack of market competition or scale</u> • The need for and process of government pre-approval of industrial natural gas projects creates uncertainty for investments in natural gas • Monopoly of local gas supply limits market competition and the entrance of third-party suppliers • Private suppliers lack long-term LNG supply contracts with foreign partners creating difficulty for securing government	<u>Regulatory and administrative barriers</u> • CHP and DE systems lack access to the electrical grid and thermal distribution network, resulting in operations in "Island Mode" and preventing these systems from maximizing their investment returns • Burdensome permitting prolongs the process to approve and construct CHP and DE • Lack of comprehensive plans for CHP and DE leads to highly fragmented operations and creates improper economies of scale <u>Institutional barriers</u> • Lack of coordination between heat supply and heat distribution systems which are managed by different parties, affecting effective operation of

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[12] Field investigation visits to Ningbo and Xi'an were conducted by the LBNL research team along with the Chinese expert team including Wei Xiangyang and Zhang Yunpeng of National Energy Conservation Center, Guan Jian of China Special Equipment Inspection & Test Institute, Hou Rui of China Machinery Industry Conservation & Resource Utilization Center, Zhang Junfeng of China National Offshore Oil Corporation, Zhuo Yuqun of Tsinghua University, Xia Shumao of China Energy Conservation & Environmental Protection Group, and Han Yafeng of Xi'an Jiaotong University in October 2014 and January 2015.

realizing steam system-wide improvements • Lack of intelligent systems and automation capability, preventing optimal boiler operation Lack of good operation practices and effective management • Use of cheaper raw coal and lack of composition testing of the coal purchased leads to sub-optimal boiler performance • Lack of good operation practices, leading to low efficiency • Use of low-end, inefficient natural gas or biomass boilers due to higher fuel prices Lack of capacity • Low education levels and lack proper training for boiler operators weakening the capacity for efficient operations • Lack of resource guides, best practices, and toolkits about energy efficiency opportunities and management practices Lack of monitoring and enforcement • Lack of tracking and reporting of boiler energy and environmental performance • Lack of strong measures to enforce established boiler efficiency targets and emissions standards	approval to build LNG receiving terminals • High investment risks for private companies due to prohibitive capital costs of building LNG projects and the price volatility of LNG and natural gas • Private suppliers leasing LNG ports from state-owned companies do not have transparent information on the port's available capacities nor do they know the time needed to obtain the approval of these state-owned companies • Uncertainty about government strategy on biomass increases hesitation of private companies to invest in biomass boilers • Production of biomass materials dominated by small firms that cannot survive without government subsidy Shortage of gas supply and high gas prices • Shortage of gas supply for industrial use due to prioritization of residential and public sector gas use • Higher industrial gas prices due to the growing gaps between demand and supply and the subsidized prices for residential and public gas use • End-users lack effective financial instruments and risk management strategies to hedge against fuel price volatility	a city's heating system • Lack of active participation of third-party players like energy service companies due to limited access to finance, slowing the expansion of CHP and DE Market and financial barriers • Utilities view CHP and DE as potential competitors that may reduce their sales • Actual costs for producing and distributing power and heat from CHP and DE are not always reflected in the tariffs, making investment in CHP and DE less attractive • Heat services for residential and public sector are often at a flat rate, disincentivizing energy savings while discouraging investments in CHP and DE • First-cost hurdle and lack of access to finance directly hinder the expansion of CHP and DE • Lack of tax and fiscal incentives and other stimulating measures to spur investment in CHP and DE Technical barriers • Lack of experience and tools for designing optimal system configurations, creating over-sized, inefficient systems • Distributed CHP lacks modular design to have a flexible capacity in providing value-added services (e.g., serving as a peaking unit), resulting in the loss of potential economic gains from CHP and DE

Sources: China Energy Newspaper, 2012; China Energy Newspaper, 2013; China LNG International Summit, 2015; MEP, 2013; Personal Communication, 2014a, 2014b; Sina News, 2013

Barriers to Improving Boiler Efficiency

Lack of Proper Standards

Over last decade, China has issued a series of standards governing industrial boilers, especially coal-fired boilers. Despite this effort, there is a lack of a proper efficiency standards regulating pulverized coal boilers, small electric boilers, and biomass boilers, which leads to inefficient boilers easily entering the market as industrial facilities replace the coal-fired boilers that are required to be retired with other types of boilers. In addition, China lacks performance indicators to evaluate the boiler performance at the system level in the steam system. Further, there is a lack of standardized operation practices, tune-up procedures, and water treatment requirements associated with industrial boiler operations, leading to reduced efficiency.

Technologies Focus Less on Energy Performance and Lack of System-Wide Solutions

The majority of China's industrial boilers are small in capacity. Average capacity of a coal-fired industrial boiler is about 3.8 tonnes/hour. Close to 67% of the total industrial boilers are smaller than 2 tonnes/hour, as illustrated in Figure 13. Traveling grate boilers represent 95% of the entire coal-fired boilers in China. Fluidized bed boilers, that are much more efficient, lower in emissions, and high in coal fuel adaptability, are used at a very limited scale, accounting for merely 3-5% of the total coal-fired boilers in China.

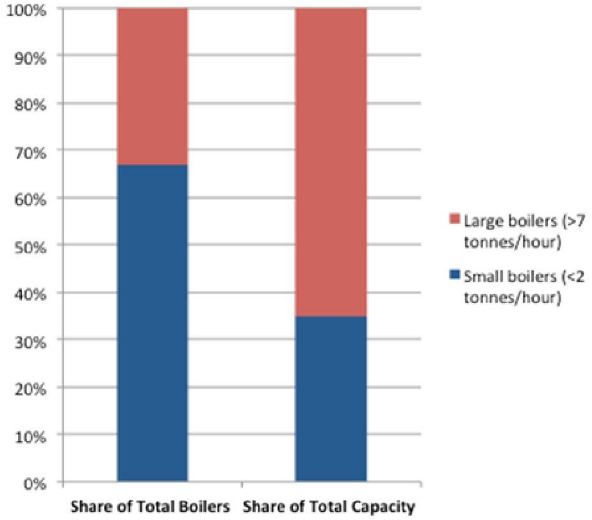


Figure 13. Breakdown of Small and Large Boilers in China's Industrial Sector

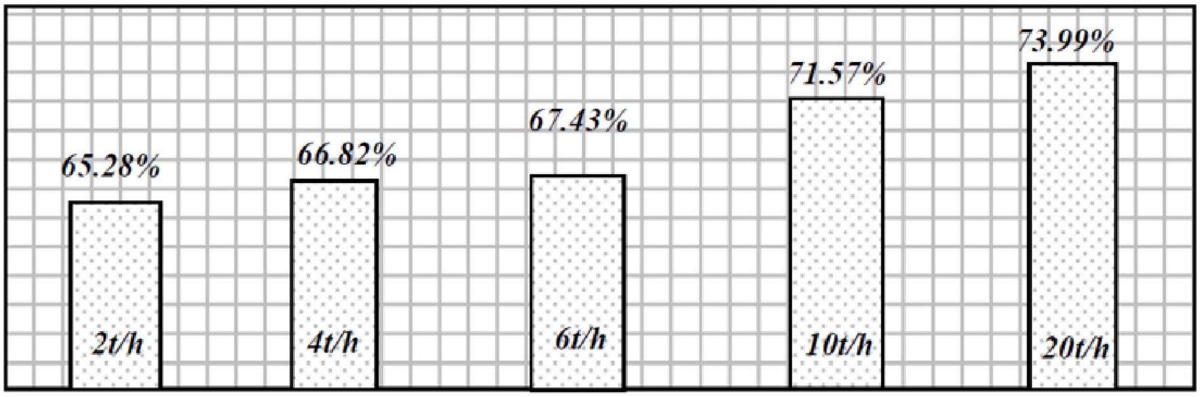
It is often the case in China that as a specialized piece of industrial equipment, boiler safety is emphasized. As a result, Chinese boiler manufacturers have focused more on pressure components and less on combustion, compromising energy performance. As a result, industrial facilities often fail to capture opportunities in steam system-wide improvements. It has been found in literature review (Zhang, 2005) and the filed investigation in Xi'an that auxiliary equipment for boilers, such as pumps and fans, are often sized larger than required. In addition, the quality and performance of the auxiliary equipment is reported to be low as well. Field research in Xi'an found that boiler steam systems have poor insulation and sealing, large openings, and high heat losses. All these problems are created by the lack of integrated steam system design for achieving optimal performance.

Another reason that industrial boiler users do not achieve optimal energy performance is the lack of intelligent systems that automate boiler operations and monitor and control combustion, temperature, oxygen, and water to enable boilers to be operated under the best conditions. Operating conditions of industrial boilers in China are significantly below optimal. A larger number of industrial boilers are quite old, manufactured in the 1970s or 1980s, and have been operating at low efficiency the last 40 years. These boilers are typically operated manually with little or no automation. Most of the controls are loop control, which cannot automatically adjust boiler operation status based on changes in energy use. Thus, it is difficult to operate and control the boiler combustion and performance to adapt to the needed changes in a short time. In addition, due to a lack of effective monitoring devices, boiler operators often lack data to make decisions quickly and effectively to ensure optimized operation.

Lack of Good Operation Practices and Effective Management

In China, raw coal is the main fuel input for industrial boilers. However, the quality of coal is very poor, with high ash and sulfur content. Very often, boiler operators choose to use raw coal, instead of less polluted but more expensive washed coal. The field investigation in Xi’an found that some boiler owners did not conduct composition testing on the coal purchased. The coal used in boilers is often raw coal, without washing, screening, or proper blending. Poor control of coal used for industrial boilers leads to incomplete combustion, sub-optimal boiler performance, low thermal energy efficiency of boilers, and wasted fuels.

Based on a report commissioned by the Chinese Academy of Engineering, the average efficiency level of industrial coal-fired boilers in China is only about 60%. If the efficiency can be improved to 80% or higher, it is estimated that about 100 million tonnes of coal can be saved on an annual basis (Gao, 2013). Figure 14 shows the thermal efficiency of various sizes of industrial boilers based on an industrial boiler survey conducted by China’s Ministry of Science and Technology and Ministry of Environmental Protection in 18 Chinese cities (Gao, 2013). One viable solution to improving boiler energy efficiency is to adopt larger and more efficient boilers.



Source: Gao, 2013

Figure 14. Thermal Efficiency of China’s Industrial Boilers

The field investigation in Xi'an found that boiler thermal efficiency is low mainly for three reasons. First, boilers have poor performance on key parameters related to efficiency, such as excess air, high exhaust gas temperature, and the unburned carbon content in the ash, leading to significant amount of heat losses. Even though the majority of coal-fired boilers are equipped with economizers, the thermal recovery efficiency of these economizers is fairly low. Second, the field research found that less than 60% of the boilers in Xi'an have effectively installed and used condensate recovery. Most boilers were not designed to incorporate steam condensate recovery and boiler users are reluctant to invest in condensate recovery after boilers began operation. Some boilers did install condensate recovery devices, but did not implement proper measures to treat condensate recovery, which led to low quality of condensate recovery and cannot be reused. Lastly, some condensate recovery devices did not take into account acid corrosion problems in the condensate recovery systems.

Our field investigation also found that with the government mandates to phase out small coal-fired boilers, many industrial facilities took actions to procure replacement boilers. Due to higher natural gas or biomass prices, however, these facilities selected low-end natural gas or biomass boilers that were less energy efficient.

Lack of Capacity

In China, there is a general lack of technical capacity among boiler operators who normally have low education levels. The lack of adequate training on use of boilers and auxiliary equipment and energy management further weakens the capacity for efficient operation of boilers. Boiler operators often do not have the most updated knowledge and information to improve the energy and environmental performance of boilers. For example, based on the investigation in Xi'an, about 50% of the boiler technicians have an education level lower than high school. Some boiler owners in Xi'an did not even provide boiler operation training to technicians before they started working. Field research in Xi'an and Ningbo also indicated that boiler operators have quite low compensation and fast turnover, which leads to minimal responsibility and lack of motivation. The lack of proper resources such as resource guides, best practices, and toolkits related to boiler energy efficiency further exacerbates the problems, pointing to a need for enhancing the capacity of the boiler operators.

Lack of Monitoring and Enforcement

Weak enforcement of relevant standards also adds to the problem of lower efficiency boiler operations. Taking water treatment as an example, even with boiler water quality standards, it is reported that water used in China's industrial boilers is of poor quality. LBNL's field investigation in Xi'an found that only about 70% of the boilers were equipped with water treatment devices. Some boiler owners did not conduct proper maintenance, using water softening devices as filtering devices. Some boiler owners installed deaerators but only used them occasionally. In Xi'an, only half of the boilers meet the national water quality standards. Due to poor water quality, industrial boilers have experienced issues of heavy scaling, sometimes with scaling more than 5 millimeters (mm) or 10 mm thick. Investigations in Xi'an found that some companies rely on chemicals for water treatment, rather than adopting proper water treatment procedures. This made de-scaling or scale prevention in the boiler operating stage even more difficult. Moreover, in order to keep good water quality inside the boilers, rather than adjusting boiler blow-down rates based on water quality, some boilers kept boiler blow-down at a very high level, sometimes up to 20-30%, which significantly increased energy consumption (Zhang, 2005).

There is also a lack of strong monitoring and reporting on boiler energy and environmental performance. This could have direct impacts on enforcement. In the U.S., to implement the Maximum Achievable Control Technology (MACT) standards for boilers, the U.S. Environmental Protection Agency (U.S. EPA) has not only instituted requirements for monitoring, recordkeeping, and data reporting for commercial and industrial boilers but has also created a national database with information on over 150,000 boilers that together consume about 40% of all energy consumed in related sectors (U.S. EPA, 2013a; U.S. EPA, 2013b; U.S. EPA, 2014). Practices in data monitoring and reporting from other countries can provide valuable experience for China.

