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Energy Efficiency Potentials in Industrial Steam Systems in China

Development of a steam systems energy efficiency cost curve

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Steam system experts:

Greg Harrell, Energy Management Services, Lead expert and co-author.

Riyaz Papar, Hudson Technologies.

Veerasamy Venkatesan, VGAEC Inc.

Giorgio Bocci, Independent consultant.

Dou Wenyu and Wang Zhongwei, China Special Equipment Inspection and Research Center.

Contents

Abstract

China became the world's largest emitter of energy-related CO_2 in 2007 and the world's largest energy consumer in 2009. China was responsible for nearly 21 per cent of global energy use and 26 per cent of energy-related CO_2 emissions in 2011. The industrial sector dominates the country's total energy consumption, accounting for about 70 per cent of primary energy use and 72 per cent of the country's CO_2 emissions in 2012. For these reasons, the development path of China's industrial sector will greatly affect the future energy demand and dynamics of not only China, but the entire world.

Steam is used extensively as a means of delivering energy to industrial processes. On average, industrial steam systems account for around 30 per cent of manufacturing industry energy use worldwide. There exists a significant potential for energy efficiency improvement in steam systems; however, this potential is largely unrealized. A major barrier to effective policymaking, and to more global acceptance of the energy efficiency potential of steam systems, is the lack of a transparent methodology for quantifying steam system energy efficiency potential based on sufficient data to document the magnitude and cost-effectiveness of these energy savings by country and by region.

The goal of this study is to develop and apply a steam system energy efficiency cost curve modelling framework to quantify the energy saving potential and associated costs of implementation of an array of steam system optimization measures. The developed steam systems energy efficiency cost curve modelling framework will be used to evaluate the energy efficiency potential of coal-fired boiler and steam systems in China's industrial sector. Nine energy efficiency technologies and measures for steam systems are analysed.

This study found that total cost-effective (i.e. the cost of saving a unit of energy is lower than purchasing a unit of energy) and technically feasible fuel savings potential in industrial coal-fired steam systems in China in 2012 was 1,687 PJ and 2,047 PJ, respectively. These account for 23 per cent and 28 per cent of the total fuel used in industrial coal-fired steam systems in China in that year, respectively. The CO_2 emission reduction potential associated with the cost-effective and total technical potential is equal to 165.82 $MtCO_2$ and 201.23 $MtCO_2$, respectively. By comparison, the calculated technical fuel saving potential for industrial coal-fired steam systems in China is approximately 9 per cent of the total coal plus coke used in Chinese manufacturing in 2012 and is greater than the total primary energy use of over 160 countries in the world in 2010. Several sensitivity analyses were conducted, their policy implications discussed, and uncertainties and limitations of this study are presented.

Introduction

Objective of the study

The objective of this study is to develop and apply a steam system energy efficiency cost curve modelling framework to quantify the energy saving potential and associated costs of the implementation of an array of steam system optimization measures.

On average, industrial steam systems account for approximately 30 per cent of manufacturing industry energy use worldwide (Yang and Dixon, 2012). Despite the existence of significant potential for energy efficiency improvement in steam systems (IEA, 2007), this potential is largely unrealized. The lack of information about potential savings and their magnitude as well as the lack of suitable policy frameworks and supporting programmes are key reasons why this potential remains untapped. A major barrier to effective policymaking, and to global acceptance of the energy efficiency potential of steam systems, is the lack of a transparent methodology for quantifying steam system energy efficiency potential based on sufficient data to document the magnitude and cost-effectiveness of these energy savings by country and by region. It is far easier to quantify the incremental energy savings of substituting an energy-efficient boiler for a standard boiler than it is to quantify the energy savings of applying energy efficiency practices to an existing steam system, which goes beyond the boiler itself and includes the steam distribution network, heat recovery systems, and even steam end users. The former is dependent on the appropriate matching of the replacement boiler, but reasonable assumptions can be made that an incremental benefit against current practice will occur. The latter is based on the concept of changing current practice by applying commercially available technologies in the most energy-efficient manner, and requires on-site evaluation to maximize system efficiency. Providing a modelling framework for quantifying steam system energy efficiency potential that moves beyond case studies of individual applications is needed.

The development of such a steam system energy efficiency cost curve modelling framework will support greater global acceptance of the energy efficiency potential of industrial steam systems. This framework is applied to China as a case study. The steam systems energy efficiency cost curve modelling framework is used to quantify the energy saving potential and associated cost by the implementation of certain steam system optimization measures. The purpose of this research is to provide guidance for national policymakers and is not a substitute for a detailed technical assessment of the steam systems energy efficiency opportunities of a specific plant.

Introduction to steam systems

Steam is used extensively as a means of delivering energy to industrial processes. Steam holds a significant amount of energy on a unit mass basis that can be extracted as mechanical work through a turbine or as heat for process use. In addition, steam can be used to control temperatures and pressures during chemical processes, strip contaminants from process fluids, dry paper products, and in other miscellaneous applications (IEA, 2007). Equipment that uses steam varies substantially among industries and is generally process- and site-specific (Energetics, 2012). Table 1 shows examples of steam end-use equipment and processes in energy-intensive industrial subsectors.

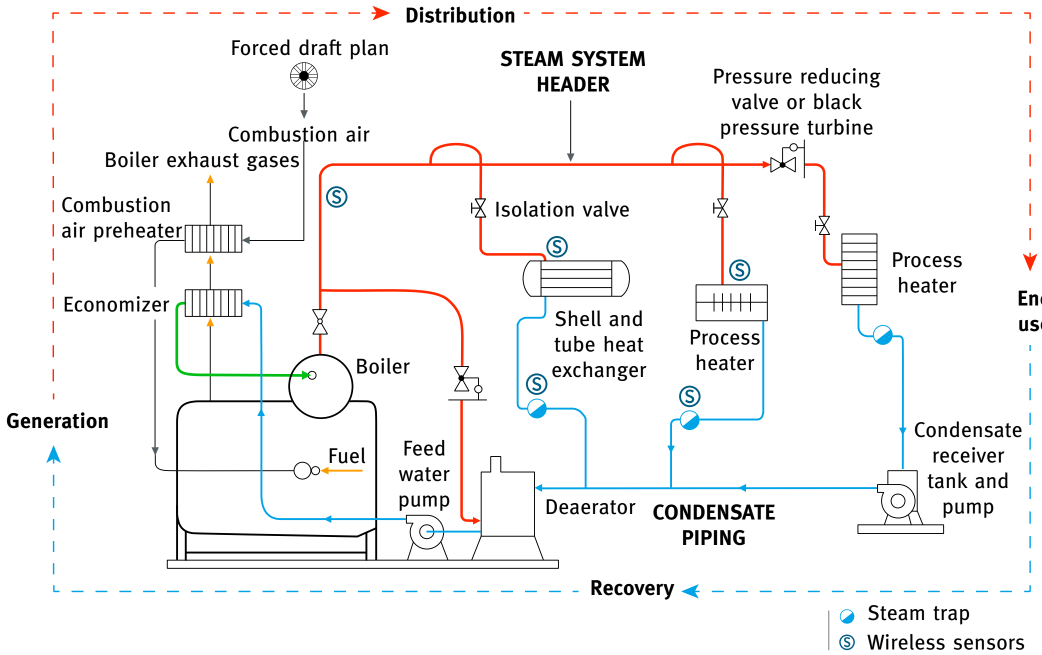
Table 1. Steam end-use equipment in energy-intensive industries (U.S. DOE/AMO, 2012)

Equipment	Process application	Industry subsector
Condenser	Steam turbine operation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Distillation tower	Distillation, fractionation	Chemicals, petroleum refining
Dryer	Drying	Forest products
Evaporator	Evaporation/concentration	Chemicals, forest products, petroleum refining
Process heat exchanger	Alkylation, process air heating, process water heating, gas recovery/light ends distillation, isomerization, storage tank heating, visbreaking/coking	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Reboiler	Fractionation	Petroleum refining
Reformer	Hydrogen generation	Chemicals, petroleum refining
Separator	Component separation	Chemicals, forest products, petroleum refining
Steam ejector	Condenser operation, vacuum distillation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Steam injector	Agitation/blending, heating	Chemicals, forest products, petroleum refining
Steam turbine	Power generation, compressor mechanical drive, hydrocracking, naphtha reforming, pump mechanical drive, feed pump mechanical drive	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Stripper	Distillation (crude and vacuum units), catalytic cracking, asphalt processing, catalytic reforming, component removal, component separation, fractionation, hydrogen treatment lube oil processing	Chemicals, petroleum refining
Thermo-compressor	Drying, steam pressure amplification	Forest products

Steam systems are made up of a range of components. Figure I provides a schematic diagram of a typical steam system.

The use of steam in different industry subsectors varies widely. In the United States, the top five steam-consuming industrial subsectors are forest products, chemicals, petroleum refining, food and beverage, and iron and steel (Energetics, 2012). In China, the top five steam-consuming industrial subsectors in 2012 were the chemical industry, smelting and pressing of ferrous metals (iron and steel industry), petroleum refining, food and beverage, and the textile industry.[1]

Figure I. Steam system schematic diagram (U.S. DOE/AMO, 2012)



The efficiency of steam boilers varies by design and fuel type. A well designed boiler fired by coal is typically about 84 per cent efficient (IEA, 2007). If natural gas, fuel oil or biomass is used as a fuel in a similar boiler instead of coal, the efficiency of the boiler is often lower. However, it should be noted that the boiler is only one part of an industrial steam supply system; distribution losses throughout the system can be quite important. While there are no detailed statistics regarding global system efficiencies, a study conducted by Energetics in 2012 estimated that overall industrial steam systems efficiency in the United States is around 60 per cent (Energetics, 2012).