Barriers to Fuel Switching

Lack of Effective Compliance Plan and Strategies

Elimination of small coal-fired boilers has become a key task for China's cities. This task is primarily carried out by the local environmental protection bureaus in order to meet the air pollution reduction mandate. Although the elimination is enforced through mandatory requirements coupled with lump sum financial compensation,[13] there is a lack of both comprehensive plans to direct city actions after the phase-out and effective programs to guide industrial facilities to develop strategies to continuously meet their needs for heat and/or steam following the phase-out. Neither applicable planning nor adequate technical support are in place to help facilities to effectively make the change, thus missing key opportunities to develop effective strategies and to deploy optimal solutions.

Market Uncertainty and Lack of Market Competition

NDRC issued a Directive on November 4th, 2013 requiring that any proposed projects using natural gas or replacing coal with natural gas have to first have a secured gas supply contract. Without such a pre-condition, projects using natural gas will not be approved and construction needs to be stopped. The Directive also requires that all gas-fired CHP facilities be included in the 2013-2015 government electricity expansion plans and cannot be developed outside the government plan (Twenty-First Century Business Herald, 2013). This could bring uncertainty for investment in natural gas-fired systems. Moreover, NDRC has further mandated that demand for natural gas must first be met in the residential and public sectors. This could lead to even larger shortfalls for industrial use of natural gas.

Local gas company monopolies have limited market competition and the entrance of third-party suppliers, causing difficulties for industrial users to find alternative suppliers and to negotiate gas prices. In Ningbo, for example, there is only one regional natural gas supplier – a provincial gas company that owns and manages the local distribution network and pipeline assets. Because of the monopoly power of the provincial gas company, industrial users face difficulty in negotiating natural gas prices. The lack of negotiation power over pricing has increased the cost burden for industrial users even more in a city like Ningbo where the natural gas price is already higher due

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[13] The compensation amount varies in regions. For example, Xi'an offers RMB 20,000 per tonne/hr of capacity while in Ningbo facilities are compensated with unit value of RMB 40,000 per tonne/hr.

to the fact that the city is located at the end of the West-to-East Gas Transmission Line. Recently, some private suppliers have started getting into the gas distribution business, building storage tanks near industrial facilities and delivering LNG to these customers at a slightly lower price than that of the provincial gas company. Although entering into the market of private gas delivery companies might provide options for industrial users, without proper oversight and enforcement of strict safety rules, this private delivery of natural gas increasingly becomes a serious safety concern.

For cities like Ningbo that are also LNG ports, greater use of LNG could be an alternative to natural gas supplied through a pipeline. However, port cities like Ningbo are facing challenges that prevent them from increasing the use of LNG. First, almost all LNG receiving terminals were built and operated by the state-owned companies like China National Offshore Oil Corporation (CNOOC). Since private suppliers lack long-term LNG contracts with foreign partners, it is very difficult for them to secure government approval to build LNG receiving terminals. There are also significant investment risks for private companies to develop LNG projects due to high capital costs. In addition, lack of transparent information on the port's available capacities and on the time needed to obtain the approval of using the port creates difficulty for the private suppliers to lease LNG ports.

There is also market uncertainty related to using biomass as a replacement for coal in boilers. On one hand, the central government's focus on increasing biomass use for power generation creates a situation where private companies are hesitant to invest in biomass boilers. On the other hand, production of biomass materials are dominated by small firms that cannot survive without government subsidies, creating uncertainty for biomass boiler users to secure a reliable supply of biomass fuels.

Shortage of Gas Supply for Industrial Use and High Gas Prices

Cleaner fuels such as natural gas are increasingly used to replace polluting coal in China due to the worsening air pollution confronting many cities. However, lack of natural gas supply especially for the industrial sector prevents a widespread switch to natural gas. Because of the increased need for natural gas, the gap between demand and available supply for the fuel increased by 40% in 2013, accounting for 6% of total natural gas demand in China (National Business Daily, 2013).

The industrial use of natural gas is further constrained by the increasing consumption of natural gas for meeting the growing heating needs in China's cities. In China's winter heating zone, the total building area equipped with heat supply has more than tripled from 1 billion square meters to 4.5 billion square meters in last 10 years (China Energy Newspaper, 2012). This service growth requires a significant increase in the use of fuels to produce a large amount of heat.

Industrial natural gas users have been facing higher gas prices due to the growing gap between demand and supply and the subsidized prices for residential and public gas use. To address the shortage of natural gas supply, NDRC raised the price of natural gas in 2014 from an average price of 1.69 to 1.95 Yuan/m^3, an increase of 15%. This price increase raises the cost of using natural gas (National Business Daily, 2013). The natural gas price for industrial users is higher than that paid by residential customers and public institutions, which is on average 30% lower (China News, 2015). This makes the industrial natural gas price about four times higher than the coal price.[14] The natural gas price is less flexible due to the lack of competitiveness in supplying natural gas. Despite of potential decrease of imported natural gas price due to the lower price of international natural gas supply, China's current high natural gas price significantly increases the operation costs of industrial natural gas users. To offset the much higher fuel price, industrial users often chose to install cheaper – thus less efficient – gas boilers, creating a possible situation that replacing coal with natural gas will not cut air pollution due to the higher NOx emissions of the less efficient boilers.

Industrial users also experience high LNG prices. From August 2014 to November 2014, China's average price of spot LNG imports increased from \$11/MMBtu to almost \$13/MMBtu (ICIS & C1 Energy, 2014). However, end-users lack effective financial instruments and risk management strategies to hedge against fuel price volatility.

Barriers to Deploying CHP and Distributed Energy Systems

Although the Chinese government has provided policy support to both CHP and distributed energy, the uptake of these technologies faces a number of barriers on several fronts. Some of these barriers are unique to large CHP projects while other barriers exist for small, distributed applications.

Regulatory and Administrative Barriers

The lack of consistent and predictable access to electric grids and thermal distribution systems is one of the greatest barriers to both CHP and distributed energy deployment in China. There is a need for a defined and predictable process and schedule as much as technical standards for interconnection regarding the accessibility to the thermal network or electricity grid. Because of grid companies' restrictive rules on interconnection, CHP and distributed systems are often operated in "Island Mode," which creates missed economic opportunities for CHP and distributed energy projects to sell surplus power and/or heat in a bigger market. The risk of not being connected and perceived "negative" economic consequence lead investors to often believe that investments in CHP could not be recovered in a preferred amount of time.

Even when CHP units are connected to the grid and are allowed to sell power to the grid, the amount of electricity to be sold is strictly capped by the heat to electricity ratio. This cap is often applied to the large thermal power plants and established to ensure CHP systems are built to the right size and meet heat demand. However, a cap limiting the amount of electricity could be sold to the grid based on the pre-determined heat to electricity ratio would greatly reduce the flexibility for the use of CHP. While recognizing the heat to electricity ratio is critical to ensure the right size for CHP units, a mandate on this would make CHP projects less economically attractive or would mean that they operate as a partial load with lower efficiency. To ensure CHP projects are implemented in an optimal way, it is important this cap can be removed.

Another regulatory barrier to the wide use of CHP in China is the time-consuming permitting process to approve and construct a new CHP plant. Investors and project developers often opt to install traditional boilers (which are more energy-intensive and emit higher emissions) for heat in

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[14] Based on the weighted average coal price of December 2014 to April 2015 that considers seasonal price variation due to the changing demand for coal in different seasons.

order to avoid the lengthy approval process for building a CHP plant. A more prompt and less burdensome permitting process is needed to accelerate the expansion of CHP projects.

In China, CHP development could face some difficulty (at least in perception) under the nation's effort to eliminate small coal-fired systems. CHP units, especially coal-fired units, might be perceived as small thermal power plants that could be phased out under the central government's "elimination" policy. Due to this concern, local governments are more willing to build over-sized units, resulting in lower operation efficiency and prolonged payback time for investors. This is exacerbated by the lack of effective forecast and regulatory oversight for heat planning in China. This ad-hoc approach to develop CHP systems has led local CHP systems and heat distribution facilities to become highly fragmented. As a result, proper economy of scale or higher energy utilization has not been achieved. The lack of a comprehensive and concerted effort to plan for CHP has fostered uncoordinated establishment of heat/power supply networks and operations.

Institutional Barriers

Ideally, a city's heat supply, distribution, and consumption should be integral components of the city's heating system. However, in many Chinese cities, these components are separately controlled by different entities. For example, most thermal power plants are owned and operated by state-owned enterprises while distribution systems are owned and operated by entities under the governance of local governments. Lack of coordination between the heat supply and heat distribution system is an institutional barrier to effective operation of urban heating system including the use of CHP applications. In addition, there is a lack of active third-party players like energy service companies (ESCOs), thus slowing the expansion of CHP and distributed energy. While ESCOs are active in pursuing industrial retrofits in China, they have not yet entered into the field of CHP and distributed energy systems. There is potential for third-party players like ESCOs to unlock this opportunity if they have the access to financing.

Market and Financial Barriers

Electricity utilities and heat service providers perceive the development of CHP and distributed energy as market threats to their businesses. They often view CHP units and distributed systems as potential competitors that may not only reduce their sales but also increase risks and costs if connecting these units to existing grids or heat distribution systems. This perceived market threat and risks have led utility companies to be less willing to cooperate in facilitating interconnection of CHP and distributed energy systems in China.

Both coal and natural gas, which are used by CHP units as fuels, are purchased at market prices, while the services these units provide - electricity and heat - are often subsidized, especially for public and residential uses. The actual costs for producing and distributing power and heat from CHP therefore cannot be properly reflected in the tariffs. This makes attracting investment for CHP deployment difficult. The ineffectiveness of pricing is also seen in China's heating services provision. CHP developers often find it hard to compete with conventional boiler houses in terms of service price. For buildings in Beijing, for example, the price for heat service from a locally-operated boiler house was 19 RMB/m^2 while prices for district heating and heat produced from coal-fired CHP systems ranged between 24 RMB/ m^2 and 30 RMB/ m^2 (China Energy Newspaper, 2012).

Existing practices in charging heating services at a flat rate per square meter without metering the actual consumption in China's building sector disincentivize energy saving or efficiency improvement because any improvement made will not reduce the charge. A flat-rate scheme also makes it hard for service providers to recover investment costs and to be profitable. Outside China, a heat tariff is broken into two parts: a fixed tariff or capacity charge that a user has to pay regardless of whether there is actual consumption and a variable rate where consumers are charged based on the level of consumption. Due to the capped heat price, heat service providers who own and operate heat distribution systems often do not have adequate funding to upgrade distribution systems and thus rely on low-cost maintenance measures. As a result, heat losses in the distribution process are high, reducing the overall efficiency of the heating system.

There is also a first-cost hurdle for deploying highly efficient systems like CHP which requires significant upfront investment. When deciding on projects, industrial users often focus on the project's initial capital costs and pay less attention to the operational cost (e.g., fuel and maintenance costs), which is closely tied to the system efficiency (Personal Communication, 2014b). Without proper measures such as incentives or financing for overcoming the first-cost hurdle, CHP projects face great difficulty in becoming widely adopted.

Unlike large, state-owned enterprises that have an easy access to finance, most industrial customers and energy service companies in China are relatively small in terms of assets and thus experience difficulties accessing finance. Tight lending control makes financing even harder. In an effort to curb the expansion of energy-intensive sectors, for example, the Chinese government has made it more difficult for these sectors to borrow money. While this restriction is important for curbing the unmanaged expansion of energy-extensive sectors, it to a large extent blocks a vital pathway for these sectors to obtain financing to adopt more efficient measures such as CHP.

Despite the Chinese government's push for greater CHP deployment, there is a lack of tax incentives and other stimulating measures to spur greater investment in CHP. Before 1994, CHP operators were only charged a 5% business tax, which was refunded after the tax was paid. After the 1994 tax reform, however, this tax benefit disappeared. CHP operators have been treated the same as other types of business, paying 17% sale tax for electricity generated and 13% sale tax for heat produced. Although government policies have been issued (e.g., by the National Energy Administration) to encourage distributed energy demonstration projects, no stimulating measures such as incentives and favorable tax treatment are yet available to support this policy. Over the past years, the Chinese government has been providing a significant level of public funding to incentivize a wide variety of energy efficiency retrofits. These incentives have, however, not been extended to neither CHP nor distributed energy projects.

Technical Barriers

Chinese power design institutes and power plant developers are competent in building large-scale thermal power plants. However, the design principles for distributed CHP systems are different from those for large plants (Personal Communication, 2014b). The lack of ability to create an optimal design for a distributed CHP system compromises its expected efficiency. In the optimal operation mode, for example, advanced gas turbines manufactured by General Electric (GE) could achieve an efficiency level as high as 90%, but the same turbine technology can only achieve an average efficiency level of 30-40% in China due to less optimal design of

CHP systems as well as the inability to sell power to the market (Personal Communication, 2014a).

CHP systems achieve the greatest efficiency when production of heat and electricity can be optimized. Greater integration of CHP and distributed energy systems within a grid and heat service network is essential to improve the performance of these systems. For example, when some CHP units for providing heat are idle during non-heating seasons, they can be used for producing electricity (or even cooling) if these systems are linked to other users. For another example, a CHP system powered by natural gas could become an electricity peaking unit to help electric utilities meet its peak load. So far, distributed CHP in China lacks modular design to have a flexible capacity, resulting in the loss of potential economic gains from optimal use of CHP and distributed energy.

8. Roadmap to Remove Barriers to Capturing Greater Opportunities for Industrial Boilers

China needs effective strategies to realize cost-effective opportunities and remove the barriers identified in this assessment. Based on the relevant experience of the U.S., we recommend the strategies highlighted below.

Take a holistic approach to addressing coal-fired industrial boilers

To effectively address the boiler issues, China needs to consider adopting a holistic approach and take systematic actions such as those outlined by the framework in Figure 15. The core strategy of this holistic approach is to use solving the issues related to industrial coal-fired boilers as a trigger to drive policy changes and broader actions. Adopting a holistic approach also requires the concerted and coordinated efforts of government agencies.