Overview of manufacturing industry in China

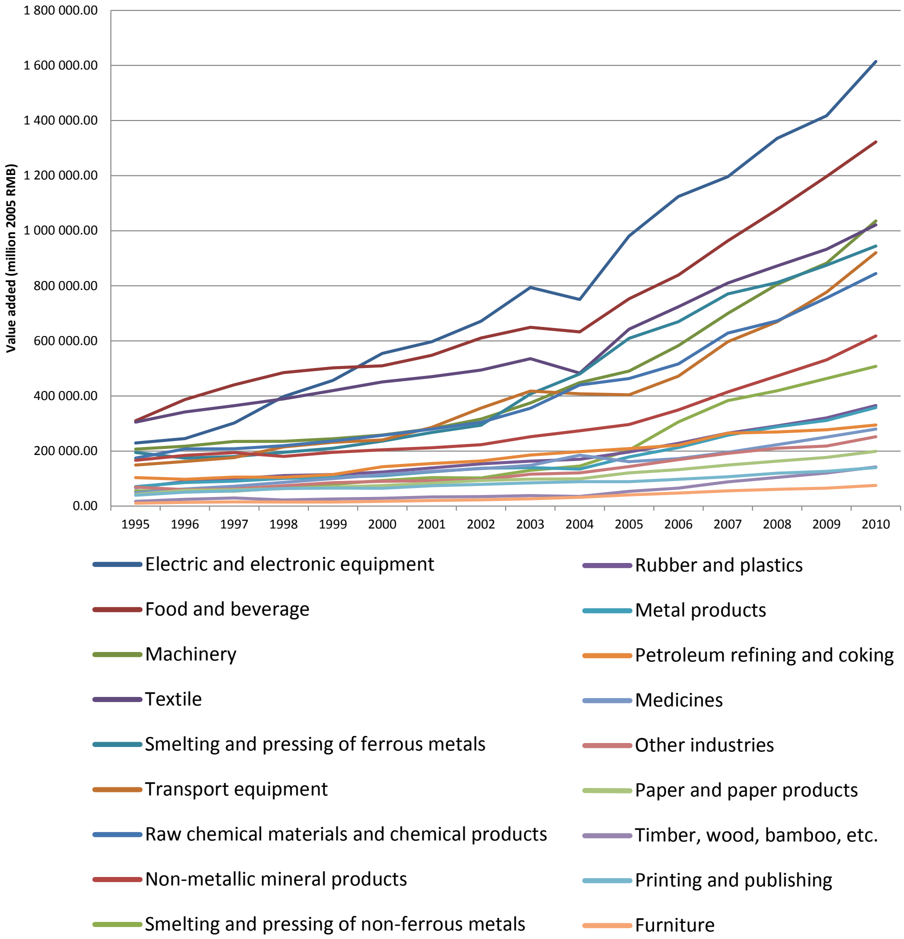
China has experienced unprecedentedly rapid economic growth over the last thirty years. The annual gross domestic product (GDP) grew at an average rate of 10 per cent from 1980 to 2010 (NBS, 1981-2013). China became the world's largest emitter of energy-related CO_2 in 2007 and the world's largest energy consumer in 2009 (IEA, 2011). China was responsible for nearly 21 per cent of global energy use and 26 per cent of energy-related CO_2 emissions in 2011 followed by the United States, which represented around 18 per cent of global energy use and 18 per cent of global energy-related CO_2 emissions in the same year (IEA, 2013a,b).

[1] Calculated based on NBS (2013) - see table 7.

Unlike most countries, China's energy consumption pattern is unique because the industrial sector dominates the country's total energy consumption, accounting for approximately 70 per cent of primary energy use and 72 per cent of country's CO_2 emissions[2] in 2012 (NBS, 2013). For this reason, the development path of China's industrial sector will greatly affect future energy demand and the dynamics of not only China, but the entire world.

China is the world's second largest economy after the United States. In 2010, China's manufacturing value added was equal to 10,935 billion 2005 RMB,[3] accounting for around 35 per cent of China's total gross domestic product (GDP) that year (NBS, 1996-2011).[4] Total Chinese manufacturing value added (in 2005 RMB) increased by 383 per cent over the period 1995-2010. This rate of increase is 2.8 times higher than the rate of increase in primary energy use, which increased by 137 per cent over the same period. Figure II shows that electric and electronic equipment manufacturing, food and beverage production, and the textile industry had the highest value added during the period 1995-2010. Between 1995 and 2010, there was no major shift between shares of value added from total manufacturing value added among the subsectors.

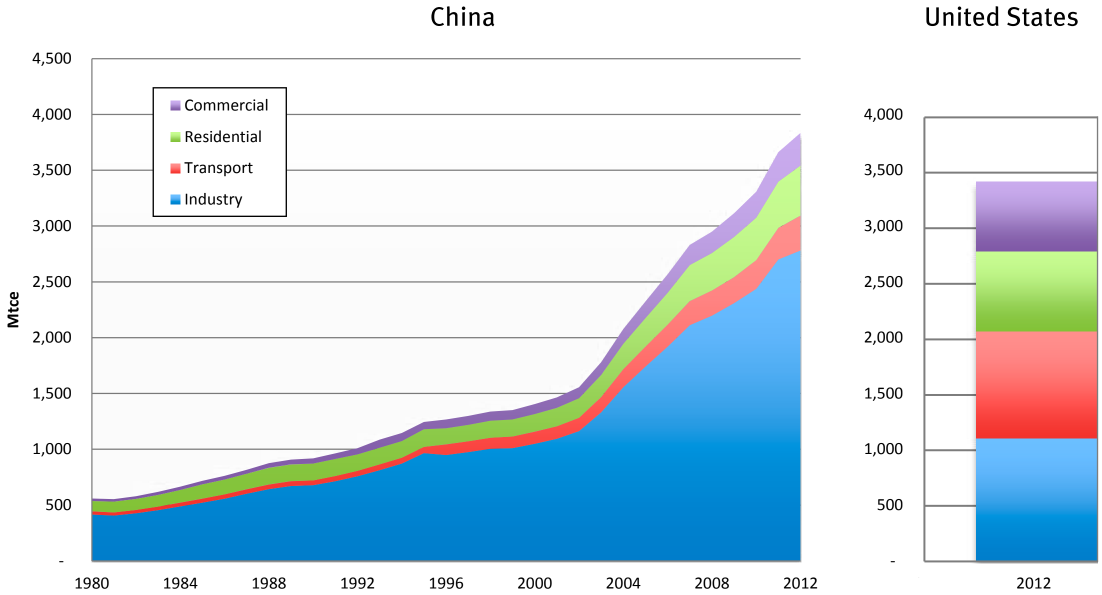
Figure II. Value added (million 2005 RMB) of different manufacturing subsectors in China, 1995-2010 (NBS, 1996-2011)



[2] Carbon dioxide emissions were estimated based on reported energy data multiplied by IPCC default emission factors (NBS, 1981-2011; IPCC, 1996).
[3] Using an exchange rate of 6.8 RMB/US$ in 2010, this is equal to US$1,608 billion.
[4] It should be noted that manufacturing does not include power generation, mining, and several other sectors that are often included under "industry" sector in Chinese statistics.

The industry-dominated energy end-use structure in China is very different from the structure found in industrialized countries. For example, as illustrated in figure III, industry only accounted for 31 per cent of total energy in the United States in 2010.

Figure III. Primary energy use by sector in China (1980-2012) and the United States (2012) (NBS 1981-2013; U.S. DOE/EIA 2013b)



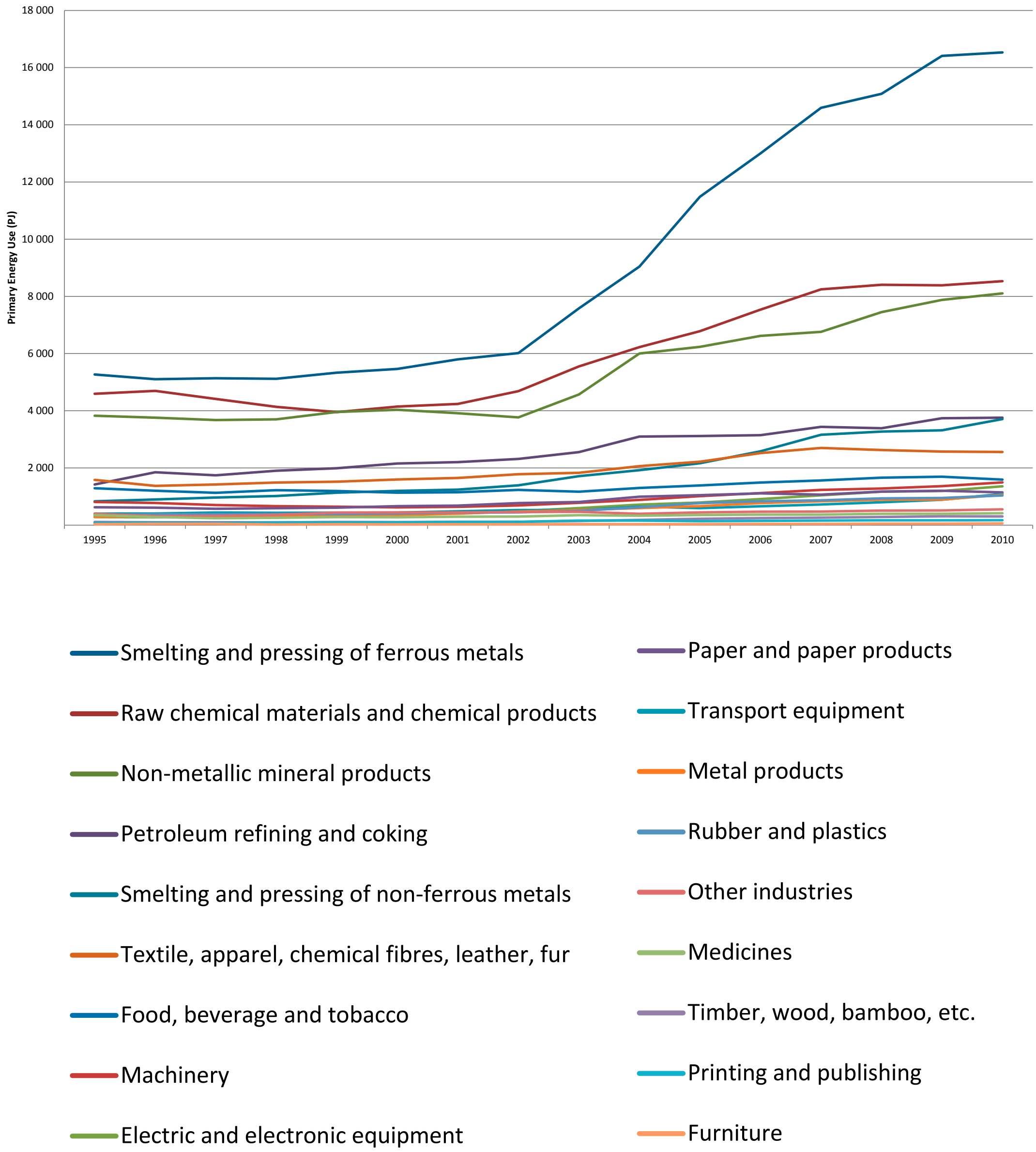
In 2010, the total primary energy use of Chinese manufacturing was 53,491 petajoules (PJ) which is a 36 per cent increase from the 2005 level (39,474 PJ) and a 137 per cent increase in primary energy use since 1995 (22,551 PJ). The increase in primary energy use during the period 1995-2010 varied among the manufacturing subsectors, but overall, the primary energy use of all manufacturing subsectors in China increased during this period. Figure IV shows the trend of primary energy use of different manufacturing subsectors in China during 1995-2010.

Figure IV shows that the smelting and pressing of ferrous metals, manufacturing of raw chemical materials and chemical products, and non-metallic mineral products manufacturing subsectors were the top three primary energy-consuming manufacturing sectors in China during the period 1995-2010. Manufacturing of furniture, printing and publishing, and the processing of timber, manufacturing of wood and bamboo subsectors were the lowest energy-consuming sectors.

Overview of boiler and steam systems in China and Chinese industry

In 2009, there were 595,200 boilers in use in China. Of these, there were 10,400 power plant boilers, 432,000 production and district heating boilers, 116,800 pressure water boilers, and 36,000 organic fluid heaters (Gao and Zhang, 2013). In 2010, these boilers used 2.24 billion tons of coal, or about 70 per cent of China's total raw coal production of 3.24 billion (Dai and Xiong, 2013).

Figure IV. Primary energy[5] use of manufacturing subsectors in China, 1995-2010 (NBS, 1981-2013)



Boilers are widely used in Chinese industry. With China's rapid industrialization and urbanization, boilers manufactured in China also grew rapidly. During the 11th Five Year Plan (FYP) period (2006-2010), the annual growth rate of boilers used in China was more than 14 per cent and the number of boilers in use reached 607,000 in 2010 (Dai and Xiong, 2013). In 2012, industrial steam systems accounted for around 25 per cent of the total fuel used in Chinese industry in that year.[6]

[5] In primary energy use reported in NBS (1996-2011), electricity use is converted from final to primary energy using average power generation efficiency in China in various years. The losses in the refining for the production of petroleum products and in coke making for production of coke are not included in the primary energy reported in NBS (1981-2011).

[6] See table 7 for the calculation based on NBS (2013) and U.S. DOE/EIA (2013).

In 2010, the average capacity of in-use boilers in China was about 3.4 tons of steam per hour (t/h). As such, the total capacity of China's 607,000 boilers was 2,064,000 t/h in that year (Dai and Xiong, 2013). Based on coal use, boilers under 10 t/h accounted for around 50 per cent of total coal consumption in industrial boilers in China (Gao and Zhang, 2013). Coal-fired boilers account for around 80-85 per cent, oil- and gas-fired boilers account for around 15 per cent, and boilers that use other fuels (e.g. electricity, biomass, etc.) account for less than 5 per cent of the of total boiler capacity in China (Dai and Xiong, 2013). Unlike most developed countries, where coal-fired boilers outside of the power sector have been largely phased out, the majority of industrial boilers in China still burn coal. This is due to the cost advantages of coal relative to oil and natural gas, and the lack of large-scale domestic supplies of oil and natural gas in China.

The coal-fired industrial boilers in China are mainly tiered burning boilers, which account for 95 per cent of coal-fired boilers. The number of circulating fluidized bed boilers with high efficiency, low pollution, and high coal fuel adaptability features is limited, representing 3-5 per cent of China's boilers (Gao and Zhang, 2013).

During the 11th FYP period, about 15 per cent of coal-fired industrial boilers were retrofitted for energy efficiency improvement (Dai and Xiong, 2013). However, compared with developed countries, the efficiency level of coal-fired industrial boilers in China is still low (Gao and Zhang, 2013). Therefore, in 2006, China's National Development and Reform Commission (NDRC) put coal-fired boiler (furnaces) retrofits as one of the first items in the 11th FYP Ten Key Energy Saving Projects programme. Two additional projects, the "Regional Combined Heating and Power Project" and the "Waste Heat and Waste Pressure Utilization Project" were also directly related to steam system optimization (IIP, 2014).

Similar to many developing countries and even some developed countries, the focus on improvements for industrial steam systems in China has been mainly on the equipment (primarily boilers) rather than the entire steam system, which includes steam generation, distribution, end uses, and heat recovery systems. Although system optimization might be more difficult than changing a piece of equipment since it requires a more holistic knowledge and assessment of the system, it will often yield much greater energy saving compared to replacing a single component with a more efficient one. Besides, the presence of energy-efficient components (e.g. boilers), while important, provides no assurance that an industrial steam system will be energy-efficient. Misapplication of equipment to demand, mismanagement of the system, and operation below the optimal efficiency in the industrial steam systems are common (Williams et al., 2006). Therefore, there is a need for shifting the paradigm in China to focus attention on steam systems optimization and efficiency as a whole rather than focusing solely on boiler efficiency. The study presented in this report adopts such a holistic approach, focusing on steam system efficiency rather than on boilers alone.

1

Methodology

This study focuses on coal-fired boilers and steam systems used in Chinese industry.[7] The "steam system" boundary analysed in this study consists of the generation, distribution and recovery components of steam systems. The steam end uses and energy efficiency potential of the steam end uses are not included in this study. Furthermore, since electricity use accounts for only 1-2 per cent of the total energy use in the industrial steam systems, this study only focuses on fuel use and fuel savings in industrial steam systems and does not include electricity consumption or electricity efficiency measures and associated savings.

Since the focus of this study is on the fuel and thermal efficiency aspects of the steam system, cogeneration (or combined heat and power) and cogeneration components are not included for a number of reasons. First, cogeneration presents major complicating factors associated with system operation, performance evaluation and opportunity analysis. Second, many steam systems do not incorporate cogeneration components. Third, the thermal issues discussed in this study remain intact (although altered in magnitude) even if the system contains cogeneration components. In other words, this study can be used as a guide for the thermal aspects of steam system evaluation noting that evaluations of the thermal aspects of cogeneration systems require a high degree of modelling and evaluation sophistication.

In addition, this study does not focus on fuel switching opportunities. It should also be noted that fuel switching (fuel selection) often happens because of economic-based decisions and most of the time, efficiency is not the target. For example, it is common for a fuel switch from natural gas to coal to increase system efficiency, but the major reduction in operating costs will arise from fuel unit cost.

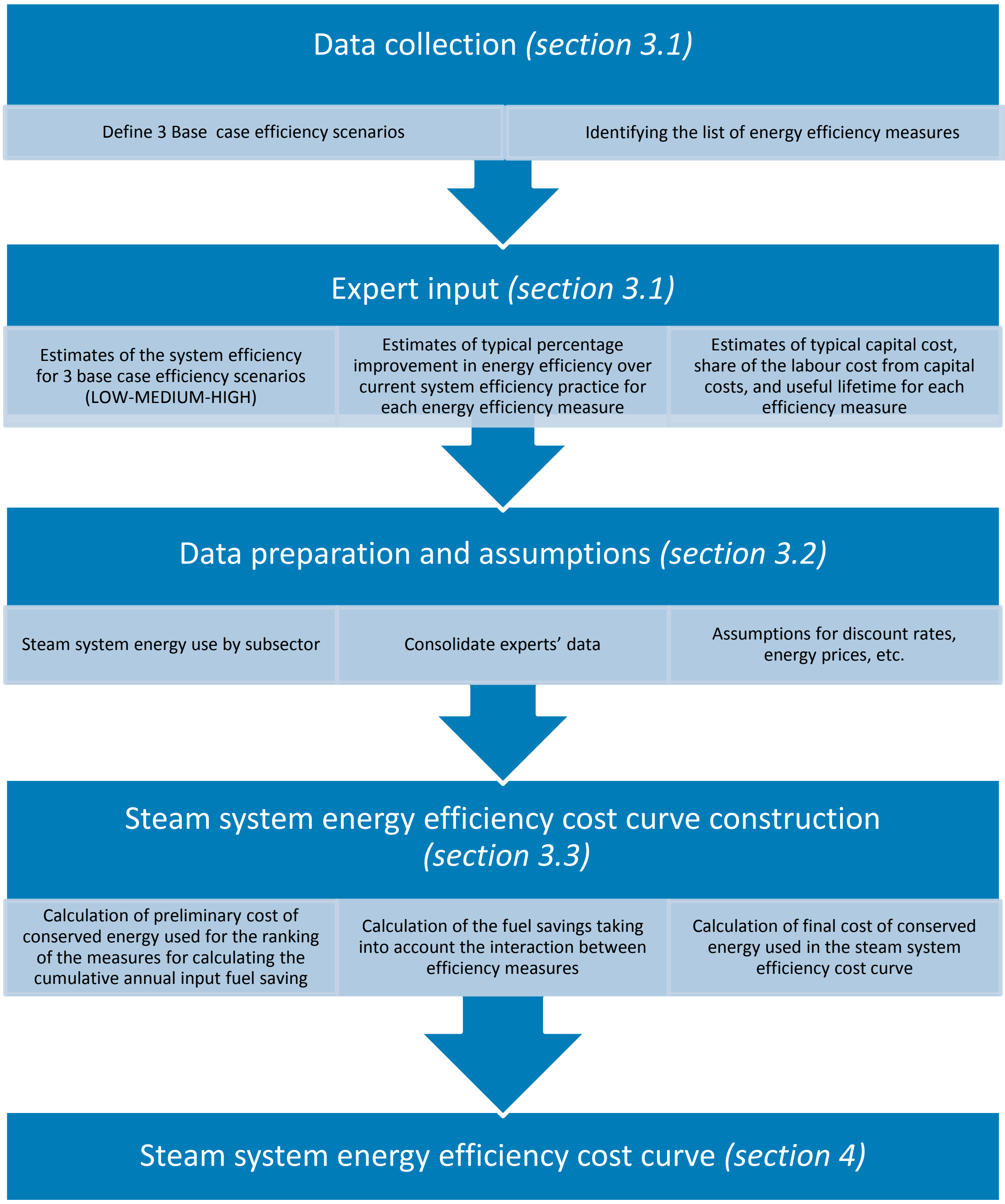
Also, fuel type (coals, fuel oils, natural gas, biomass) has a significant influence on overall efficiency (fuel energy-to-load energy conversion). A coal-fired boiler burning high-quality coal with good combustion control and thermal energy recovery can operate with an efficiency of 90 per cent (in high heat value, HHV) while a biomass boiler with excellent combustion control and thermal energy recovery can only attain 70 per cent (in high heat value, HHV). Inclusion of the fuel type is outside the scope of this study because the dominant fuel in China is coal and the typical quality of coal in China is moderate.