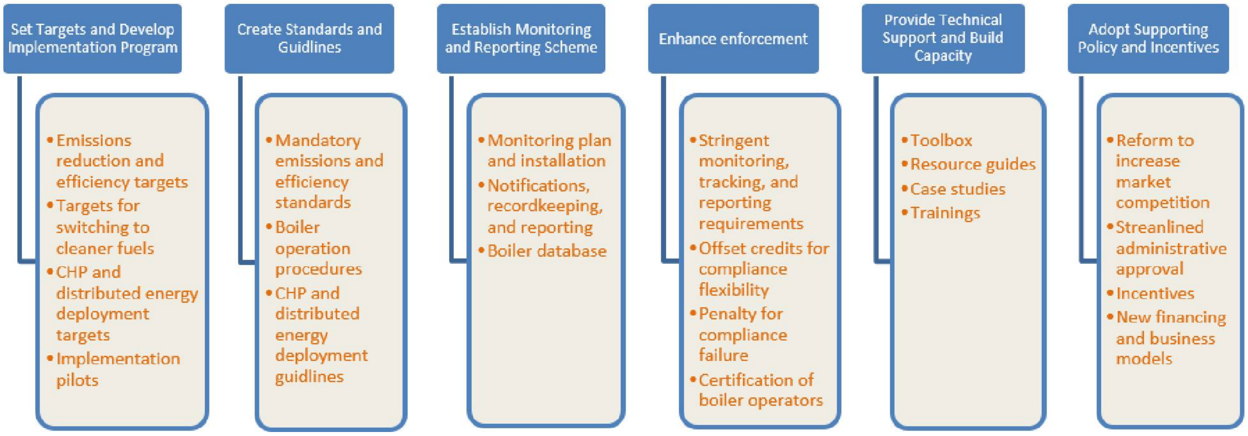

Figure 15. Illustration of holistic approach for improved industrial boilers

Develop and deploy cost-effective compliance strategies

Without effective compliance strategies, opportunities with the potential to create greater savings, reduce waste, and promote CHP and distributed energy could be missed. The requirement for eliminating small coal-fired boilers presents a perfect opportunity for industrial facilities to adopt compliance strategies that are cleaner, more efficient, and have positive economic returns over time. It is important for city governments to provide the necessary resources to support facilities' development and deployment of cost-effective compliance strategies. It is also important for cities to leverage the opportunity to undertake appropriate plans that will accelerate and coordinate efficiency improvement, fuel switching, and the adoption of CHP and distributed energy.

Create enabling policy

Pursuing broad compliance strategies requires policy changes on several fronts. First, China can increase market competition and reduce "soft costs" by adopting facilitation policies and reducing administrative hurdles to encourage the market entrance of private service providers and third-party suppliers. Second, city governments can effectively engage the private sector through public-private partnerships in building gas supply infrastructure and expanding the heat distribution networks. Third, continuing reforms on gas pricing are needed to reduce disparities in prices between the industrial sector and other sectors (e.g., residential) and to reduce the windfall profit of monopolized gas companies. Fourth, to attract private investments China could establish a "feed-in" tariff for CHP and distributed energy projects to encourage technological cost reductions and to provide market certainty that help attract finance for these projects. Finally, China could consider improving policies to facilitate the increased access of private businesses or industrial CHP and distributed energy systems to state-owned gas distribution systems, LNG receiving terminals, local electric grids, and cities' thermal distribution networks.

Accelerate technology development and deployment via incentives

Technology advancement is important to addressing the boiler challenge. China will continue to use coal as a main energy resource in the foreseeable future and has plans to use coal in a cleaner and more efficient manner. Nonetheless, it is also important for the country to make strategic efforts in the research and development, technology development, and market deployment of alternative solutions to avoid creating an energy infrastructure that will be dependent on coal in the long run. Tax and financial incentives provided by the government could help accelerate the development and deployment of alternative energy solutions such as boiler system optimization, low carbon fuels (such as natural gas, shale gas, biomass, and solar thermal), and integrated applications such as waste-to-energy, CHP and distributed energy.

Develop effective standards and guidelines

It is important for China to formulate effective energy efficiency standards and associated testing protocols that set proper energy performance requirements for industrial boilers consuming coal or alternative fuels. China also needs to develop effective standards or consistent procedures governing boiler-related coal processing, operations, tune-up, and water treatment as well as specifications that set goals for boiler and ancillary parts performance at the system level. To ensure the optimal performance of boilers, policies need to consider setting necessary requirements for boiler design, manufacturing, and operations. In addition, the development of standards regulating the performance of CHP and distributed energy is essential to the widespread adoption of these applications. Finally, it is important for China to formulate rules and standards for interconnecting CHP and distributed resources with power and heat networks.

Promote advanced technologies and integrated solutions via implementation pilots

Creating pilots can be an important way to demonstrate and validate new solutions. City pilots can help cities shift into new ways of planning that focus on integrated solutions and networked opportunities. Specific technology adoption pilots under the city pilots could be created to demonstrate diverse types of solutions such as advanced coal processing technology, efficient and low-emissions burners, intelligent boiler monitoring and controls, steam system optimization, community-scale distributed energy centers employing CHP, co-generation of steam, heat, cooling and power, boiler preheating enabled by solar thermal application, and other such technologies.

Stimulate greater investment via innovative business models and financing mechanisms

In China, innovations in business models and financing are essential to stimulating private investments in advanced technologies and integrated solutions. China can consider several different models. For example, boiler manufacturers' business models can change such that instead of supplying equipment, they can supply steam or heat services. Another financing model that may be considered is one that is similar to the Power Purchase Agreements (PPAs), a popular option in the U.S. This model would require the development of a service scheme with fee payment or a long-term service purchase agreement. China can also encourage the formation of public-private partnership in which the administrator of a local industrial park can aggregate the needs of its industrial customers and solicits bids for heat/steam/electricity services.

Strengthen enforcement and enhance its effectiveness via great flexibility

It is necessary for China to continue to strengthen regulation compliance enforcement efforts. To this end, it is essential for China to enhance its capacity in monitoring, reporting, and verifying regulation compliance. Establishing a national database through one centralized point of access (like the EPA's Compliance and Emissions Data Reporting Interface or CEDRI[15]) can be an effective way to reporting of regulation compliance. To increase the effectiveness of China's enforcement efforts, it is also important for the country to improve the flexibility of its mechanisms. For example, China could consider issuing industrial facilities credits for retrofitting that the facility owners can use to offset their obligations on emissions controls. China could also create customized requirements on tune-up schedules that fit facilities' operation conditions. It would be best if China avoids one-size-fits-all types of enforcement policies and allows for greater flexibility so that industrial facilities can find the most cost-effective way to achieve regulation targets while still being in compliance with government requirements.

Enhance technical support and build strong capacity

It is important for China to develop effective technical assistance programs to assist in the adoption of energy-efficiency technologies, the use of CHP and distributed energy, and the implementation of best practices. The technical assistance program should provide assessment tools, trainings, technical guides, and case studies.

Capacity building is a critical step in gaining buy-in from stakeholders on the need for solutions and in helping stakeholders understand the solutions. It is important for China to develop effective capacity building programs designed for a diverse groups of stakeholders including industrial companies, government agencies, service providers, manufacturers, and investors. These programs should also cover a wide range of topics such as regulations and standards to retrofit technologies, fuel switching, renewable energy, operations and maintenance, and contracting and finance. In addition, to ensure effective regulations enforcement, government-funded training activities are needed to provide examiners, inspectors, and verifiers with the knowledge and skills needed to do their jobs. Trainings should encourage use of effective formats such as hands-on courses and low-cost deliveries such as webinars and on-demand video courses.

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[15] Information about CEDRI can be found at http://epa.gov/ttn/chief/cedri/index.html

9. Enhancing U.S.-China Collaboration

Recommended Areas for Collaboration

Continued U.S. China collaboration in addressing the energy and environmental challenges posed by coal-fired industrial boilers is important. It is worth emphasizing that:

- This is a concrete area in which the U.S. and China can collaborate to show the world the strong commitment both countries have to working together to address climate change and make broad and tangible impacts on GHG-induced energy use.
- The U.S. is taking a holistic approach by combining regulations, technical advancement, market strategies, standards, and enforcement to implement its national boiler Maximum Achievable Control Technology (boiler MACT) program while China is set to fully develop programs to carry out its national Boiler Action Plan. The two countries thus have much to share and multiple areas to collaborate.
- Given the interest of both national and city governments in China in this area, the collaboration can also take the opportunity to employ both top-down and bottom-up approaches.
- The collaboration could create greater impacts if the resources of various U.S. institutions such as the U.S. Department of Energy (U.S. DOE), the U.S. Environmental Protection Agency (U.S. EPA), the Trade Development Agency, national laboratories, industrial associations, and private companies can be leveraged. Success could also be enhanced if the collaboration can take advantage of targeted funding opportunities in China provided by the Chinese government, the World Bank, and the Asian Development Bank.

Some recommended areas for joint collaboration are highlighted below.

Support City Pilots and Deploy U.S. Technologies to Realize Changes

The National Development and Reform Commission (NDRC) and the city governments in Ningbo and Xi'an have all expressed a desire to use the two cities as pilots for implementing China's Boiler Action Plan and for the second phase of the U.S. China boiler collaboration. It is expected that the experiences and lessons learned from and the solutions that are adopted in the pilots will be used as models to provide best practices that can guide the design and implementation of actions for other cities tasked to carry out the China's Boiler Action Plan. U.S. support for the pilots would open windows of opportunity for exploring innovative financing mechanisms, more effective business models, and GHG reduction-focused city planning while demonstrating and promoting advanced U.S. technologies and solutions related to boiler efficiency and CHP and DE.

Share Policy Experiences to Affect Policy Changes

The U.S. – both at the Federal and state level – has rich experience in making regulatory and policy changes to address pollution, improving the efficient use of energy, and promoting CHP and DE. In the U.S., policies and regulations are often developed to effectively align industrial interests and minimize implementation costs. Through supporting and participating in the city pilots in China, local best practices in policy-making and regulation enforcement at the State and city level in the U.S. can be effectively transferred to China. In addition, China's deregulation on natural gas prices requires an increased emphasis on effective risk management for natural gas users to hedge against volatile fuel prices. China can learn from the U.S. in developing risk management regulations and practices for minimizing the market risks. Sharing policy experiences can create a policy dialogue on identifying the needs for and ways to make policy changes. China can greatly benefit from being informed about these policy experiences, especially so that China does not create policies that would create market barriers to reform.

Develop Localized Decision Tools and Resource Kits to Assist Changes

The U.S. has much to share on development and use of decision-making tools and resource kits that effectively identify optimal opportunities for addressing industrial boilers through energy efficiency and fuel switching. The U.S. Department of Energy (DOE) has established the Boiler MACT Technical Assistance Program and utilized a suite of tools and resource kits including a MACT decision tree tool for assist industrial facilities in identifying optimal boiler compliance strategies along with heat and steam system assessment tools such as PHAST and SSAT to assess system-wide retrofit opportunities[16]. A series of technical guidelines regarding boiler maintenance, steam system optimization, and CHP/DE design and operations have also been developed by the DOE and the EPA. These and other resources can be used and adapted for China to effectively assist cities in realizing energy-savings and GHG reductions opportunities that would otherwise be missed.

Strengthen Collaboration on Developing Standards and Enforcement Strategies to Ensure Effective Changes

China is interested in collaborating with the U.S. on developing energy efficiency standards. This is an area where that the two countries can share their respective best practices and develop or harmonize relevant standards or protocols. The U.S. could also focus on sharing its experiences in enforcement on emissions controls and boiler compliance to increase the effectiveness of Chinese cities' enforcement practices that have so far made stakeholders less willing to comply.

Expand Collaboration in Capacity-Building to Make Long-Lasting Changes

Collaboration on targeted trainings not only builds capacity for efficient and low carbon energy use but it can also grant access to potential customers for U.S. businesses who actively share their best practices. A DOE-sponsored industrial energy efficiency training program[17] has shown some early success in improving efficiency practices in China's industrial plants via targeted trainings. This success could be scaled up via the U.S. China boiler collaboration and expanded to cover more topics including energy efficiency, CHP, distributed energy, risk management of natural gas, enforcement strategies, and financing. The expansion could become more structured and desirable if it aligned with China's ongoing industrial efficiency training initiatives sponsored by international organizations such as the World Bank.

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[16] For detailed information on DOE's Boiler MACT Technical Assistance Program, visit: http://www.energy.gov/eere/amo/boiler-mact-technical-assistance-program

[17] The international Industrial Energy Efficiency Training and Deployment (IIEETD) program launched by the U.S. DOE and conducted by various institutions including Lawrence Berkeley National Laboratory and Oak Ridge National Laboratory with participation of several U.S. companies has trained 300 Chinese specialists in employing DOE's process heating and steam system assessment tools over a two-year period. Some trainees became qualified trainers.

Possible activities for U.S. China collaboration in boiler roadmap implementation

There are a series of specific activities that U.S. and China could carry out for implementation of the recommended actions. Below is a list of activities that focuses on policy exchanges, implementation pilots, and technical support.

Policy Exchange with Chinese Stakeholders

- Undertake a study tour to the U.S. by key Chinese stakeholders including National Development & Reform Commission (NDRC), General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ), Ministry of Environmental Protection (MEP), National Energy Administration (NEA), Ministry of Industry and Information Technology (MIIT) and pilot cities. The tour will be an important opportunity for participating Chinese decision-makers to learn about design and enforcement of energy and environmental policies in general in the U.S. and in particular U.S. programs such as the Environmental Protection Agency's Boiler MACT regulation and the Department of Energy MACT compliance program. The study tour can also focus on flexible rule-making that transforms regulation targets from end-of-the-pipe control to pollution prevention (e.g., credit offsets, output-based emission limits, efficiency performance-based regulations, etc.). Potential topics for policy dialogue can also include market barriers and market reform, engaging the private sector, price reform, and public-private partnerships.
- Workshops in China on specific topics focusing on best practices and lessons learned related to energy and environmental policy-making and policy implementation.
- Boiler and system standardization collaboration.
- Integration of the boiler collaboration with the ongoing Climate-Smart/Low-Carbon Cities Initiative so that the two pilot cities – Ningbo and Xi'an - can serve as a model for collaboration in promoting climate-smart cities while addressing industrial boilers.