Figure V shows a schematic diagram of the methodology used for this study. First, a data collection questionnaire was developed to obtain expert input to supplement the existing data. Input

[7] In Chinese statistics, the term "industry" refers to manufacturing as well as mining of coal and minerals, oil and gas extraction, power generation, and production and distribution of water. These subsectors of industry (other than manufacturing) are not included in the present study.

was sought from seven steam system experts from the United States, Europe and China and responses were received from four of these experts. Information was sought from the experts on the energy efficiency of systems in a market with a defined set of characteristics (i.e. base case efficiency scenarios), the creation of a list of common energy efficiency measures for steam systems, and the energy savings and implementation costs associated with these measures. A Delphi-type analysis method was used in which several cycles of input, analyses and reviews were performed to better define these inputs into the resulting steam system energy efficiency cost curve. Details concerning this expert input are provided in section 1.1.

Figure V. Schematic diagram of the methodology used for this study



1.1 Data collection

Data were collected from experts using a questionnaire that solicited their expert judgment related to industrial steam systems efficiency levels of three base case efficiency scenarios and the efficiency improvement measures that could be implemented in each scenario.

1.1.1 Base case system efficiency scenarios

Three base case efficiency scenarios (LOW-MEDIUM-HIGH) for industrial steam systems were established based on previous research and expert opinion. The first step in establishing a base case was to create a unique list of system energy efficiency practices representative of each of the three efficiency scenarios for steam systems. The initial lists were created by the authors and then circulated to the experts for further review and revision. Tables 2-4 provide the list of practices defined for each base case efficiency level.

The efficiency of the steam system was defined as:

$$\text{Steam system efficiency} = \frac{\text{(Energy delivered by the steam system)}}{\text{(Fuel energy input to the system)}} \qquad \text{(Eq. 1)}$$

The experts were asked to review the list of proposed energy efficiency practices for each of the three efficiency scenarios (LOW-MEDIUM-HIGH) and to either approve or make recommendations to improve the groupings provided. The experts were then asked to provide a low to high estimated range of the system energy efficiency (expressed as a percentage) they would expect to see when auditing a system in an industrial plant with the characteristics given for each efficiency scenario. A range of efficiency was requested, rather than a single value to better align with the variations that are likely to be found in industrial settings. There was a good degree of agreement among the experts concerning the range of efficiency that could be expected from these base case scenarios.

After defining the base cases, a “base case” value was assigned to the country of study, i.e. China, for the purpose of providing a reference point for the current industrial steam system performance in China, based on available information. While it is important to acknowledge that this approach blurs the real variations that may exist in system performance from one plant to another or from one industrial sector to another within China, it is consistent with the level of precision possible with the available data and with the purpose of the analysis. The purpose is the estimation of energy efficiency improvement potential in industrial steam systems and the associated cost of such improvement by the implementation of a list of measures and technologies identified in this study.

Table 2. Characteristics of LOW efficiency base case scenarios for steam systems

	GENERATION
1	No combustion gas oxygen monitoring, air-fuel control is simple, and no periodic tuning events occur
2	In solid fuel and oilfired boilers (fuels that present combustion-side fouling), sootblowing is accomplished on an irregular basis
3	No flue gas heat recovery equipment (feedwater economizer and/or combustion air preheater) is installed on the boiler resulting in elevated flue gas temperature
4	In coal-fired boilers, unburned carbon in ash (commonly known as loss on ignition (LOI)) is not monitored regularly and is managed poorly

5	No heat recovery from boiler blowdown (and feedwater quality is poor to moderate)
	DISTRIBUTION
6	Steam leaks are seldom investigated and repaired
7	Significant amount of damaged, poor, or no insulation of steam piping, valves, fittings and vessels
8	Steam traps are fixed on a very irregular basis without maintenance programmes
	RECOVERY
9	Poor or no condensate recovery
10	Flash-steam is not recovered

Note: In the LOW efficiency base case, it is assumed that more than 60 per cent of the items listed in the table are in poor condition as noted in table 2.

Table 3. Characteristics of MEDIUM efficiency base case scenarios for steam systems

	GENERATION
1	No continuous combustion gas oxygen monitoring, air-fuel control is simple, periodic tuning events do occur
2	Solid fuel and heavy oil boiler sootblowers are actuated on a regular basis but timing is infrequent and cleaning effectiveness has not been evaluated
3	The final flue gas temperature is elevated and a significant energy recovery potential remains
4	In coal-fired boilers, unburned carbon in ash (loss on ignition (LOI)) is monitored regularly but timing is infrequent and significant corrective actions are not clearly applied to reduce the LOI
5	No heat recovery from boiler blowdown but feedwater quality is managed well
	DISTRIBUTION
6	Steam leaks are investigated and repaired when leaks are observed but no systematic detection and repair system in place
7	Thermal insulation is generally in good condition but significant sections of piping and equipment are un-insulated
8	Steam traps are the responsibility of area managers and no unified maintenance strategy is in place for overall steam trap management
	RECOVERY
9	Condensate recovery is moderate
10	Flash-steam is partially recovered

Table 4. Characteristics of HIGH efficiency base case scenarios for steam systems

	GENERATION
1	Continuous combustion gas oxygen monitoring and automatic-continuous air-fuel trim control is in place with appropriate oxygen and combustibles targets
2	Solid fuel and heavy liquid fuel boilers utilize sootblowing on a regular basis and flue gas temperature impacts are evaluated to ensure effectiveness
3	Flue gas thermal energy is effectively recovered to the lowest practical values
4	In coal-fired boilers, unburned carbon in ash (loss on ignition (LOI)) is monitored regularly and frequently and corrective actions are applied to reduce LOI
5	Boiler water quality is maintained to appropriate standards and blowdown thermal energy is effectively recovered

	DISTRIBUTION
6	Steam leaks are regularly investigated and repaired with a systematic detection and repair system in place
7	Steam piping, valves, fittings, vessels and equipment are properly insulated
8	Steam traps are fixed on regular basis with a systematic maintenance programme
	RECOVERY
9	High level of condensate recovery
10	High level of flash-steam is recovered

1.1.2 Determining the impact of energy efficiency measures

In order to determine the impact of the energy efficiency measures, a list of potential measures to improve steam system energy efficiency was developed and sent to the experts for review. Experts were asked to provide their opinion on the energy savings likely to result from the implementation of each measure, taken as an independent action, expressed as a percentage improvement over each of the LOW-MED-HIGH base cases. The experts provided a percentage improvement for each measure over the base case scenarios using a 0-100 per cent scale. For example, if an energy efficiency measure improves the efficiency by 10 per cent in a steam system operating with 60 per cent efficiency, the new system would have 66 per cent efficiency. The percentage efficiency improvement by the implementation of each measure over the LOW base case will be greater than that of the MEDIUM base case, which will in turn be greater than the value given for the HIGH base case. For example, since the LOW base case is defined as having no installed flue gas heat recovery equipment (item 3 in table 2), the percentage improvement from installation of flue gas thermal energy recovery technologies (i.e. economizer and/or air heater) would be expected to be greater than that of the HIGH base case, for which flue gas thermal energy is effectively recovered to the lowest practical values (item 3 in table 4). The experts were also asked to evaluate the list of measures. Based on the responses received, some adjustments were made to the list of measures, requiring a second round of review to validate the percentage efficiency improvement values. The final list of measures is comprised of nine energy efficiency measures and technologies (see table 6).

The experts were also asked to provide cost information for each measure when the measure is implemented over the LOW efficiency base case, disaggregated by steam system size range. As the system becomes more efficient, the energy saving potential of each efficiency measure decreases. In other words, the extent of the application of energy efficiency decreases (for example, shorter pipe length requires insulation); hence, the cost of implementation of each measure will decrease when they are implemented over the MED and HIGH base case efficiency. Therefore, experts were asked to provide an estimate of “how much the cost of each efficiency measure will decrease (as a percentage) if implemented over the MED and HIGH efficiency base cases compared to the costs that are given for implementation of measures over LOW efficiency base case”. These shares were applied to the given cost data before using them for the MED and HIGH efficiency base case.

The steam system size ranges were selected based on categories developed for the characterization of the United States industrial/commercial boiler population, which is one of the most detailed studies available (Energy and Environmental Analysis, 2005). For the purpose of this study, the term “steam system size” refers to the aggregate boilers steam generation capacity (ton per hour (t/h)) for the system.

In addition to the energy efficiency improvement and cost, the experts were also asked to provide the useful lifetime of the measures. Finally, the experts were asked to indicate the share of labour cost from the typical installed cost provided by experts for each energy efficiency measure. This share was used to adjust the typical cost given by two of experts whose cost data were based on experiences in the United States This adjustment was necessary because there is a large gap between labour costs in the United States and China.

A manufacturing labour cost of US$36/h was assumed in the United States based on U.S. BLS (2012) and US$3/h in China based on Deloitte (2013). Because of limited available data, materials/equipment costs were not adjusted and were assumed to be equivalent across all countries studied. The materials/equipment costs can vary from country to country. These variations in cost would benefit from further study.

Initially, two additional energy efficiency measures were on the list of system optimization measures. These two measures were *(a)* pressure reducing valve optimization in backpressure steam turbines and *(b)* condensing turbine optimization. These two measures were removed from the final list of the efficiency measures used in the analysis primarily for two reasons. First, a large number of industrial facilities in China operate without combined heat and power components. Second, the presence of steam turbines operating in a combined heat and power arrangement greatly complicates the analysis and the results. Unlike simple steam systems where only steam is produced, the outputs of cogeneration systems to which the two aforementioned turbine-related measures are applicable are both steam and electricity. The unit cost of fuel and electricity dramatically affect the analysis decisions. Hence, the cogeneration system optimization should be viewed and analysed taking both of the outputs into account and not only steam. This was beyond the scope of this analysis. In addition, there is a lack of information and data on the potential application of these two turbine-related measures in Chinese industry. It should be noted that many large Chinese industrial facilities have combined heat and power plants.

It should also be noted that one of the best ways to improve the energy efficiency in industry and of a steam system is through a cogeneration or combined heat and power system (CHP) in which the system produces both steam and electricity (IEA, 2007; U.S. DOE/AMO, 2014). However, because of the complexities mentioned above, the addition of new cogeneration/CHP components was not included in this analysis. The adoption of these two measures and some other steam system energy efficiency measures and technologies that are not included in this analysis has the potential to increase the energy saving potential above what is calculated in this analysis.

For typical capital costs of each efficiency measure, the authors aimed to identify rough estimates given the scope of the analysis. There were five categories based on steam system size ranges for which an estimate of the implementation cost of the measure in United States dollars was sought. The actual installed cost of some efficiency measures can be highly variable and dependent on country-specific and plant-specific conditions, such as the number and type of steam end uses. The need to add or modify physical space to accommodate new equipment can also be a factor. Finally, in developing countries, the cost of imported equipment, especially energy-efficient equipment, can be higher due to scarcity, shipping and/or import fees.

This report uses the estimated full cost of the measures analysed rather than the incremental cost for energy-efficient measures. This was driven by the goal of the analysis, which is to assess the total potential for energy efficiency in existing industrial steam systems in the base year assuming a 100 per cent penetration rate. Therefore, energy savings are based on the assumption that all the measures are installed in the base year to determine how much energy saving potential exists in that year. In this case, the full cost of the measures should be applied since the existing systems are not all at the end of their lifetime. However, for other types of studies, such as energy efficiency cost curves used to develop future scenarios, the incremental cost (the difference between the cost of an energy-efficient technology and conventional technology) can be used, since new stock can be installed at the end of the lifetime of the existing ones in the future years. Table 6 in section 1.2 below includes the consolidated expert input for energy efficiency improvement measures.

1.2 Data preparation and assumptions

1.2.1 *Expert input consolidation*

The experts were asked to assign system efficiency, expressed as a range, for the LOW-MED-HIGH efficiency base cases. Table 5 contains the consolidated results, including the base case values used in developing the energy efficiency cost curve model. There was a high degree of agreement among the experts regarding the range of steam system energy efficiency that would be expected to result from the list of characteristics assigned to the three base cases. As can be seen, the average values (average of low and high values) for the LOW-MED-HIGH efficiency base case were used.

Table 5. Consolidated steam system efficiency for LOW-MED-HIGH efficiency base case

	STEAM SYSTEM EFFICIENCY		
	Low end (%)	High end (%)	Average (%) [used in the analysis]
LOW level of efficiency	57%	65%	61%
MEDIUM level of efficiency	65%	78%	71%
HIGH level of efficiency	78%	87%	82%

After defining the base case efficiencies for steam systems, China was determined to currently fall into the LOW "base case" for the industrial steam system efficiency performance based on the information available and expert judgment. This despite the fact there are perhaps many plants in China with steam system efficiency equal to MED or even HIGH base case efficiency. Thus, the results of this study in nature encompass this generalization of the Chinese industry.

Table 6 shows the consolidated experts input data for the typical percentage improvement in efficiency over each base case efficiency (LOW-MED-HIGH), the lifetime of measures, as well as an estimated typical implementation cost of the measure, differentiated by system size.

1.2.2 *Steam systems energy use by industry subsector*

The base year for this analysis is 2012 since this is the most recent year for which energy use data are available in China.

Calculating the fuel saving potential requires information on fuel use by industrial steam systems in China.[8] In Chinese statistics, only the fuel use is reported for each industrial sector and it is not disaggregated by the end use (e.g. steam systems, process heating systems, etc.). Therefore, the fuel use of industrial steam systems in China was estimated using a subsector level calculation as follows. In the United States, the Manufacturing Energy Consumption Survey (MECS) published by the Energy Information Administration of the Department of Energy (U.S. DOE/EIA) publishes energy use in manufacturing subsectors by end use.

[8] The calculation procedure is explained in more detail in section 1.3.3.

Table 6. Energy efficiency measures, percentage efficiency improvement, lifetime, and cost-consolidated experts input

No.	Energy efficiency measure	Typical % improvement in energy efficiency over current system efficiency practice			Typical life of measure (years)	Typical installed cost in China by system size when the measure is implemented over LOW efficiency base case (US$) [a]					The decrease in typical installed cost when implemented over MED base case (%)	The decrease in typical installed cost when implemented over HIGH base case (%)
		% Improvement over LOW eff. base case	% Improvement over MED eff. base case	% Improvement over HIGH eff. base case		<4 t/h	4 - 19 t/h	19 - 38 t/h	38 - 94 t/h	> 94 t/h		
1.1.[b]	Excess air management: Tune existing positioning control (or simple control)	5.0%			0.5	200	300	300	400	500	N/A	N/A
1.2.[b]	Excess air management: Upgrade from simple control to standard oxygen trim[b]		1.5%		10	17,600	24,900	43,000	67,900	86,000	N/A	N/A
1.3.[b]	Excess air management: Upgrade from standard oxygen trim to oxygen trim with CO tuning[c]			0.5%	10	26,300	26,300	44,400	67,900	86,000	N/A	N/A
2	Flue gas thermal energy recovery (Economizer and/or air heater)	7.4%	4.4%	1.0%	16	72,500	145,000	290,000	870,000	1,160,000	20	40
3	Sootblower optimization	3.5%	1.1%	0.5%	12	1,800	13,700	32,500	54,600	76,700	40	40
4	Loss on ignition (LOI) optimization	5.0%	3.0%	1.0%	10	72,500	72,500	181,300	290,000	507,500	50	50
5	Optimization of boiler blowdown and recovery of heat from boiler blowdown	2.8%	1.5%	0.4%	12	14,500	23,800	36,600	67,300	70,600	22	25
6	Optimization of insulation of steam piping, valves, fittings and vessels	5.0%	2.0%	0.5%	10	15,600	39,600	87,700	214,600	300,800	60	60
7	Implementation of an effective steam trap maintenance programme	2.2%	1.1%	0.4%	7	8,100	17,600	44,000	94,700	143,400	40	60
8	Optimization of condensate recovery	4.1%	1.9%	0.4%	12	24,900	53,000	113,900	248,800	347,200	40	60
9	Flash-steam recovery	3.9%	2.5%	0.4%	10	38,000	71,500	172,600	500,500	674,200	25	25

[a] The installed cost data in the table are rounded to the nearest US$100.

[b] Measures 1.1 to 1.3 are all for excess air management. It is assumed that measure 1.1 is applicable to the LOW efficiency base case, measure 1.2 to the MED efficiency base case, and measure 1.3 to the HIGH efficiency base case.

[c] For measures 1.2 and 1.3, based on the above note, cost data are for when the measure is implemented over the MED and HIGH efficiency base case, respectively.

The 2010, United States manufacturing energy use data from the U.S. DOE/EIA (2013a) was used to calculate the share of steam system fuel use in total fuel use in each manufacturing subsector listed in table 7. Then, the calculated shares were applied to the fuel use data in each industrial subsector in China in 2012 (NBS 2013) to estimate the fuel use by industrial steam systems in each industrial subsector in China in 2012. Table 7 shows that the total fuel used in Chinese industrial steam systems in 2012 was 8,850 petajoules (PJ). Since this study focuses on coal-fired steam systems, which account for 80-85 per cent of the industrial boiler capacity in China (Dai and Xiong, 2013), there is a need to further calculate the fuel used in the coal-fired steam systems. Assuming that coal-fired steam systems account for 82.5 per cent of total industrial boilers in China, the total fuel used in coal-fired industrial steam systems in China in 2012 is estimated to be 7,301 PJ.

Although it should be noted that the structure within industrial subsectors might vary between China and the United States, this calculation is done at the subsector level in order to make the best estimate possible given available data. Once China starts to report energy use by end use for the industrial sector, these values can be refined.

Table 7. Total fuel use and steam system fuel use in Chinese industry by subsector in 2012

No.	Industry subsector	Fuel use in 2012 (TJ)[a]	Estimated steam system fuel use as % of overall fuel use in the sector in 2012 (%)[b]	Calculated steam system fuel use in 2012 (TJ)
1	Food, beverage and tobacco	825,115	63%	522,960
2	Textile, apparel, chemical fibres, leather, fur	758,400	57%	429,283
3	Timber, wood, bamboo, etc.	94,215	15%	14,132
4	Furniture	15,926	7%	1,138
5	Paper and paper products	573,659	72%	411,519
6	Printing and publishing	42,318	20%	8,464
7	Petroleum refining and coking	3,486,947	32%	1,116,803
8	Raw chemical materials and chemical products	7,072,038	60%	4,209,379
9	Medicines	226,891	29%	66,733
10	Rubber and plastics	192,297	43%	82,670
11	Non-metallic mineral products	6,014,876	2%	128,224
12	Smelting and pressing of ferrous metals	13,765,300	11%	1,537,486
13	Smelting and pressing of non-ferrous metals	803,544	11%	89,750
14	Metal products	175,762	12%	21,585
15	Machinery	536,515	8%	42,356
16	Transport equipment	383,309	25%	97,216
17	Electric and electronic equipment	187,865	25%	46,966
18	Other industries	79,738	29%	23,452
	Total	**35,234,715**		**8,850,115**

[a] *Source:* NBS (2013);

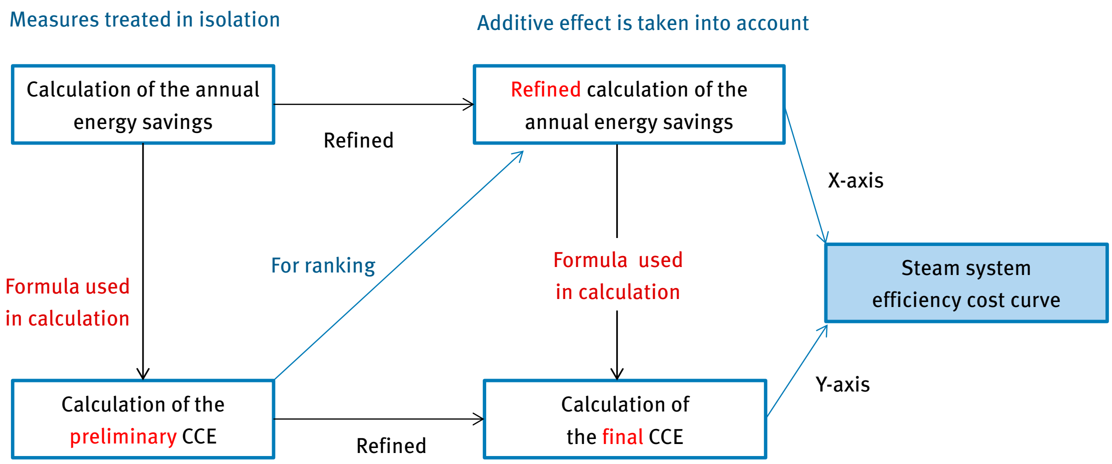
[b] *Source:* Calculated from U.S. DOE/EIA (2013a)

As can be seen from table 7, the top five steam consumers in Chinese industry by subsector (and their share from total industrial steam systems fuel use) are: raw chemical materials and chemical products (48 per cent), smelting and pressing of ferrous metals (17 per cent), petroleum refining and coking (13 per cent), food, beverage and tobacco (6 per cent), and the textile, apparel, chemical fibres, leather, fur industry (5 per cent).