Pilots to Demonstrate Advanced Technologies

Reverse trade mission

The U.S. Trade and Development Agency (USTDA) promotes matching U.S. businesses with foreign buyers through reverse trade missions (RTMs) to the U.S. The proposed RTM could have the boiler system as one of the focus areas such as clean combustion, steam system efficiency, and boiler system monitoring and automated control but also focus on other applications as well such as CHP, air pollution monitoring and control, smart grids, etc. Potential participants in the RTM include NDRC, NEA, MIIT, MEP, the governments of Ningbo and Xi'an, manufacturers, industrial customers, investors, and service companies

Trade missions or technology roundtables in the pilot cities

Trade missions or technology roundtables in Ningbo and Xi'an to aim at understanding the market conditions, share product information, and identify solutions/technologies that align well with local market needs could be hosted by the two pilot cities, organized by various organizations, and attended by U.S. companies, technology providers, and investors.

Demonstration of technologies/solutions in pilot cities

NDRC's plan of making Ningbo and Xi'an as two pilot cities for the U.S.-China boiler collaboration and scaling up the experiences to other cities that deal with industrial boilers will provide an ideal platform and opportunity to demonstrate feasible technologies through the pilots and for further deploying them nationwide through the scale-up.

NDRC's Department of Resources Conservation and Environmental Protection, the leading agency in the U.S.-China boiler collaboration, is responsible for developing and issuing a national recommended energy technology catalogue. Government incentives for energy users and procurement greatly favor the products and technologies included in the catalogue. One effective way for NDRC to scale up the successfully-demonstrated technologies in the pilots is to include them in the national recommended technology catalogue. Another way for promoting use of advanced technologies, especially those from the U.S., is for NDRC to work with China's Ministry of Commerce to reduce the import tax on imported high-efficiency products in the pilots.

USTDA could support U.S. companies to carry out the proposed demonstration pilots. The two pilot cities can be the Chinese host for the USTDA-supported demonstration pilot. Depending on the plan of NDRC and the two pilot cities, one city could carry out one demonstration project while another city could carry out a different project. Below are just some examples of the types of possible demonstration pilots. Additional efforts can be identified through consultation with the U.S. industry and the Chinese pilot cities. The USTDA, U.S. Commerce, DOE CHP Technical Assistance Partnerships, national labs, business promotion organizations such as the Energy Collaboration Program (ECP), the American Society of Mechanical Engineers (ASME), the American Boiler Manufacturers Association, the CHP Association, etc. can help identify and recommend U.S. technologies that are suitable for the Chinese market.

Piloting innovative financing and business models

The proposed pilots will not only serve as a central platform for showcasing the advanced solutions but also a key opportunity to develop and test innovative financing and business models. Creating sound financing is critical for addressing a key market barrier to wide adoption of efficient technologies and essential for deploying the U.S. technologies that have high up-front costs but greater lifecycle energy-saving performance. Possible activities include:

- In a demonstration pilot, identify an industrial park in Xi'an or Ningbo that is willing to support a community-scale CHP system. This potential demonstration can use an innovative service-purchase agreement and third-party financing secured by on-bill payment. Under this model, a U.S. company can form a joint special purpose venture (SPV) with a Chinese boiler manufacturer or energy service company to enter into an agreement with the industrial park administration and design, develop, finance, and install the project that will use advanced and energy-efficient technologies (e.g., micro turbines, boiler system automation, low NOx combustion technology) from both the U.S. and China.
- The SPV could then operate the system during the contractual term and be responsible for providing combined services of heat, steam, electricity, and cooling to the neighboring industrial users located in the pilot industrial park, sending monthly service bills to the customers. The financing could be backed by the revenue-generation contract with the industrial park and repaid from and secured by service bills, meaning that customer default could result in service interruption. An example of this model is the FDA White Oak CHP distributed energy project which is designed, built, financed, and operated by Honeywell

under a 20-year contract with the U.S. General Services Administration (GSA) for the Food and Drug Administration (FDA) (Honeywell, 2012)

Developing such a model would have great significance. It could help companies enter into China's huge but untapped energy service market and transform businesses from merely a product provider to a service provider that would generate long-term revenue. China's recent electricity market reform is breaking the monopoly of State Grid and allows institutional end-users like industrial parks to select their own electricity suppliers. This reform could present a great opportunity for the SPV type of business model serving an industrial park.

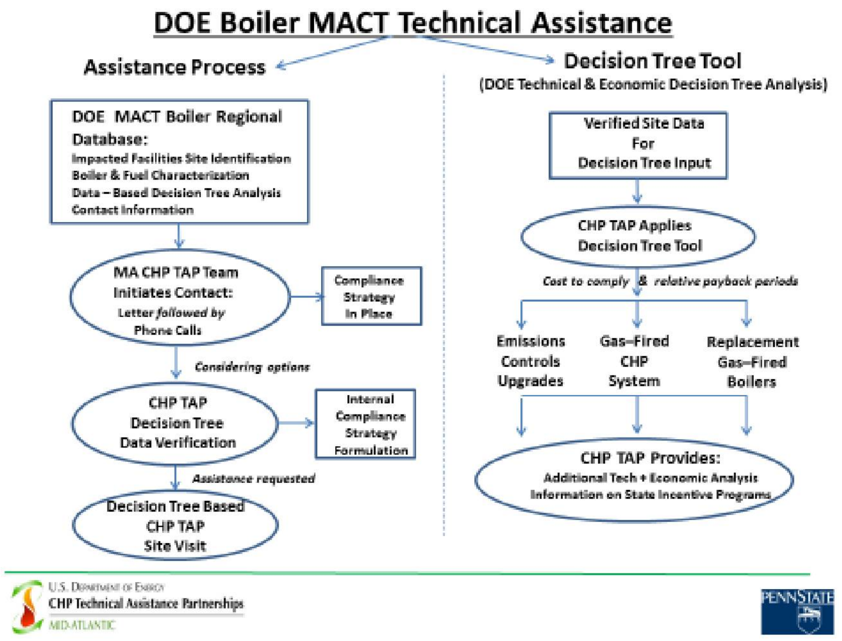
The financing for this community-scale CHP system and other demonstration project could be leveraged from available loan programs offered by the World Bank (WB), Global Environment Facility (GEF), and Asian Development Bank (ADB) in China. The pilots could leverage these programs to support the boiler roadmap implementation. In addition to available resources from multinational donor agencies, the proposed roadmap implementation can also leverage resources from development banks in each country (e.g., U.S. Ex-Im Bank and China Development Bank) which can support U.S. technology exports and Chinese domestic project development, respectively.

The proposed demonstration pilot could also adopt additional innovative mechanisms to further reduce potential investment risks. One approach is to involve insurers which could help reduce potential investment risks and create successful financing and business models for the roadmap implementation. For example, if the aforementioned joint SPV procured a service shortfall insurance, the insurer will pay the loss of providing agreed-upon amount of heat/steam/electricity service by the SPV due to causes such as natural gas supply shortage or equipment malfunction, thus enhancing the reliability of the services provided to the industrial park by the SPV.

Targeted Technical Assistance

There are many opportunities for targeted technical assistance in support of the Chinese pilot cities, including:

- Customize the U.S. decision tree analysis tool to help Chinese pilot cities to identify energy-efficient and emission abatement-driven compliance strategies. Figure 16 is a flow chart of the DOE MACT decision tree analysis tool.



Source: Freihaut, 2014

Figure 16. DOE MACT Decision Tree Analysis Tool

- Disseminate DOE energy system optimization tools (e.g., Steam System Modeler and PHAST) as well as facility-level energy profiling tool suite (e.g., Plant Energy Profiler, Energy Footprint, etc.) to identify opportunities for maximize GHG reduction potentials[18].
- Organize trainings and workshops through USTDA's International Business Partnership Program (IBPP) program. USTDA's IBPP aims to connect potential international customers with U.S. manufacturers and service providers in order to open commercial opportunities for U.S. companies via conferences, workshops, and training. Every year, USTDA funds dozens of workshops and technical conferences in China on a wide variety of topics.

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[18] Link to DOE tools: http://www.energy.gov/eere/amo/software-tools

References

Abdelaziz, E. A., R. Saidur, and S. Mekhilef. 2011. "A review on energy saving strategies in industrial sector." *Renewable and Sustainable Energy Reviews* 15: 150.

Administration of Quality Supervision, Inspection and Quarantine of China (AQSIQ) and the Standardization Administration of China (SAC), 2010. "Monitoring and testing for energy saving of coal-fired industrial boilers", October 30. [Chinese text]

Administration of Quality Supervision, Inspection and Quarantine of China (AQSIQ) and the Standardization Administration of China (SAC), 2009. "The minimum allowable values of energy efficiency and energy efficiency grades of industrial boilers (GB 24500-2009)", October 30. [Chinese text]

Asia-Pacific Partnership on Clean Development and Climate (APP), 2006. "RDG-06-07: Facilitate Deployment of Highly Efficient CHP Applications, Including Fossil and Biomass Fueled Industrial, Institutional and District Energy CHP Projects in Partner Countries". http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/CPD/RDG-06-07.pdf

Asia-Pacific Partnership on Clean Development and Climate (APP), 2009. "Project Status Report Form". http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/PSU/RDG-06-07-PSU.pdf

Asia-Pacific Partnership on Clean Development and Climate (APP), 2010a. "Project Registration Form". http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/CPD/RDG-09-38.pdf

Asia-Pacific Partnership on Clean Development and Climate (APP), 2010b. "Project Status Update". http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/PSU/REDG-09-38.pdf

Asian Development Bank (ADB), 2012. "44011-013: Heilongjiang Energy Efficient District Heating Project", September.

Aunan, Kristin, Jinghua Fang, Haakon Vennemo, Kenneth Oye, and Hans M. Seip. 2004. "Co-benefits of climate policy—lessons learned from a study in Shanxi, China." *Energy Policy* 33: 567.

Boiler Inspection Institute (BII) of Xi'an. 2014. *Xi'an Boiler Information and Statistics*

Carbon Trading Portal, 2015. http://tanpaifang.com/ (accessed on June 2, 2015)

China Coal Market Portal, 2015. http://portal.cctd.com.cn/datacenternew.jsp?path=010101&id=21&name=%C9%C2%CE%F7%CA%A1 and http://portal.cctd.com.cn/datacenternew.jsp?path=01020101&id=C015&name=%C4%FE%B2%A8%B8%DB

China Electricity Council (CEC), 2011. "Summary statistics report on China's power sector (2010)." http://tj.cec.org.cn/tongji/niandushuju/2011-02-23/44236.html

China Energy Newspaper (sponsored by People.com), 2012. "Urban Combined Heat and Power Systems Face Three Main Obstacles", December 10th. http://paper.people.com.cn/zgnyb/html/2012-12/10/content_1156995.htm

China Energy Newspaper (sponsored by People.com), 2013. "Heat and Power Sector Welcomes Favorable Governmental Policies", July 8th. http://paper.people.com.cn/zgnyb/html/2013-07/08/content_1266150.htm

China LNG International Summit. 2015. "Focus: Private Companies Enter LNG Market in China", April 17. http://www.chinalng.cc/hangyexinwen/2015/0417/598.html

China News, 2015. "Beijing to increase non-residential natural gas; residential natural gas price will stay the same", April 1. http://news.qq.com/a/20150401/014226.htm

Coria, Jessica. 2009. "Environmental policy, fuel prices and the switching to natural gas in Santiago, Chile." *Ecological Economics* 68: 2877.

Dechert, Sandy. 2015. "China Coal Consumption & CO_2 Emissions Drop In 2014." http://cleantechnica.com/2015/03/13/china-coal-consumption-co2-emissions-drop-2014/

Demirbas, Ayhan. 2005. "Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues." *Progress in Energy and Combustion Science* 31: 171.

Deng, SH, Aifang Cao, Xiuya Shi. 2011. "Ningbo Combustion Prohibition Zone Completed in Three Year," *China Environmental Newspaper*. P5. April 18, 2011.

Du, KJ. 2012. "The Improvement and Application of Pulverized Coal Compound Combustion Technology in Chain-grate Stoker Industrial Boiler." *Industrial Boiler Magazine*. 2012(6)

Editorial Board of the China Electric Power Yearbook. 2003-2011. China Electric Power Yearbook, 2003-2011 editions. Beijing: China Electric Power Press.

Energy Research Institute of China (ERI). 2013. *Roadmap Study on Achieving Technical Energy Conservation Potential in China's Industrial Sector by 2020* (2020年中国工业部门实现节能潜力的技术路线图研究), Beijing: China Scientific Technology Press.

Fang, Jinghua, Guanghai Li, Kristin Aunan, Haakon Vennemo, Hans M. Seip, Kenneth Oye, and Janos M. Beer. 2002. "A proposed industrial-boiler efficiency program in Shanxi: Potential CO_2-mitigation, health benefits and associated costs." *Applied Energy* 71: 275.

Fang, Jinghua, Taofang Zeng, Lynn I. Shen Yang, Kenneth Oye, Adel F. Sarofim, and Janos M. Beer. 1999. "Coal utilization in industrial boilers in China: a prospect for mitigating CO_2 emissions." *Applied Energy* 63: 35.

Freihaut, Jim. 2014. "DOE Mid-Atlantic CHP Technical Assistance Project: Boiler MACT Activities." A presentation made for the Chinese Boiler Study Tour to the U.S. Philadelphia, PA. November 18, 2014.

Gao JJ. 2013. "Research on China High Energy Consuming Equipment Operation Status and Energy Saving Solutions", the final report of the Research Project on China High Energy Consuming Equipment Operation Status and Energy Saving Solutions commissioned by the Chinese Academy of Engineering. Beijing, China: China Science Press. March 2013.