1.3 Construction of a steam systems energy efficiency cost curve

Figure VI shows a schematic of the calculation process for the construction of a steam system energy efficiency cost curve. The details of each step are explained in next subsections.

Figure VI. Schematic diagram of the calculation process for construction of a steam systems energy efficiency cost curve



1.3.1 Introduction to the energy efficiency cost curve

The energy efficiency cost curve is an analytical tool that captures both the engineering and economic perspectives of energy conservation. The curve shows the energy conservation potential as a function of the marginal cost of conserved energy (CCE). The CCE can be calculated from equation 2.

$$\text{CCE} = \frac{(\text{Annualized capital cost} + \text{Annual change in O\&M costs})}{(\text{Annual energy savings})} \qquad \text{(Eq. 2)}$$

The annualized capital cost can be calculated from equation 3.

$$\text{Annualized capital cost} = \text{Capital cost} * \frac{d}{1-(1+d)^{-n}} \qquad \text{(Eq. 3)}$$

d: discount rate, n: lifetime of the energy efficiency measure

After calculating the CCE for all energy efficiency measures, the measures are ranked in ascending order of CCE. In an energy efficiency cost curve, a unit price of energy line is determined. All measures that fall below the energy price line are identified as “cost-effective”. That is, saving a unit of energy through the adoption of the cost-effective measures is less expensive than buying a unit of energy. On the curves, the width of each measure (plotted on the x-axis) represents the annual energy saved by that measure. The height (plotted on the y-axis) shows the measure's cost of conserved energy.

The energy efficiency cost curve provides the CCE, annualized cost of energy efficiency measures, annualized energy cost saving, annualized net cost saving, and annualized energy saving by each individual technology or a group of technologies. If dE is the energy saving potential by a technology, then the annualized cost of energy efficiency measure, the annualized energy cost saving, and the annualized net cost saving of that technology can be calculated from:

$$AC = dE * CCE \qquad \text{(Eq. 4)}$$

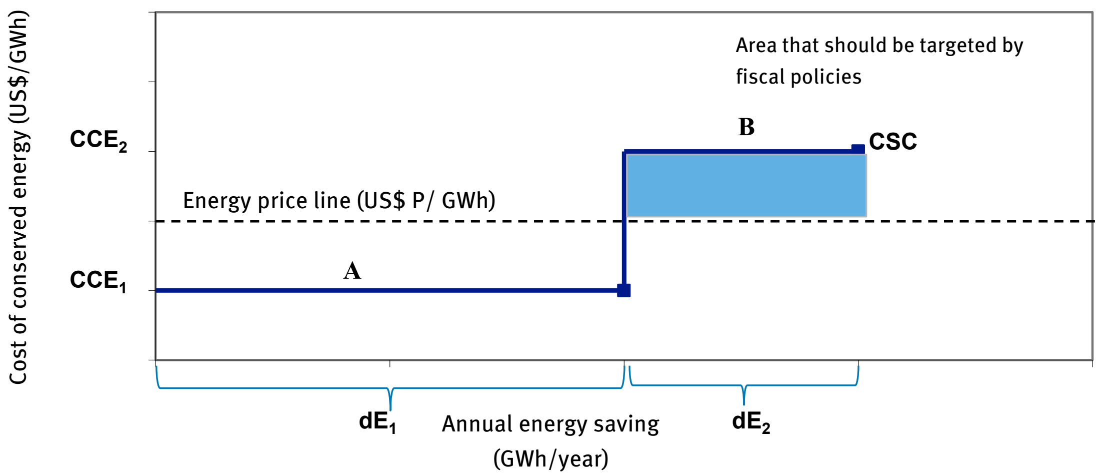
$$AECS = dE * P \qquad \text{(Eq. 5)}$$

$$ANC = AC - AECS = dE * (P-CCE) \qquad \text{(Eq. 6)}$$

Where:
AC: Annualized cost of energy efficiency measure (US$), AECS: Annualized energy cost saving (US$), ANC: Annualized net cost saving (US$), P: Energy price, and dE: Energy saving in CSC.

Figure VII shows a schematic of an energy efficiency cost curve that helps the visualization of this discussion.

Figure VII. Schematic view of an energy efficiency cost curve



For the cost-effective energy efficiency measures in the energy efficiency cost curve, the annual net cost saving is positive, but for the measures whose CCE is above the energy cost line, the annualized net cost saving is negative. That is, for cost-effective measures, net annual revenue results from implementing those measures from the net energy cost saving, whereas for non-cost effective measures the annualized cost of implementing the measures is higher than the annualized cost saving. Thus, the annual net cost saving for non-cost effective measures is negative. However, it should be emphasized that even in the case of non-cost effective measures, the significant cost saving occurs from energy saving which is equal to dE*P as mentioned above.

Therefore, from an energy policy point of view, any fiscal policy for non-cost effective energy efficiency measures should target the annualized net cost saving of the measure which is the area between the energy efficiency cost curve and the energy price line. For measure A which is cost-effective, the annual net cost saving is positive, whereas for measure B which is non-cost effective the annual net cost saving is negative. For measure B, the area between energy price line and curve should be targeted by fiscal policies.

1.3.2 Discount rate

The discount rate refers to the interest rate at which the future values associated with a project are discounted to the present value, taking into account the time value of money. Similarly, it is also used to annualize the cost into the future years for a lifetime of a project or technology. In this study, a real discount rate of 15 per cent was assumed for the analysis. However, since it is one of the key variables used in the cost of conserved energy calculation, a sensitivity analysis of the final results with varying discount rates is presented in section 2.2. It should be noted that the choice of the discount rate also depends on the purpose of the analysis and the approach (prescriptive versus descriptive) used. A prescriptive approach (also called social perspective) uses lower discount rates (4-10 per cent), especially for long-term issues such as climate change or public sector projects (Worrell et al. 2004). Low discount rates have the advantage of treating future generations equally to the current generation, but they also may cause relatively certain, near-term effects to be ignored in favour of more uncertain, long-term effects.

A descriptive approach (also called private-sector or industry perspective), uses relatively high discount rates between 10 and 30 per cent in order to reflect the existence of barriers to energy efficiency investments (Worrell et al. 2004). These barriers include perceived risk, lack of information, management concerns about production and other issues, capital constraints, opportunity cost, and preferences for short payback periods and high internal rates of return (Bernstein, et al. 2007 and Worrell, et al. 2000). As a result, the 15 per cent discount rate used for these analyses is slightly higher than the high end of discount rates used from a social perspective and close to the lower end of the discount rates used from a private-sector or industry perspective. The sensitivity analysis of the results with respect to the discount rate will show how the movement towards each of these two perspectives will influence the results. In addition, since the energy efficiency measures for the steam systems are cross-cutting technologies/measures, the selection of a discount rate is further influenced by the assumption of fewer barriers to the implementation of these measures compared to process-specific, capital-intensive technologies in each industrial sector (i.e. the installation of an efficient grinding mill or a kiln system in the cement industry). Thus, the lower discount rate used for these cross-cutting measures is consistent with a private-sector or industry perspective.

1.3.3 Annual fuel saving potential calculation method

For the calculation of annual fuel savings achieved by the implementation of each energy efficiency measure in an industrial steam system, the following inputs were available:

(a) Base case efficiency for industrial steam systems in China (as previously described, we assigned LOW base case efficiency for industrial steam systems in China, based on the authors' judgment and expert consultation).

(b) For each energy efficiency measure, the experts provided a typical percentage improvement in steam system energy efficiency over the base case efficiency.

(c) Fuel use in coal-fired industrial steam systems in China in 2012 (calculated as explained in section 1.2.2).

From this information, the annual fuel saving from the implementation of each individual energy efficiency measure, where measures are treated individually and can be implemented in isolation regardless of the implementation of other measures, can be calculated following the steps given below:

1. Annual input energy for coal-fired industrial steam systems in 2012 (TJ/yr) = Industrial coal-fired steam systems fuel use in China in 2012

2. Annual useful energy used in coal-fired industrial steam systems with base case efficiency (TJ/yr) = [Annual input energy for coal-fired industrial steam systems in 2012 (TJ/yr)] * [Base case efficiency of coal-fired industrial steam systems in China in 2012]

3. New system efficiency after the implementation of an energy efficiency measure = [Base case efficiency of steam systems] * [1+ % system efficiency improvement by the implementation of the efficiency measure]

4. Annual useful energy used in the coal-fired industrial steam systems with new efficiency (TJ/yr) = [Annual input energy for coal-fired industrial steam systems in 2012 (TJ/yr)] * [New system efficiency]

5. Annual useful energy saving = [Annual useful energy used in industrial steam systems with base case efficiency (TJ/yr)] - [Annual useful energy used in industrial steam systems with new system efficiency (TJ/yr)]

6. Annual input energy saving in coal-fired industrial steam systems in 2012 (TJ/yr) = [Annual useful energy saving (TJ/yr)] / [New system efficiency after the implementation of the energy efficiency measure]

In the procedure explained above, input energy use is the fuel that is supplied to the steam system (boiler) as input. In this study, this is equal to the total fuel used in coal-fired industrial steam systems in China in 2012 (7,301 PJ) calculated in section 1.2.2. The useful energy use, however, is the energy that is converted to the actual service through the system. The useful energy is the energy that is provided by steam at the end use. Therefore, the useful energy use is calculated by taking into account the steam system efficiency and multiplying that by the input energy use. Since the system efficiency is always lower than 100 per cent, the useful energy use is always less than the input energy use.

In practice, the implementation of one measure can influence the efficiency gain by the next measure implemented. When one measure is implemented the base case efficiency is improved. Therefore, the efficiency improvement by the second measure will be less than if the second measure was implemented first or was considered alone. Hence, the measures could not be treated as isolated actions. To overcome this problem, the aforementioned equations were refined so that the measures were treated in relation to each other (as a group). In other words, the efficiency improvement by the implementation of one measure depends on the efficiency improvement achieved by the previous measures implemented. The refined method used is shown below. A numerical example of this calculation is also presented in box 1.

1. Annual input energy for coal-fired industrial steam systems in 2012 (TJ/yr) = Industrial coal-fired steam systems fuel use in China in 2012

2. Annual useful energy used in coal-fired industrial steam systems with Base case efficiency (TJ/yr) = [Annual input energy for coal-fired industrial steam systems in 2012 (TJ/yr)] * [Base case efficiency of coal-fired industrial steam systems in China in 2012]

3. Cumulative new system efficiency after the implementation of an energy efficiency measure = [Base case efficiency of steam systems] * [1+ Sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented]

4. Annual useful energy used in the coal-fired industrial steam systems with new efficiency (TJ/yr) = [Annual input energy for coal-fired industrial steam systems in 2012 (TJ/yr)] * [Cumulative new system efficiency]

5. Cumulative annual useful energy saving = [Annual useful energy used in industrial steam systems with base case efficiency (TJ/yr)] - [Annual useful energy used in industrial steam systems with new efficiency (TJ/yr)]

6. Cumulative annual input energy saving in coal-fired industrial steam systems in 2012 (TJ/yr) = [Cumulative annual useful energy saving (TJ/yr)] / [Cumulative new system efficiency after the implementation of the efficiency measure]

In this method, the cumulative annual energy saving is calculated by taking into account the additive effect of the measures rather than treating the measures completely in isolation from each other. For instance, when calculating the cumulative annual energy saving achieved by the implementation of measure 3 and all the previous measures (measures 1 and 2), the sum of the percentage efficiency improvement by the implementation of measures 1, 2, and 3 is used in the above calculation.

Box 1. Example of the calculation of energy saving and final cost of conserved energy (CCE)

The cumulative annual input energy saving from the implementation of energy efficiency measure #1 (Excess air management: Tune existing positioning control) and #2 (Sootblower optimization) on the curve, where measures are treated in relation with each other, can be calculated as follows:

1. Annual input energy for coal-fired industrial steam systems in 2012 (PJ/yr) = 7,301

2. Annual useful energy used in industrial steam systems with base case efficiency (PJ/yr) = 7,301 * 0.61 = 4,454

3. Cumulative new system efficiency after the implementation of measure #1 and #2 = 0.61* [1+ 0.085] = 0.662

4. Annual useful energy used in the industrial steam systems with new efficiency (PJ/yr) = 7,301 * 0.662 = 4,832

5. Cumulative annual useful energy saving with measure #1 and #2 (PJ/yr) = 4,454 – 4,832 = 379

6. Cumulative annual input energy saving with measure #1 and #2 in 2012 (PJ/yr) = 379/ 0.662 = 574

The calculation of the cumulative energy savings rather than individual savings is also desirable since the cumulative energy savings will be used in the construction of the steam systems energy efficiency cost curve. However, the ranking of the measures significantly influences the energy saving achieved by each measure. In other words, given a fixed percentage improvement of efficiency for each individual measure, the higher the rank of the measure, the larger the energy saving contribution of that measure to the cumulative energy savings. To define the ranking of the efficiency measures before calculating the cumulative energy savings from the method described above, the preliminary CCE was calculated (see below for an explanation of the CCE calculation) for each measure assuming that the measures are independent of each other (i.e. treating them in isolation without taking into account any additive effect). Then, these measures were ranked based on their preliminary CCE. This ranking was used to calculate the final cumulative annual energy saving as well as the final CCE, which are described in more detail below.

1.3.4 *Cost of conserved energy (CCE) calculation method*

Since the capital cost data provided by the experts was for the implementation of each measure/technology on each steam system size, the CCE was calculated assuming the implementation of each measure only on one of each steam system size. Since the energy efficiency improvement achieved by each measure and its cost are different under each efficiency base case (see table 6), calculations should be performed for a specific base case. As mentioned above, industrial steam systems in China were characterized as LOW efficiency base case. Then the energy efficiency improvement and cost of measures given under the LOW efficiency base case in table 6 were used for calculating the CCE and annual energy savings. The CCE was calculated following the steps described below:

(a) Capital cost data was provided in categories based on a range of steam system sizes, expressed in t/h. The average t/h value of each range was used as a representative size in the analyses, except for the first and last category for which the boundary values are assumed. The size ranges are shown in the table below.

Table 8. The industrial steam systems size range and the representative sizes used in this analysis

Size range (t/h)	‹4	4 - 19	19 - 38	38 - 94	› 94
Size used in the analysis (t/h)	4	12	29	66	94

(b) The annualized installed cost of implementing each measure on one system was calculated using the cost data in table 6 and equation 3 given in section 1.3.1.

(c) A real discount rate of 15 per cent was assumed for this analysis. The lifetime of the measures were provided by the experts for each efficiency measure (table 6).

(d) Because only one type of cost (installed cost) was available for each measure, this cost was used for the calculation of the CCE without regard for any change in operations and maintenance (O&M) cost (given in eq. 1). Some of the measures themselves are improvements in maintenance practices. Therefore, the CCE can be calculated from the following formula:

$$\text{CCE (US\$/GJ-saved)} = \frac{\text{(Annualized installed cost (US\$)}}{\text{(Annual Input energy savings (GJ)}} \qquad \text{(Eq. 7)}$$

(e) For calculating the energy savings achieved by the implementation of each measure on one steam system for each system size, it was necessary to combine the information from above on the cost of measures with some assumptions for typical boiler (not system) efficiency,

pressure and annual operation hours for each representative size for which the CCE is calculated. These assumptions are made based on values provided by the experts as well as personal communications with the China Special Equipment Inspection and Research Institute (CSEI, 2013). Table 9 shows the values used in the analysis for these parameters.

Table 9. Assumed industrial steam system operation parameters and calculated annual fuel use by system size

Representative size (t/h)	Typical boiler efficiency in Chinese industry (%)	Typical pressure (bar)	Typical annual operation hours (hr/y)	Latent heat of evaporization (enthalpy of steam—enthalpy of feedwater) (kJ/kg)	Annual fuel use by one steam system (GJ/y)
4	70%	1.0	2,150	2,287	26,512
12	73%	10.3	6,065	2,361	225,552
29	77%	20.7	7,412	2,378	652,517
66	78%	27.6	7,412	2,810	1,762,658
94	79%	55.2	7,412	3,029	2,680,819

(f) The annual energy savings for each measure implemented only on one steam system under the LOW base case scenario was calculated separately using the following approach:

1. Annual input energy for one steam system (GJ/y) = [Steam gen capacity (t/h)] * [Latent heat of evaporation (GJ/t)] * [Typical annual operation hours (hr/y)] / [Typical boiler efficiency in Chinese industry (%)]

The result of this calculation is shown in the last column of table 9.

2. Annual useful energy used in one system with base case efficiency = [Annual input energy for one system (GJ/y)] * [Base case efficiency of the steam system]

3. New system efficiency after the implementation of the efficiency measure = [Base case efficiency of the system] * [1+ % system efficiency improvement by the implementation of the measure]

4. Annual useful energy used in one system with NEW system efficiency (GJ/y) = [Annual input energy for one system (GJ/y)] * [New system efficiency]

5. Annual useful energy saving for one system (GJ/y) = [Annual useful energy used in one system with base case efficiency] - [Annual useful energy used in one system with NEW efficiency]

6. Annual input energy saving for one system (GJ/y) = [Annual useful energy saving for one system] / [New system efficiency after the implementation of the efficiency measure]

(g) Once the annual cost and annual energy savings are calculated for one system, the CCE can be calculated for each representative system size (five CCEs for five sizes).

(h) Only one CCE value can be displayed on the energy efficiency cost curve. Therefore, the CCEs calculated for different steam systems sizes need to be consolidated. To consolidate the CCEs of all size ranges for each measure, the industrial boiler distribution by number and by size was used to calculate the weighted average CCE. This weighted average CCE was used in the steam system energy efficiency cost curve. The industrial boiler distribution by size for the size categories used in this study was not available for China. Hence, we used the data from the report Characterization of the United States Industrial/Commercial Boiler Population (Energy and Environmental Analysis. 2005). China-specific boiler data would permit greater refinement of these assumptions for future analyses.

The CCE calculated above is the preliminary CCE since in the calculation of this CCE the additive effect is not taken into account. This preliminary CCE was used for the ranking of the measures before the final calculation of the cumulative energy saving could be done in which the additive effect of the measures is taken into account.

Once the measures are ranked based on the preliminary CCE, the final CCE can be formulated from the following formulae. (A numerical example of this calculation is also presented in box 2.)

1. Annual input energy for one steam system (GJ/y) = [Steam generation capacity (t/h)] * [Specific enthalpy of steam (GJ/t)] * [Typical annual operation hours (hr/y)] / [Typical boiler efficiency in Chinese industry (%)]

2. Cumulative new system efficiency after the implementation of the efficiency measure = [Base case efficiency of the steam system] * [1+ Sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented]

Unlike the energy savings that are shown as cumulative savings on the steam system energy efficiency cost curve (x-axis), the CCE for each individual measure is shown separately on the curve (figure VIII). In other words, the y-axis on the cost curve shows the CCE for each individual measure separately. Therefore, the cumulative input energy savings for one system cannot be used in the calculation of the final CCE. For the calculation of the final CCE, it is necessary to determine the individual input energy savings for one system for each measure. This is done, for example, for measure number (i) using the following equations:

1. Cumulative annual useful energy used in one system with cumulative new system efficiency after the implementation of the efficiency measure (i) (GJ/y) = [Annual input energy for one system (GJ/y)] * [Cumulative new system efficiency after the implementation of the efficiency measure (i)]

2. Cumulative annual useful energy used in one system with cumulative new efficiency after the implementation of the efficiency measure (i-1) (GJ/y) = [Annual input energy for one system (GJ/y)] * [Cumulative new system efficiency after the implementation of the efficiency measure (i-1)]

3. Individual annual useful energy saving for one system for measure (i) (GJ/y) = [Cumulative annual useful energy used in one system with cumulative new efficiency after the implementation of the efficiency measure (i)] - [Cumulative annual useful energy used in one system with cumulative new efficiency after the implementation of the efficiency measure (i-1)]

4. Individual annual input energy saving for one system for measure (i) (GJ/y) = [Individual annual useful energy saving for one system for measure (i) (GJ/y)] / [Cumulative new efficiency after the implementation of the efficiency measure (i)]

5. Final CCE of measure (i) = [Annualized installed cost of measure (i)] / [Individual annual input energy saving for one system for measure (i)]

For each measure, the final CCE is used for the construction of a steam systems energy efficiency cost curve along with the cumulative annual input energy saving explained in section 1.3.3. It should be noted that on the energy efficiency cost curves presented in the next section, the CCE is the final CCE for each individual measure.