Habib, M. A., M. Elshafei, and M. Dajani. 2008. "Influence of combustion parameters on NOx production in an industrial boiler." *Computers & Fluids* 37: 12.

He, K., Y. Lei, X. Pan, Y. Zhang, Q. Zhang, and D. Chen. 2010. "Co-benefits from energy policies in China." *Energy* 35: 4265.

Heilongjiang Provincial Government, 2012. "PRC: Heilongjiang Energy Efficient District Heating Project", May. http://www.aecen.org/sites/default/files/china_iee_report_heilongjiangenergyefficientdistrictheatingproj_2012.pdf

Honeywell. 2012. "Project Profile: Federal Research Center at White Oak." https://buildingsolutions.honeywell.com/en-US/newsevents/resources/Publications/honeywell-hbs-white%20oak-case%20study.pdf

ICIS and C1 Energy. 2014. "China Gas Markets. August 25, 2014." http://www.icis.com/globalassets/ias/global/pdfs/lng-assets/china-pricing-sample-1.pdf

Industrial Policy and Regulation Division (IPRD) 产业政策与法规处. (2014). "Xi'an's Industrial Transformation and Improvement Status (西安市工业转型升级工作情况)". 30 July, 2014.

Industry and Information Technology Department of Shaanxi Province (IITDSP). 2012. "Shaanxi Province Industry and Information Technology Department's Notice on the Launch of Industrial Boiler Energy Conservation and Retrofit Demonstration Promotion (陕西省工业和信息化厅关于组织开展工业锅炉窑炉节能改造示范推广活动的通知)." 18 October 2012.

Laursen, K., and J. R. Grace. 2002. "Some implications of co-combustion of biomass and coal in a fluidized bed boiler." *Fuel Processing Technology* 76: 77.

Lawrence Berkeley National Laboratory (LBNL), 2014. "Key China Energy Statistics 2014". https://china.lbl.gov/sites/all/files/key_china_energy_stattistics_2014_online.final_.pdf

Li, Jun, Artur Brzdekiewicz, Weihong Yang, and Wlodzimierz Blasiak. 2012a. "Co-firing based on biomass torrefaction in a pulverized coal boiler with aim of 100% fuel switching." *Applied Energy* 99: 344.

Li, Jun, Weihong Yang, Wlodzimierz Blasiak, and Anna Ponzio. 2012b. "Volumetric combustion of biomass for CO_2 and NOx reduction in coal-fired boilers." *Fuel*: 624.

Liu, Manzhi. (2015). *City Survey and Pilot City Industrial Boiler Survey- Xi'an.* (城市调查和试点城市的锅炉调查-西安).

Mao, Xianqiang, Xiurui Guo, Yongguan Chang, and Yingdeng Peng. 2005. "Improving air quality in large cities by substituting natural gas for coal in China: Changing idea and incentive policy implications." *Energy Policy* 33: 307.

Ministry of Environmental Performance (MEP), 2014. "Emission Standard of Air Pollutants for Boilers (GB 13271-2014)". May 16, 2014. http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqgdwrywrwpfbz/201405/W020140530580815383678.pdf

Ministry of Environmental Protection (MEP). 2013. "Soliciting Public Feedback on 'Emission standard of air pollutants for boilers'", August 2. [Chinese text] http://www.zhb.gov.cn/gkml/hbb/bgth/201308/t20130805_256939.htm

Ministry of Environmental Protection of China (MEP). 2012. "Notice on Releasing 'Twelfth Five-Year Plan on Air Pollution Prevention and Control in Key Regions'", October 29. [Chinese Text]. http://www.mep.gov.cn/gkml/hbb/bwj/201212/t20121205_243271.htm

Ministry of Finance (MOF). 2011. "Guiding Opinions on the Development of Natural Gas-Based Distributed Energy", October 9. [Chinese text]. http://www.mof.gov.cn/zhengwuxinxi/zhengcefabu/201110/t20111018_600273.htm

Ministry of Industry and Information Technology (MIIT). 2014. "Seven governmental agencies jointly releasing the Comprehensive Implementation Plan of Improving Coal-Fired Boiler Energy-Saving and Environmental Protection Performance", October 29. [Chinese text]. http://www.miit.gov.cn/n11293472/n11293832/n11293907/n11368223/16241288.html

Morgenstern, Richard, Alan Krupnick, and Xuehua Zhang. 2004. "The ancillary carbon benefits of SO2 reductions from a small-boiler policy in Taiyuan, PRC." *Journal of Environment & Development* 13 (2): 140.

National Bureau of Statistics of China (NBS). (2011, 2012, 2013, 2014). *China Statistical Yearbook*. 2011, 2012, 2013, 2014.

National Business Daily, 2013. "National Development and Reform Commission: Non-Residential Natural Gas Price Increases, Mixed Impacts to Industries", June 29th. http://www.nbd.com.cn/articles/2013-06-29/753898.html

National Development and Reform Commission (NDRC), Ministry of Housing and Urban-Rural Development (MOHURD), and National Energy Administration (NEA). 2014. "Implementation Guidelines of Demonstration Projects on Natural Gas-Based Distributed Energy". October 23. http://www.chinade.org.cn/upload/accessory/201411/201411515363837712775.pdf

National Energy Administration (NEA) and the Ministry of Environmental Protection (MEP), 2014. "Notice on Biomass Boiler Demonstration Projects". June 18. [Chinese text] http://zfxxgk.nea.gov.cn/auto87/201407/t20140708_1818.htm

National Energy Administration (NEA). 2012a. "White Paper: China Energy Policy (2012)". [Chinese text]. http://www.nea.gov.cn/2012-10/24/c_131927804.htm

National Energy Administration (NEA). 2012b. "Biomass Energy Development Plan of the 12th Five-Year", July 24. [Chinese text]. http://zfxxgk.nea.gov.cn/auto87/201212/t20121228_1568.htm

National Energy Administration (NEA). 2012c. "Biomass Energy Development Plan of the 12th Five-Year", July 24. [Chinese text]. http://zfxxgk.nea.gov.cn/auto87/201212/t20121228_1568.htm

Ningbo City Government (NCG). 2011a. "Notice regarding areas prohibiting the sale and usage of highly polluting fuels (关于划定禁止销售使用高污染燃料区域的通告)." 15 April 2011.

Ningbo City Government (NCG). 2011b. "Notice regarding increasing areas prohibiting the sale and usage of highly polluting fuels (关于增加划定禁止销售使用高污染燃料区域的通告)." 19 December 2011.

Ningbo City Government (NCG). 2013. "Notice regarding increasing areas prohibiting the sale and usage of highly polluting fuels(关于增加划定禁止销售使用高污染燃料区域的通告)." 19 March 2013.

Ningbo City Government (NCG). 2014a. *Ningbo Air Pollution Prevention Action Plan (2014 - 2017) 宁波市大气污染防治行动计划 (2014～2017 年).* 30 May 2014.

Ningbo City Government (NCG). 2014b. “Ningbo City Government Notice on the Issuance of Ningbo City Air Pollution Control Action Plan (2014-2017) (宁波市人民政府关于印发宁波市大气污染防治行动计划（2014～2017 年）的通知).” 3 June 2014.

Ningbo City Quality and Technical Supervision Bureau (NCQTSB). 2014. *Ningbo City Industrial Boilers and Overall Structural Condition (宁波市城市工业锅炉使用总体及结构状况)*. 24 October 2014.
Ningbo Development & Reform Commission (NBDRC). 2015c.
http://www.nbdpc.gov.cn/SiteModules/ExpandMan/GuestBook/View.aspx?GBId=2171&num

Ningbo Development and Reform Commission (NBDRC). 2012. *Ningbo Energy Development “Twelfth Five Year Plan” (宁波市能源发展“十二五”规划)*. December 2012.

Ningbo Development Reform Commission (NBDRC). 2015a. *Ningbo city economy and industry structure (城市经济发展和产业结构)*

Ningbo Development Reform Commission (NBDRC). 2015b. *Ningbo boiler operation status and future development plans (宁波锅炉运行情况及未来发展计划)*. 23 Jan 2015.

Ningbo Economic and Information Technology Commission (NEITC), Ningbo Bureau of Statistics, Ningbo Development and Reform Commission. 2014a. *Ningbo’s Industrial Energy Efficiency 2013 Annual Report 宁波工业产业能效 2013 年度报告*. September 2014.

Ningbo Economic and Information Technology Commission (NEITC). 2014b. *City Summary of Industry Sector in 2013. (2013 年全市工业经济运行情况综述)*. January 2014.

Ningbo Entry-Exit Inspection and Quarantine Bureau (NEEIQB). 2014. “LNG Imports Creates Explosive Growth for Zhejiang Province (浙江省 LNG 进口量爆发式增长).” 24 January 2014. http://www.nbciq.gov.cn/xwbd/ywjx/201401/t20140124_95150.html.

Ningbo Key Development Areas Leading Group Office (NKDALGO). 2014. “Notice on the Issuance of ‘Ningbo City Key Development Areas and Industries’ Misplacement Improvement and Development Guiding Opinions’ 关于印发《宁波市重点开发区域产业错位提升发展指导意见》的通知.” 8 May 2014.

Ningbo People’s Government Office (NPGO). 2012. “Ningbo Municipal People’s Government Office’s Notice on the Issuance of Ningbo City’s ‘Twelfth Five Year Plan’ Energy Saving, Emission Reduction Comprehensive Implementation Program (宁波市人民政府办公厅关于印发宁波市“十二五”节能减排综合性工作实施方案的通知).” 3 August 2012.

Ningbo’s Municipal Finance Bureau (NMFB). 2011. “Management Plan of Special Subsidies for Eliminating Coal-fired boilers in Ningbo (关于印发《宁波市淘汰燃煤锅炉专项补助资金使用管理办法》的通知).” 11 April 2011.
http://qyzc.ningbo.gov.cn/art/2011/4/11/art_18030_84.html.

Personal Communication, 2014a. Personal communication with Linjun Li of Solarturbine via email correspondence.

Personal Communication, 2014b. Personal communication with Wendi Tao of ECP in Beijing.

Personal Communication, 2015. Personal communication with Zhang Dianjun of International Financing Corporation via correspondence.

Platts. 2015. “China cuts non-residential gas prices, merges existing two-tier system,” http://www.platts.com/latest-news/natural-gas/singapore/china-cuts-non-residential-gas-prices-merges-26027761

Qianjiang Evening News. 2015. “Ningbo’s energy intensity reduced by 5.8% last year, well achieving the double-control target.” June 5, 215. http://finance.sina.com.cn/china/dfjj/20150625/110322514695.shtml

Reynolds, Conor C., and Milind Kandlikar. 2008. “Climate impacts of air quality policy: Switching to a natural gas-fueled public transportation system in New Delhi.” *Environmental Science and Technology* 42 (16): 5860.

Saidur, R., E. A. Abdelaziz, Ayhan Demirbas, M. S. Hossain, and S. Mekhilef. 2011. “A review on biomass as a fuel for boilers.” *Renewable and Sustainable Energy Reviews* 15: 2260.

Shan’xi Provincial Pricing Bureau (SPPB). 2015. “Announcement on Adjusting Shan’xi Grid Tariff.” http://www.spic.gov.cn/newstyle/pub_newsshow.asp?id=1012912&chid=100173

Sims, Ralph E. H., Hans-Holger Rogner, and Ken Gregory. 2003. “Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation.” *Energy Policy* 31: 1315.

Sina News. 2013. “First Private-Owned LNG Station in Construction: will be difficult for ENG to break the oil & gas market monopoly”, August 17. http://finance.sina.com.cn/chanjing/gsnews/20130817/100616479941.shtml

Sina News. 2015. “Natural Gas Price Adjustment Is Coming and Adjustment could be larger than 0.40 RMB/m^3,” August 6. http://finance.sina.com.cn/chanjing/cyxw/20150806/214722897550.shtml

Song, W.Ch.1999. “Development strategy of natural gas for 21 century in China.” *Natural Gas Industry*. 19 (4), 23–27.

State Council. 2013. “China’s Energy Development Plan of the 12th Five-Year Plan (能源发展“十二五”规划)”, January 1. http://www.gov.cn/zwgk/2013-01/23/content_2318554.htm

State Council. 2014. “Energy Development Strategy Action Plan (2014-2020) 能源发展战略行动计划（2014-2020 年）”, June 7. http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm

Streets, D. G., and S. T. Waldhoff. 2000. “Present and future emissions of air pollutants in china: SO_2, NOx, and CO.” *Atmospheric Environment* 34: 363.

Suramaythangkoor, Tritib, and Shabbir H. Gheewala. 2010. “Potential alternatives of heat and power technology application using rice straw in Thailand.” *Applied Energy* 87: 128.

U.S. Energy Information Administration (U.S. EIA), 2015. “China: International energy data and analysis”. http://www.eia.gov/beta/international/analysis.cfm?iso=CHN

U.S. Energy Information Administration (U.S. EIA), 2015. “Natural Gas Prices.” http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm (accessed on May 20, 215)

U.S. Environmental Protection Agency (U.S. EPA), 2013a. “Industrial/Commercial/Institutional Boilers and Process Heaters”. http://www.epa.gov/airtoxics/boiler/boilerpg.html

U.S. Environmental Protection Agency (U.S. EPA), 2013b. "Summary of Regulations". http://www.epa.gov/airtoxics/boiler/imptools/areaboilerbrochure.pdf

U.S. Environmental Protection Agency (U.S. EPA), 2014. Central Data Exchange. http://www.epa.gov/cdx/

U.S. Environmental Protection Agency Combined Heat and Power Partnership and Asia Pacific Partnership on Clean Development and Climate (U.S. EPA and APP), 2008. *Facilitating Deployment of Highly Efficient Combined Heat and Power Applications in China: Analysis and Recommendations*. March. http://www.asiapacificpartnership.org/pdf/REDGTF/USEPACHPP_APP_ChinaCHP_FINAL.pdf

U.S. Federal Business Opportunities (U.S. FBO), 2010. "China - Distributed Energy Combined Cooling, Heat and Power Tri-generation Model Projects", August. https://www.fbo.gov/index?s=opportunity&mode=form&id=1327196a7be42f868d3583cf6068f6c1&tab=core&tabmode=list&

United Nations Industrial Development Organization (UNIDO). 2014. *Energy Efficiency Potentials in Industrial Steam Systems in China: Development of a steam systems energy efficiency cost curve.* Vienna, 2014. http://www.unido.org/fileadmin/user_media_upgrade/What_we_do/Topics/Energy_access/EE_Potentials_Steam_Systems_China_.pdf

United Nations, 2013. *United Nations Commodity Trade Statistics Database*. New York: United Nations.

Wang, Zhenming, 2007. "The latest developments of China's distributed energy: CHP." Presentation by Wang Zhenming. June 2007.

World Alliance for Decentralized Energy (WADE), 2010. "Executive Summary: The Potential of Clean DE and CHP in China". http://www.localpower.org/WADE-APP-Summary.doc

World Alliance for Decentralized Energy (WADE), 2010. "Executive Summary: The Potential of Clean DE and CHP in China". http://www.localpower.org/WADE-APP-Summary.doc

World Bank. 2004. *China - Heat Reform and Building Energy Efficiency (GEF) Project*. Washington, DC: World Bank. http://documents.worldbank.org/curated/en/2004/03/5457864/china-heat-reform-building-energy-efficiency-gef-project

World Bank. 2014. *China - Heat Reform and Building Energy Efficiency Project*. Washington DC; World Bank Group. http://documents.worldbank.org/curated/en/2014/04/19459764/china-heat-reform-building-energy-efficiency-project

Xi'an Academy of Special Equipment Inspection and Testing - Testing Center (XASEIT- TC) 西安特种设备检验检测院- 检测中心. 2015. "Xi'an industrial boiler energy consumption and energy efficiency test (西安市工业锅炉能耗现状及其能效测试的开展)." 23 January, 2015.

Xi'an Development and Reform Commission (XDRC). 2014. *Xi'an economic and social development environment, energy and industrial boiler overview. (西安市经济社会发展环境、能源及工业锅炉总体情况介绍)*. 15 October 2014.

Xi'an Evening News (XEN). 2008. "Xi'an Municipal People's Government Executive Meeting on Cogeneration Planning (西安市政府常务会议审议通过《热电联产规划》)". 9 May 2008.

Xianyang Development and Reform Commission (XYDRC). 2014. *Energy Saving Low-Carbon Development Plan (陕西省 2014-2015 年节能减排低碳发展行动实施方案).* 9 September 2014.

Yang, Ming, and Robert K. Dixon. 2012. "Investing in efficient industrial boiler systems in China and Vietnam." *Energy Policy* 40: 432.

Zhang, Qinglin. 2005. "Improve China's Industrial Coal-Fired Boilers Operation Efficiency and Research on Energy-Saving Measures," *Clean Coal Technologies*, 11(2). [Chinese text]

Zhang, Yimin, Jon Mckechnie, Denis Cormier, Robert Lyng, Warren Mabee, Akifumi Ogino, and Heather L. Maclean. 2010. "Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada." *Environmental Science and Technology* (44): 538.

Appendices

Appendix 1: Reviewed Publications

Fuel Switching from Coal to Natural Gas

Reynolds and Kandlikar (2008) and Streets and Waldhoff (2000) discussed the potential climate impacts of fuel switching from coal to natural gas and pointed out that air pollution and climate change are inextricably connected because fossil fuel combustion generates both greenhouse gases, aerosols, and criteria air contaminants. For developing countries, large synergies exit between climate and air pollution and policies are needed to leverage the opportunities (Morgenstern et al., 2004). Researchers studied the implication of replacing coal with natural gas as a cleaner combustion fuel. Mao et al. (2005) explored the rationality of using natural gas for municipal energy consumption by comparing two cases: 1) using natural gas as a cleaner fuel versus using it as a chemical industry raw material; 2) using natural gas a cleaner-coal technology. The authors concluded that use of natural gas as a cleaner fuel could achieve higher energy savings.

Mao et al. (2005) conducted cost-benefit analyses of natural gas substitution in two Chinese cities, Beijing and Chongqing. The results showed that substituting natural gas for coal could make economic sense (based on the cost-benefit approach) in large cities, with dense population and intensive economic activity. However, the out-of-date information underscores the need for assessing the cost-effectiveness of fuel switching with up-to-date information.

Barriers to adopt natural gas as the main fuel in China are also discussed in the literature. Mao et al. (2005) further analyzed the potential barriers to a higher natural gas penetration. These barriers include: 1) relatively high costs (fuel prices, equipment expenditure, and operational costs) compared to coal; 2) the city's natural gas initial installation fee or gas source fee sets a high access threshold and make the use of natural gas less attractive; and 3) high capital cost of urban natural gas pipeline system construction and a lack of high-capacity long-distance pipelines across the country.

Researchers suggested ways to increase natural gas adoption rates. For example, Mao et al. (2005) suggested that China could: 1) allow more private and foreign investor access to the natural gas industry, 2) implement economic incentives, 3) adopt necessary command and control instruments (such as designate non-coal areas), and 4) launch market reform in the natural gas industry. Based on a Santiago case in Chile, Coria (2009) suggested that the use of taxes on non-clean fuel might create incentives to use cleaner fuels and to reduce emissions. The author argued the use of fuel taxes may also ease administration burdens in developing countries. However, the author pointed out the disadvantages of such a policy tool as tax may not directly affect the targeted activities and could have unintended distributional impacts (e.g., more severe impact on poor households than on rich ones).

Fuel Switching to Biomass

The advantages and potential issues associated with using biomass are discussed in the literature. Sims et al. (2003) confirmed that biomass fuels are generally easier to gasify than coal. Demirbas (2005) showed biomass could be an attractive renewable fuel in utility boilers and agreed that the reduction of greenhouse gas emissions is the main advantage of increasing the use of biomass energy. Saidur et al. (2011) reviewed several aspects of burning biomass in boilers, such as composition of biomass, estimating the higher heating value of biomass, comparison between biomass and other fuels, combustion of biomass, co-firing of biomass and coal, economic and social impacts of biomass, transportation of biomass, densification of biomass, problems of biomass, and future trend of biomass energy. The authors found utilizing biomass in boilers offers many economic, social, and environmental benefits, such as cost savings, conservation of fossil fuel resources, job creation, and reduction of CO_2 and NOx emissions.

The literature also discussed the way to improve existing methods of using biomass in order to improve efficiency and address the associated problems. Li et al. (2012b) proposed a co-firing system that is based on torrefied biomass (which according to the authors provides several benefits, such as higher energy density, good grindability, high flowability, and uniformity). The authors modeled the boiler performance with five different levels biomass co-firing (0%, 25%, 50%, 75%, and 100%) and showed that firing 100% torrefied biomass in a pulverized coal boiler would not obviously decrease the boiler efficiency or fluctuate the boiler load. More importantly, the results showed the net CO_2 and the NOx emissions significantly reduced with increasing biomass substitutions in the co-firing system.

Some studies looked at the life-cycle impact of using biomass. Zhang et al. (2010) investigated life-cycle emissions and costs of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. The authors showed that 100% pellet utilization provides the greatest greenhouse gas (GHG) benefits on a kilowatt-hour basis, reducing emissions by 91% and 78% relative to coal and natural gas combined cycle systems, respectively. The authors suggested that biomass utilization in coal generating stations has a potential to cost-effectively mitigate GHGs from coal-based electricity in the near term.

Other studies focused on one type of biomass in particular. Suramaythangkoor and Gheewala (2010) investigated the potential of using rice straw in industrial boilers in Thailand. The authors found that although the cost of rice straw for power generation is not competitive with coal, but it is comparable with other biomass. The authors further found out that burning rice straw in industrial boilers is a more competitive and flexible option. The authors showed that with the properties of rice straw, it is not expected to have significant operating problems or different emissions compared with wheat straw and rice husk under similar conditions.

However, researchers agreed that using biomass poses different challenges compared to the use of coal. Sims et al. (2003) discussed the challenge to use biomass resources is to provide sustainable management, conversion, and delivery of bioenergy to the market place in the form of modern and competitive energy services. At a more technical level, Demirbas (2005) argued biomass ash composition is fundamentally different from coal ash composition. The author pointed out that the inorganic constituents of municipal, industrial, and animal waste materials cause critical problems of toxic emissions, fouling, and slagging. Metals in ash in combination with other fuel elements such as silica and sulfur and facilitated by the presence of chlorine are responsible for many undesirable reactions in combustion furnaces and power boilers.

Agreeing with previous studies on potential issues associated with using biomass, Saidur et al. (2011) pointed out "care should be taken" to other environmental impacts of biomass, such as land and water resources, soil erosion, loss of biodiversity, and deforestation. Other technical issues are also associated with using biomass in boilers, such as fouling, marketing, low heating value, storage and collections, and handling issues. Li et al. (2012a) argued that the combustion behaviors of biomass are different from those of coal. To address the technological challenge of co-firing, the authors further proposed a new concept of volumetric combustion to achieve 100% fuel switching from coal to biomass in large-scale coal-fired boilers. The authors found that the volumetric combustion would be an attractive technology for co-firing a large proportion of biomass in coal-fired boilers with high boiler efficiency and effective CO_2 and NOx emission reduction. Li et al. (2012b) summarized the current technical challenges with co-firing biomass, including cost-effective methods for getting more and wider varieties of fuels into the boiler, occurrence of insufficient gas mixing and stratified flows in the boiler, fouling and corrosion of the boiler, continuation of fly ash utilization, and impacts on performance of the flue gas cleaning.

Laursen and Grace (2002) discussed other technical issues associated with using biomass in industrial boilers. The authors conducted laboratory combustion experiments to clarify some implications of co-firing coal with hog fuel and sludge in a fluidized bed boiler. The authors found that the burnout of coal was very sensitive to excess air, especially when co-firing wet hog fuel. The tests conducted show that the capacity of limestone to capture sulfur depends on temperature and particle size. The highest Ca utilization of the limestone was 51% for the smallest particle size.

Existing literature also discussed some of the non-technical barriers to utilizing biomass. Li et al (2012a) discussed that the economics of biomass co-firing are largely impacted by deregulation and environmental requirements. High uncertainties in both arenas may make investment in biomass co-firing technologies difficult to justify. Li et al (2012b) also discussed issues such as lack of financial incentives, uncertainty of fuel price/availability, lack of legislation support, public perception of co-firing biomass, and difficulty of getting permits.

Improving Industrial Boiler Energy Efficiency

Several studies have pointed out that China's industrial boilers generally have relatively low energy efficiency. Gao (2013) showed that industrial boilers are operated at an efficiency level of 60 percent on average, compared with more than 80 percent in Europe and the United States. The author argued that if industrial boilers in China could operate at the efficiency level of Europe and the United States, it is estimated to save coal consumption over 100 million tons per year. This study utilized collected energy data of industrial boilers monitored by a few provinces and cities (Guangzhou, Nanjing, Xian, Shanghai, Gansu, and Liaoning) and revealed that the averaged thermal efficiency was only at 68.72 percent for coal-fired industrial boilers with capacity at and below 20 tons/hour. The author also reported that only 40 percent of water used by boilers meets the national standards. A large portion of boilers do not have water treatment equipment; blowdown rate of some boilers is as high as 20 -30 percent, resulting huge heat loss.

Studies have been conducted to identify applicable energy efficiency measures as well as to quantify the impacts of boiler efficiency measures. Fang et al. (2002) suggested several measures could be considered to improve boiler energy efficiency, i.e., multi-layer coal sorting, reducing the share of fine particles in the coal supply, monitoring and optimizing boiler operation, secondary air jets combined with well-shaped refractory front and rear arches, hot dust separation and recycling, briquetting, and adopting both technical and non-technical standards. Abdelaziz et al. (2011) reviewed technologies, policies, and management practices related to industrial energy saving. To improve energy efficiency of industrial boilers, the authors suggested that variable speed drives, economizers, and high efficient motors could increase efficiency and reduce CO_2, SO_2, NOx, and CO emissions. The authors also recommended using regulations, robust standards on boilers, and reducing boiler flue gas temperature. The results showed these measures could be cost-effective in suitable conditions.

Researchers also found investing in industrial boiler efficiency is economically viable and socially beneficial. Yang and Dixon (2012) analyzed case studies from China and Vietnam of assessing and investing in industrial boilers systems. Specifically for China, the authors reviewed a Global Environment Facility (GEF) project that promoted investment in industrial energy efficient boilers in China. The authors found the project was a success in terms of technology transfer, improving existing boiler efficiency, upgrading existing boiler models, providing technical assistance and training, as well as building up institutional capacity. More importantly, the authors found the project is cost-effective in reducing CO_2 emissions as well as local and regional pollutants, such as total suspended particles and SO_2 emissions.

Yang and Dixon (2012) also pointed out several factors that contribute to “a failure to recognize and realize the energy efficiency potential of boilers and steam systems” in China. These factors include the inherent complexity of boilers and steam systems; energy budget is separated from capital budgets, which reduces the influence on purchasing decisions; and lack of well-documented maintenance procedures. The authors concluded with a set of policy recommendations to optimize industrial boiler/steam system.

Environmental and Health-Related Topics

Researchers have pointed out that the end-of-pipe pollution control technologies may be constrained to large-scale boilers. Mao et al. (2005) pointed out although highly efficient scrubbing technologies for coal (such as flue gas desulfurization and fluidized bed combustion) can reduce air pollutants from coal use significantly, the technology adoption is limited to large coal users. Smaller and scattered coal users (such as small-scale boilers) use only a few “cleaner-coal” technologies, such as coal briquettes and low-sulfur coal substitution. These non-point sources also contribute to most of the low-altitude SO_2 emissions in urban zones. In addition, the authors argued that available “cleaner-coal” technologies’ pollution reduction rates are far from satisfactory. From an administrative and monitoring standpoint, the authors believe that monitoring costs associated with implementing these “cleaner-coal” measures are high and it is almost impossible to monitor all small coal users.

Existing literature also discussed the factors contribute to NOx emissions. Habib et al. (2008) researched the influence of combustion parameters on NOx emissions in industrial boilers. The authors pointed out that the formation of NOx in industrial boilers is a very complicated problem due to many parameters that influence its formation process, such as fuel to air ratio, inlet air temperature, and combustion air swirl angle.

A significant portion of the literature studied the co-benefits of improving boiler efficiency. In terms of methodologies used to quantify the environmental impacts, Mao et al. (2005) reviewed three quantification methods (a method developed by the World Bank, a benefit-transfer method, and a dose-reaction model) used to quantify the environmental health damages.

To quantify the co-benefits from boiler energy efficiency policies, Aunan et al. (2004) studied the impacts of coal consumption from the perspective of social-economic costs and health damages. Focused on Shanxi Province, China, the authors studied three types of pollutants, i.e., SO_2, particles, and CO_2 and analyzed the abatement costs and emission reduction potential of six different abatement options, including coal washing, briquetting, improved management, boiler replacement, co-generation, and modified boiler design. The authors found that the co-generation has the lowest (and negative) cost of CO_2 abatement and followed by modified boiler design and boiler replacements, which also have negative costs of CO_2 abatement. In terms of reducing Total Suspended Particles and SO_2, coal washing has the greatest potential and followed by Briquetting. Modified boiler design and boiler replacement ranked in third in terms of pollution reduction.

Fang et al. (2002) estimated the environmental, economic, and health impacts of improving industrial boilers in Shanxi Province, China. The authors analyzed six coal samples and 300 industrial boiler thermal-balance tests and found poor performance of industrial boilers in Shanxi, mainly due to high fraction of unburned carbon, high excess air, low load operation, and high waste gas temperature. The authors also pointed out the factors such as large fraction of fine particles in the feed coal unsuitable for stoker firing and the average size of the boiler population are worth noting.

At the national level and from a policy-modeling perspective, He et al. (2010) quantified the co-benefits of reducing carbon emissions and improving air quality from policies that were initially formulated to improve energy efficiency and to abate emissions of air pollutants from energy use. Their results showed significant benefits could be achieved around year 2030 if aggressive energy policies are implemented. Specifically for boilers, the authors assumed 24% of urban heating boilers will use natural gas by 2010 and the share will increase to 50% by 2030. For boiler pollution control devices, the authors assumed that 20% of circulating fluidized bed boilers would install bag houses by 2010, and the share will increase to 75% by 2030. The share of PM control in grate furnaces was expected to increase from 2% in 2020 to 30% in 2030.

Studies also show that boiler efficiency programs contribute to significant carbon and climate benefits. Morgenstern et al. (2004) examined effects and implications of a small boiler phasing out policy in downtown Taiyuan, Shanxi Province of China. The authors showed that although conventional air pollution problem is more pressing to the local city than the issue of greenhouse gas emissions, the ancillary carbon benefits associated with the phasing out policy are significant (on the order of 50% to 95% reduction). The authors pointed out this policy could have large reduction potential elsewhere in China. The authors estimated the cost for boilers to switch out of coal was almost $2,900 USD per tonne of SO_2 reduced but also pointed out the ancillary carbon reductions were free from a social perspective.

Appendix 2: Review of Boiler-Related Assessment Projects

Project Name: Heat Reform and Building Energy Efficiency Project
Sponsor Agency: World Bank/GEF
Implementing agencies: Ministry of Housing and Urban-Rural Development (MOHURD), Tianjin Municipality, and municipalities of Tangshan, Chengde, Datong, Wuzhong, Dalian, and Urumqi

Project summary

The project of Heat Reform and Building Energy Efficiency (HRBEE) was funded by the Global Environmental Facility (GEF) ($17.41 million USD) and implemented by the Ministry of Housing and Urban-Rural Development, Tianjin Municipality, and municipalities of Tangshan, Chengde, Datong, Wuzhong, Dalian, and Urumqi. The project was initiated in March 2004 and completed in April 2014. The goal of this project was to "achieve substantial, sustained and growing increases in energy efficiency in urban residential buildings and central heating systems in China's cold climate regions" (World Bank, 2004). The project aimed to adopt an integrated "two handed" approach, i.e., 1) creating a market mechanism through heat reform and heat system modernization so consumers pay for actual heat use and have controls on how much heat they consume, and 2) improving energy efficiency of urban residential buildings.

The project included three key components. The first component demonstrated the "two handed" approach in Tianjin, focusing on achieving multiple goals including improving building energy efficiency, increasing the operational efficiency of the city's heat supply systems, use of heat metering, providing means for control of heat by the end-users, cost-based heat pricing, and consumption-based heat billing. The second component replicated the "two-handed" approach in other six Northern Cities. The third component supported MOHURD to take actions such as issuing policy directives to local governments, introducing domestic and international best practices and disseminating successful implementation experiences to other cities, and coordinating local project activities.

The project was estimated to have achieved a cumulative coal savings of 2.6 million tce/year which greatly exceeded the target of 660,000 tce/year mainly due to a higher than expected outcome for building design compliance (achieved 98.7% compared to the target of 80%). However, the project only achieved 40% in cumulative new residential stock that is billed on heat consumption basis, lower than the original target of 50% (World Bank, 2014).

References

World Bank. 2004. *China - Heat Reform and Building Energy Efficiency (GEF) Project*. Washington, DC: World Bank. http://documents.worldbank.org/curated/en/2004/03/5457864/china-heat-reform-building-energy-efficiency-gef-project

World Bank. 2014. *China - Heat Reform and Building Energy Efficiency Project*. Washington DC; World Bank Group. http://documents.worldbank.org/curated/en/2014/04/19459764/china-heat-reform-building-energy-efficiency-project

Project Name: Heilongjiang Energy Efficient District Heating Project
Sponsor Agency: Asian Development Bank (ADB)
Implementing Agencies: Heilongjiang Provincial Development and Reform Commission, Heilongjiang Provincial Finance Bureau, Heilongjiang Energy Conservation Office, and various municipal governments

Project Summary

The Asian Development Bank provided loans to support the Heilongjiang Energy Efficient District Heating Project in 2012. The goal of the project is to upgrade district-heating systems in eight cities in Heilongjiang and thus reduce greenhouse gas emissions and local air pollution. The project aimed to install energy efficient heating sources and heat exchangers, insulate pipelines, and use computerize monitoring and control systems (ADB, 2012).

The project proposed to install 321 heat exchangers between primary and secondary heating networks, 271 kilometers (km) of insulated heat pipelines of the primary heating networks, three high energy efficiency heating source plants, and eight computerized Supervisory Control and Data Acquisition (SCADA) systems (Heilongjiang Provincial Government, 2012). The three proposed heat sources were all circulating fluidized-bed (CFB) boilers because CFBs are generally have higher combustion efficiency at about 87% compared to small boilers (which have an energy efficiency level of 55%) and low NOx emissions due to low combustion temperature (Heilongjiang Provincial Government, 2012). The large-size CFB boilers use limestone for desulfurization and bag filters or electrostatic precipitators for flue dust removal (Heilongjiang Provincial Government, 2012).

The project began in November 2012 and expected to be completed by October 2017. By switching to energy-efficient centralized heating systems from inefficient small heat-only boilers and household stoves, the project is expected to save 757,599 tons of raw coal per year which results to a reduction of 1 million tons of carbon dioxide, 4,500 tons of sulfur dioxide, 1,961 tons of nitrogen oxide, 22,819 tons of particulate matters, and 231,068 tons of ash (Heilongjiang Provincial Government, 2012).

References

Asian Development Bank (ADB), 2012. “44011-013: Heilongjiang Energy Efficient District Heating Project”, September.
http://adb.org/projects/details?page=details&proj_id=44011-013

Heilongjiang Provincial Government, 2012. “PRC: Heilongjiang Energy Efficient District Heating Project”, May.
http://www.aecen.org/sites/default/files/china_iee_report_heilongjiangenergyefficientdistrictheatingproj_2012.pdf

Project Name: Facilitate Deployment of Highly Efficient CHP Applications, Including Fossil and Biomass-Fueled Industrial, Institutional and District Energy CHP Projects in Partner Countries
Sponsor Agency: Asia-Pacific Partnership on Clean Development and Climate (http://www.asiapacificpartnership.org/english/about.aspx)
Managed by: U.S. Environmental Protection Agency's Office of Air and Radiation's CHP Partnership Program
Implementing Agencies: International District Energy Association, Korean District Heating Association (KDHA), World Alliance for Distributed Energy China (WADE China)

Project Summary

The goal of this project was to promote and streamline the deployment of new district energy-scale CHP projects in partnering countries. Specifically for China, the project planned to analyze China-specific technical, economic, and strategic target markets and "low hanging fruit" opportunities for DG/CHP during the first year of the project and conduct best practice workshops on CHP conceptual design, feasibility analysis, project development, policy framework, and CHP related tools in the second year. In the Year Three, the project planned to conduct workshops for identified strategic markets in major cities, provide technical assistance, and promote exceptional performers based on the "ENERGY STAR" model (APP, 2006).

Due to limited funding for Year 3, however, the project did not proceed to complete the activities planned for the Year Three (APP, 2009). The project delivered a report titled "Facilitating Deployment of Highly Efficient Combined Heat and Power Applications in China: Analysis and Recommendations". The report analyzed potential markets for deploying CHP in China and identified barriers and opportunities for promoting CHP in the country. The report provided recommendations based on the EPA CHP Partnership's experience with CHP in the U.S. market (U.S. EPA and APP, 2008).

References

Asia-Pacific Partnership on Clean Development and Climate (APP), 2006. "RDG-06-07: Facilitate Deployment of Highly Efficient CHP Applications, Including Fossil and Biomass Fueled Industrial, Institutional and District Energy CHP Projects in Partner Countries". http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/CPD/RDG-06-07.pdf

Asia-Pacific Partnership on Clean Development and Climate (APP), 2009. "Project Status Report Form". http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/PSU/RDG-06-07-PSU.pdf

U.S. Environmental Protection Agency Combined Heat and Power Partnership and Asia Pacific Partnership on Clean Development and Climate (U.S. EPA and APP), 2008. *Facilitating Deployment of Highly Efficient Combined Heat and Power Applications in China: Analysis and Recommendations*. March. http://www.asiapacificpartnership.org/pdf/REDGTF/USEPACHPP_APP_ChinaCHP_FINAL.pdf

Project Name: Accelerate Distributed Generation - Combined Heat and Power Applications in China
Sponsor Agency: Asia-Pacific Partnership on Clean Development and Climate (http://www.asiapacificpartnership.org/english/about.aspx)
Implementing Agencies: EXERGY, ICF, Solar Turbines, World Alliance for Decentralized Energy China (WADE China), Broad Air Conditioning

Project Summary

The goal of this project was to build on previous work and identify barriers and opportunities for Combined Heat and Power (CHP) for China. The project also planned to evaluate the benefits of CHP and clean distributed generation (DG) in China (APP, 2010a).

The project was expected to identify policy solutions, develop action plans, and increase stakeholder commitment at the provincial level to increase the deployment of CHP and clean DG in China. The project composed eight tasks, including 1) detailed understanding of CHP potential, 2) determine DG/CHP benefits, costs, opportunities, and threats, 3) quantitative provincial DG/CHP modeling and analysis, 4) recommend national policies and actions, 5) develop provincial action plans, 6) develop relevant best practices handbook, 7) organize provincial workshops, and 8) visit sites in the U.S (APP, 2010b).

World Alliance for Decentralized Energy China (WADE China) was the main organization implementing this project. Five provinces/municipal districts were selected, including Shanghai, Liaoning, Shandong, Jiangsu, and Sichuan, based on “a review of their fuel supply outlook including natural gas, sustainable biomass and waste thermal sources; an assessment of overall economic growth and development; an evaluation of the technical application potential for CHP” (WADE, 2010). The project found that existing CHP systems in China was mostly coal-based and were often equipped with old, inefficient coal boilers and heating loops. The estimated average of district heating boiler efficiency by the project was 60 to 65% with an estimated heat loss from district heating pipelines of 25 to 50% (WADE, 2010). Due to low efficiency and high losses of the existing CHP systems, the potential benefits of energy savings and greenhouse gas emissions reduction were low. However, the project found that large emission reduction potential exists with customer-site CHPs at individual industrial facilities and commercial/residential sites (WADE, 2010). The estimated technical potential for clean distributed energy (DE) and CHP within the five investigated districts was 144 GW of electrical generating capacity.

References

Asia-Pacific Partnership on Clean Development and Climate (APP), 2010a. “Project Registration Form”. http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/CPD/RDG-09-38.pdf

Asia-Pacific Partnership on Clean Development and Climate (APP), 2010b. “Project Status Update”. http://www.asiapacificpartnership.org/pdf/Projects/REDGTF/PSU/REDG-09-38.pdf

World Alliance for Decentralized Energy (WADE), 2010. “Executive Summary: The Potential of Clean DE and CHP in China”. http://www.localpower.org/WADE-APP-Summary.doc

Project Name: Feasibility Studies of Distributed Energy Combined Cooling, Heating and Power Tri-generation Model Projects in China
Sponsor Agency: U.S. Trade and Development Agency (U.S. TDA)
Implementing Agency: China National Energy Administration

Project Summary

The project was to conduct feasibility studies for implementing a Natural Gas Tri-generation Model Projects. The feasibility study would include technical, economic, and financial assessments of implementing distributed energy combined cooling, heat, and power tri-generation (DE-CCHP) technology in two model facilities (U.S. FBO, 2010).

The project was envisioned under the context that the National Energy Administration (NEA) of China is implementing a national distributed energy program with a goal of increasing the installed capacity of DE-CCHP to 200 GW by 2020.

The two model projects in the feasibility study were expected to produce 0.5 to 50 MW of electric power from a single unit. The USTDA funded both projects with one project in the commercial sector and the other one in the industrial sector. The feasibility study was expected to provide NEA and selected facilities with technical assessments and recommendations for site system setup and alignment with existing grid infrastructure (U.S. FBO, 2010). In addition to technical, economic, and financial analysis, the project also included components of environmental analysis, policy and regulatory analysis, impact to China and U.S. suppliers, as well as dissemination of U.S. experiences in DG-CCHP (U.S. FBO, 2010).

References

U.S. Federal Business Opportunities (U.S. FBO), 2010. “China - Distributed Energy Combined Cooling, Heat and Power Tri-generation Model Projects”, August. https://www.fbo.gov/index?s=opportunity&mode=form&id=1327196a7be42f868d3583cf6068f6c1&tab=core&tabmode=list&=

Appendix 3: Policies Related to Boiler Energy Efficiency and Fuel Switching in China

Mandates on Curbing Air Pollution

In response to severe air pollution in China, the Chinese government has made curbing key air pollutants one of the top priorities as outlined in a series of government action plans and policy directives. *The Twelfth Five-Year Plan on Air Pollution Prevention and Control in Key Regions* issued by the Ministry of Environmental Protection (MEP) in December 2012 is the first national plan for comprehensive air pollution prevention and control. The plan focuses on three key regions (Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta) and ten city clusters, including 19 provincial level jurisdictions and 117 cities. Even though these key regions account merely for 14% of China's land area, they represent about half of China's total air pollution, 71% of GDP and 52% of total coal consumption (MEP, 2012). For the first time, the plan sets ambient concentration targets for SO2, PM10, NO2, and PM2.5 as well as total emission reduction goals (percentage reduction by 2015 from 2010 level), which range from 10% to 13% for these pollutants in the targeted jurisdictions (MEP, 2012).

Comprehensive measures adopted in this five-year plan include pollution control requirements, change of industrial structure, phasing out high-polluting operations, promoting clean energy sources, piloting regional coal cap, creating coal-free zones, improving coal quality, and strengthening vehicle fuel efficiency and emission standards.

Specifically, the plan calls for complete elimination of small industrial coal-fired boilers of 10 tons steam production per hour (t/h) or less in the three key regions and in regions covered by the district-heating network. In addition, the plan mandates industrial boilers to meet emission standards by carrying out retrofits (such as replacing grate firing boiler with fluidized bed combustion boilers and pulverized coal-fired boilers and installing bag filters for de-dusting) and encourages increased adoption of combined heat and power. Furthermore, the plan calls for developing district-heating network in industrial parks by 2015 and encourages the owners of industrial boilers to switch to natural gas and biomass.

The State Council released the *Atmospheric Pollution Prevention Action Plan* on September 10, 2013 to lay out specific actions to improve China's air quality by 2017 and establishes stricter pollution reduction guidelines in three key regions in Beijing, Shanghai, and Guangzhou (State Council, 2013). In the Action Plan, cities with district heating networks are required to phase out coal-fired boilers of less than 10 t/h (in steam production) by 2017 in all built areas and new construction of coal-fired boilers under 20 t/h in these cities are prohibited. Coal-fired boilers that are larger than 20 t/h are required to install pollution control devices such as a desulfurization system. For regions without district-heating networks, the Action Plan calls for replacing coal with renewable energy source, burning high quality coal, and/or promoting the use of energy-efficient and environmental friendly boilers. In addition, the Plan calls for developing combined heat and power capacity to replace dispersed coal-fired boilers in industrial clusters areas of chemical, pulp and paper, textile, and pharmaceutical industries. In addition, the Plan outlines the pace of replacing coal with natural gas and requires industrial companies in the three key regions around Beijing, Shanghai, and Guangzhou to accelerate switching to natural gas. It requires coal-fired boilers, industrial furnaces, and self-use coal-fired stations in these regions to complete switching to natural gas by 2017 (State Council, 2013).

On April 24, 2014 the National People's Congress (NPC) amended China's *Environmental Protection Law*. This amendment is the first time since China passed the original law in 1989 and will have last-lasting impacts on the country's effort in fighting pollutions. Under this amended law, which took effect on January 1, 2015, a new penalty system which charges daily fines to pollution violations replaces the previous one-off fine system. Company managers may also face criminal penalties even possible detention for offenses, including evading pollution data monitoring, falsifying emission data, discharging pollutants without a permit, or refusing to stop construction when ordered because of a lack of environmental reviews. Under the amended law, job performance review criteria for local government officials are changed from solely economic growth to also factoring in pollution control and reduction. Lastly, the amended law gives non-governmental organizations the right to sue polluters in court (NRDC, 2014).

National Boiler Action Plan

In October 2014, seven Chinese ministries and agencies jointly issued the *Action Plan of Implementing Comprehensive Measures for Improving Energy-Savings and Environmental Protection of Coal-Fired Boiler*. It is the first time that the Chinese government outlined a comprehensive plan to focus on industrial boilers. The Plan aims at promoting 500,000 high energy-efficient boilers and increasing the market share of high-efficient coal-fired boilers from the current 5% to 40% by 2018 (MIIT, 2014). Other targets that the Plan sets include phasing out coal-fired boilers with an aggregated capacity of 400,000 tons (of steam production per hour) by 2018 and increasing the average operating efficiency of existing industrial coal-fired boilers by 6% from the 2013 level (MIIT, 2014). The Chinese government estimates that implementing the Plan will save 40 million tons of coal equivalent, reducing 1 million tons of soot, 1.28 million tons of SO_2, and 0.24 million tons of NOx, respectively (MIIT, 2014).

Under this Plan, the Chinese government outlined a number of key measures to meet the targets. These measures include phasing out obsolete boilers that are less than 10 t/h, creating advanced technology catalogues, accelerating information dissemination, issuing tax and other financial incentives, encouraging combustion optimization and control automation, improving steam system efficiency and condensing recovery, improving operation through energy assessment, benchmarking, and personnel training, increasing pollution controls through installing pollution control equipment, developing the boiler industry through R&D, improving fuel quality, promoting solar preheating, and encouraging fuel switching.

Policies to Promote Coal Replacement

China has set a goal of reducing the percentage of coal use in total energy consumption to below 65% by 2017 in its *Atmospheric Pollution Prevention Action Plan* (State Council, 2013). In particular, this Plan mandates the three key regions (Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta) to achieve negative growth in coal consumption, and gradually phase out the use of coal, by importing electricity, increasing natural gas supply, and promoting the use of non-fossil energy. In these key regions, the Plan bans any new construction of self-used coal-fired power stations or approval of any new construction coal fired power stations (except for combined heat and power). Nationwide, the Plan encourages cities to increase the use of natural gas and renewable energy to replace coal. It calls for adding an additional natural gas supply capacity of 150 billion cubic meters by 2015. Further, the plan calls for cleaner use of coal in China through a series of measures, including increasing the share of washed coal, prohibiting importing of high-ash and high-sulfur content coal, and pursuing coal quality regulations (State Council, 2013).

The Plan outlines the pace of replacing coal with natural gas. It requires industrial facilities located in the three key regions around Beijing, Shanghai, and Guangzhou to accelerate the switch to natural gas and mandates that by 2017 all boilers, industrial furnaces, and self-use stations that are burning coal complete switching to natural gas in these key regions (State Council, 2013).

The Chinese government also encourages using biomass as an alternative fuel for industrial boiler. On June 16, 2014, the National Energy Administration (NEA) and the Ministry of Environmental Protection (MEP) jointly announced the launch of *Biomass Boiler Demonstration Project*, which aims at developing 120 biomass boiler projects by 2015, especially in the three key regions around Beijing, Shanghai, and Guangzhou. The 120 demonstration projects, which cost CNY 5 billion in total, will supply heat for more than 6 million square meters of residential heating areas and supply more than 1,800 tons of steam per hour in industrial sector. The energy savings are estimated at 1.2 million tce resulting in reductions of 5 million tons of CO_2 and 50,000 tons of SO_2 emissions. To qualify for the pilot, the minimum scale of each project cannot be smaller than 20 tons per hour (t/h) with the capacity of each installed biomass boiler being no less than 10 t/h (NEA and MEP, 2014).

Policies to Promote Natural Gas-Based Distributed Energy

The Chinese government started promoting natural gas-based distributed energy in 2011 through issuing the *Guiding Opinions on the Development of Natural Gas-Based Distributed Energy*. The document set up the target for developing 1,000 natural gas-powered distributed energy projects and creating 10 distributed energy demonstration areas. The goal is to reach a total installed capacity of 50 GW of natural gas distributed energy in China by 2020 (MOF, 2011). The policy calls for development of domestic capability of producing for natural gas based distributed energy equipment through demonstration projects with the goals of increasing the share of domestic technologies to 60% when the total capacity reaching to 5 GW and increasing the share to 90% when the total capacity reaching to 10 GW.

Natural gas based distributed energy projects will benefit from the current fiscal incentives, such as subsidies provided at the local level. Distributed energy projects that are implemented through energy performance contracting can also receive tax incentives (e.g., tax exemptions). The guidelines encourage local governments to provide favorable natural gas prices to local natural gas based distributed energy projects.

These projects are expected to be located near energy load centers, such as industrial parks, tourist service centers, ecological parks, and large commercial buildings. The government also encourages co-development of natural gas based distributed energy with other renewable sources such as solar, wind, and geothermal. By June 2012, the first four demonstration projects, located in Jiangsu, Tianjin, Beijing, and Hubei Province, were approved by the central government.

After this, a series of government documents were issued to address the barriers to deployment of natural gas based distributed energy. The State Council made a further promotion of the natural gas based distributed energy through its white paper entitled *China's Energy Policy 2012*.

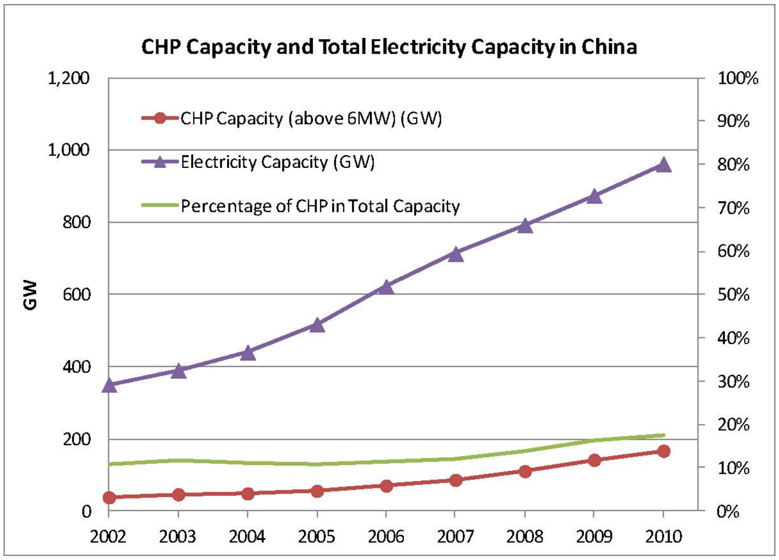
This white paper calls for developing standards for distributed energy and improving grid-interconnection for natural gas based distributed energy (NEA, 2012a). In July 2013, the National Development and Reform Commission issued *Interim Measures on Managing Electricity Generation from Distributed Energy*, which aims to remove some of the grid-interconnection barriers in distributed energy projects (NDRC, 2013). *The Atmospheric Pollution Prevention Action Plan* encourages natural gas based distributed energy projects while puts a limit on chemical projects using natural gas (State Council, 2013).

In October 2014, there central agencies - National Development and Reform Commission, Ministry of Housing and Urban-Rural Development, and National Energy Administration - jointly released the *Guidelines for Implementing Natural Gas-Based Distributed Energy Demonstration Projects*. This is the first time that the central government established detailed implementation guide to facilitate natural gas-based distributed energy demonstration projects. It requires local provinces to develop distributed energy development plan, establish application and selection procedures for demonstration projects, and develop relevant incentives, standards, and regulations (NDRC, MOHURD, and NEA, 2014).

Policies to Encourage Combined Heat and Power Application

In China, combined heat and power (CHP) capacity has been increasing at 10% on an annual basis over the last decade. However, the increase of CHP capacity is still far below the increase of electricity generation capacity, and the percentage of CHP in total power capacity is small (as shown in Appendix Figure 1). China's 2010 CHP Planning and 2020 Development Plan aims at increasing CHP installed capacity by more than 50% from the level of 2010 and reaching 200 GW by 2020.

China's 1997 *Energy Conservation Law*, which was revised in 2007 with the revisions taking effect in 2008, encourages industrial facilities to adopt CHP and waste-heat recovery to improve energy efficiency. The law also encourages utility companies to make arrangements for "clean, high efficient, and eligible CHP power-generating units to be connected to the grid."



Appendix Figure 1. Growth of CHP Capacity and Total Electricity Capacity in China
Source: CEC, 2011; Editorial Board of the China Electric Power Yearbook, 2003-2011; Wang, 2007.

The Circular Economy Promotion Law of China, released in 2008, states that industrial enterprises should adopt "advanced or appropriate recovery technologies, processes, and equipment" to utilize waste heat produced from industrial production processes. CHP projects that utilize waste heat must be approved or registered according to national laws and regulations. Based on national regulations, grid companies sign contracts with industrial facilities that adopt CHP, provide grid interconnection services, and purchase the total amount of power that is generated by grid-connected CHP systems. If grid companies refuse to purchase the power generated from waste-heat recovery, they are required to compensate industrial facilities.

The National Development and Reform Commission (NDRC), the Ministry of Finance (MOF), the Ministry of Housing and Urban-Rural Development (MOHURD), and the National Energy Administration (NEA) released a guidance document titled *Guiding Opinion on Developing Natural Gas Based Distributed Energy* in October 2011. This document outlines the goal to develop demonstration pilots during the 12th Five-Year Plan (2011-2015). By the end of 2015, the target is to establish about 1,000 natural gas distributed energy projects and to develop about 10 demonstration zones to showcase different characteristics and uses of natural gas based distributed energy. By 2020, the goal for total installed capacity of natural gas based distributed energy is 50 GW.