Box 2. Example of final CCE calculation:

Assuming that measures #1 and #2 are already ranked based on the preliminary CCE, the final CCE for measure #2 for systems smaller than 4t/h is calculated as follows:

1. Annual input energy for one steam system (GJ/y) = [4 (t/h) * 2,287 (MJ/t) * 2,150 (hr/y) / 0.70] / 1000 = 26,512

2. Cumulative new system efficiency after the implementation of efficiency measure #2 = 0.61* [1+ 0.085] = 0.662

3. Cumulative annual useful energy used in one system with cumulative new system efficiency after the implementation of measure #2 (GJ/y) = 26,512 * 0.662 = 17,551

4. Cumulative annual useful energy used in one system with cumulative new efficiency after the implementation of measure #1 (GJ/y) = 26,512 * 0.641 = 16,994

5. Individual annual useful energy saving for one system for measure #2 (GJ/y) = 17,551 - 16,994 = 557

6. Individual annual input energy saving for one system for measure #2 (GJ/y) = 557 / 0.662 = 841

7. Final CCE of measure #2 for systems smaller than 4t/h = 331 / 841 = 0.4

Similar final CCE calculation is done for all steam system sizes. Then, the industrial boiler distribution by number and by size is used to calculate the weighted average final CCE.

It should also be noted that the purpose of these analyses is to identify the cost effectiveness and to estimate the total fuel savings potential for industrial steam systems in China. This study does not address scenario analysis based on the assumption of different penetration rates of the measures in the future, but rather identifies the magnitude of the total energy saving potential and the associated costs in the base year. A future scenario analysis and a study on the penetration of the efficiency measures could be a topic for future research.

2

Results and discussions

Based on the methodology explained above, a steam systems energy efficiency cost curve was constructed for the industrial sector[9] in China, to separately capture the cost-effective and total technical potential for energy efficiency improvement in industrial steam systems. Furthermore, the CO_2 emissions reduction potential associated with the fuel savings was calculated using the CO_2 emissions factor of 98.3 kgCO_2/GJ for coal used in industrial boilers (IPCC 2006). On the cost curve, the average unit price of bituminous coal[10] for Chinese industry in 2012 is also presented which is estimated to be 5.2 US$/GJ (SXCOAL 2013; CCTD 2013).

It should be noted that these potentials are the total existing potentials for the energy efficiency improvement in the studied industrial steam systems in the base year. In other words, the potential presented here is for a 100 per cent penetration rate. It is acknowledged that a 100 per cent penetration rate is not likely and, in any event, values approaching a high penetration rate would only be possible over a period of time. Although conducting a future scenario analysis by assuming different penetration rates for the energy efficiency measures was beyond the scope of this study, it could be the subject of a follow-up study.

2.1 Industrial steam systems energy efficiency cost curve

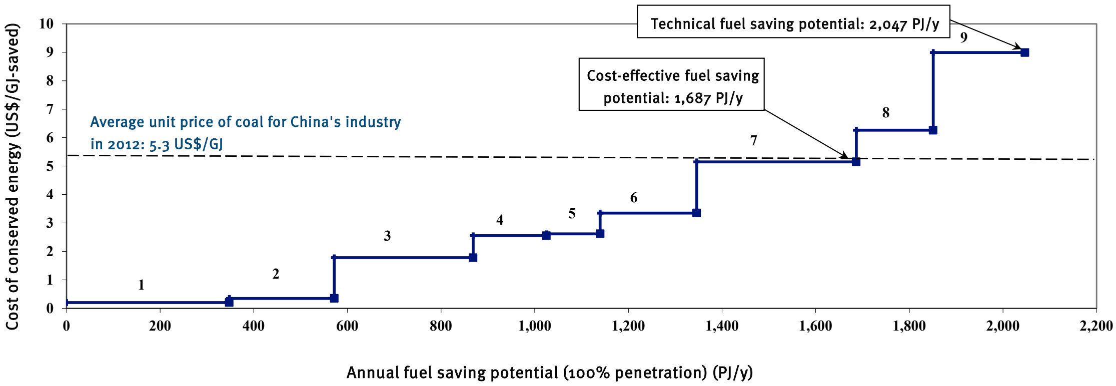
Figure VIII shows the steam systems energy efficiency cost curve for Chinese industry. The measures related to each number on the supply curve are given in table 10 along with the cumulative annual fuel saving potential, final CCE of each measure, and cumulative CO_2 emission reduction potential. In the tables, the energy efficiency measures that are above the bold line are cost-effective (i.e. their CCE is less than the average unit price of coal) and the efficiency measures that are below the bold line in the tables and are shaded in gray are not cost-effective.

As can be seen from the steam systems energy efficiency cost curves, in China seven out of nine energy efficiency measures are cost-effective, i.e. their cost of conserved energy is less than the average unit price of coal in China in 2012. Measure 1: Excess air management: tune existing positioning control (or simple control) is the most cost-effective measure for the steam systems optimization followed by measure 2: Sootblower optimization. On the other hand, measure 9: Loss on ignition (LOI) optimization is ranked last, has the highest CCE, and is not cost-effective. Figure VIII shows that the energy saving achieved by each individual measure is significant and all of the measures have a substantive contribution to the overall energy saving potential.

[9] In Chinese statistics, the term “industry” refers to manufacturing as well as mining of coal and minerals, oil and gas extraction, power generation, and production and distribution of water. These subsectors of industry (other than manufacturing) are not included in the present study.

[10] The average net calorific value of dominant bituminous coal used in China is around 20.9 GJ/t.

Figure VIII. Steam systems energy efficiency cost curve for Chinese industry



Note: This curve provides an indication of the relative cost-effectiveness of system energy efficiency measures at the national level in China. The cost-effectiveness of individual measures will vary based on plant-specific conditions.

Table 10. Cumulative annual fuel saving and CO_2 emission reduction potential for industrial steam systems efficiency measures in China ranked by their final CCE

No.	Energy efficiency measure	Cumulative annual fuel saving potential in industry (PJ/y)	Final CCE (US$/ GJ-saved)	Cumulative annual CO_2 emissions reduction potential from industry ($ktCO_2$/y)
1	Excess air management: tune existing positioning control (or simple control)	348	0.2	34,177
2	Sootblower optimization	572	0.3	56,227
3	Optimization of insulation of steam piping, valves, fittings and vessels	868	1.8	85,368
4	Optimization of boiler blowdown and recovery of heat from boiler blowdown	1,025	2.6	100,769
5	Implementation of an effective steam trap maintenance programme	1,140	2.6	112,049
6	Optimization of condensate recovery	1,346	3.4	132,304
7	Flue gas thermal energy recovery (Economizer and/or air heater)	1,687	5.1	165,817
8	Flash-steam recovery	1,851	6.3	181,953
9	Loss on ignition (LOI) optimization	2,047	9.0	201,231

Table 11 shows that the total cost-effective and technical fuel savings potential in industrial coal-fired steam systems in China in 2012 was estimated to be 1,687 PJ and 2,047 PJ, respectively, which account for 23 and 28 per cent of the total fuel used in industrial coal-fired steam systems in China in 2012, respectively. The CO_2 emission reduction potential associated with the cost-effective and total technical potential is estimated to be 165,817 $ktCO_2$ and 201,231 $ktCO_2$, respectively. Hence, it is clear that a significant portion of the energy saving potential that can be achieved by implementation of the nine energy efficiency measures in the steam systems are cost-effective in China, i.e. it cost less to implement these measures to save a GJ of coal used than to purchase a GJ of coal.

Table 11. Total annual cost-effective and technical energy savings and CO_2 emission reduction potential for Chinese industrial coal-fired steam systems

	Cost-effective potential	Technical potential
Annual fuel savings potential in industrial coal-fired steam systems in China in 2012 (100% penetration) (PJ/y)	1,687	2,047
Share of savings from the total fuel used in coal-fired industrial steam system in China in 2012	23%	28%
Annual CO_2 emission reduction potential from industrial coal-fired steam systems in China in 2012 (100% penetration) ($ktCO_2$/y)	165,817	201,231

By comparison, the total technical fuel savings potential in industrial coal-fired steam systems in China calculated in this study is around 17 per cent of the total coal and 9 per cent of total coal plus coke used in Chinese manufacturing in 2012 (NBS, 2013). In fact, the calculated technical fuel saving potential is greater than the total 2010 primary energy use of over 160 countries and territories in the world (U.S. DOE/EIA 2014). These comparisons show the large magnitude of the energy savings and CO_2 emissions reduction potential that can be achieved only by implementing nine energy efficiency measures in industrial coal-fired steam systems in China.

Furthermore, it should be noted that this study presents a conservative estimate of the energy savings and CO_2 emissions reduction potential in Chinese steam systems. First, there are additional steam systems optimization measures that are not included in this report for various reasons, some of which are discussed in chapter 1. Second, this study only focuses on industrial coal-fired boilers, which account for 80-85 per cent of industrial boilers in China, and does not include boilers that burn other fuels (e.g. natural gas, coal, biomass, etc.). Therefore, the actual energy saving potentials in industrial steam systems in China is even larger than what is calculated in this study. Third, in this study, the energy efficiency opportunities at the steam end use are not included. Including the steam end uses in the analysis would result in a significant increase in the energy saving potential. Finally, combined heat and power systems are not addressed in this study. These areas could be the subject of future analyses.

Overall, the relative cost-effectiveness of the steam systems energy efficiency measures presented in figure VIII are generally consistent with what could be expected based on field experiences. However, because of the uncertainties and limitations of this analysis (see section 2.3) that are by necessity based on a generalization of the benefits of each energy efficiency measure across a wide variety of system types and operating conditions in Chinese industry, the results of this study should be interpreted with caution. While this lack of granularity may be suitable to support policymaking needs, it is not a substitute for individualized plant assessments of steam system efficiency opportunities.

2.2. Sensitivity analysis

In the previous sections, the cost-effective and technical energy efficiency improvement potentials were presented and discussed for industrial coal-fired steam systems in China. Since several parameters play key roles in the analysis of energy efficiency potentials, it is important to see how changes in some of those parameters can influence the cost effectiveness of the calculated energy efficiency potentials. A sensitivity analysis was conducted for two of the key parameters–the discount rate and the unit price of fuel–because they can significantly influence the results.

The choice of discount rate can differ based on the purpose of the analysis and the unit price of coal varies within China by region and by industry.

In general, the cost of conserved energy has a direct proportional relationship with the discount rate. In other words, reduction of the discount rate will reduce the cost of conserved energy, which will increase the cost-effective energy saving potential (depending on the energy price) and vice versa. Table 12 illustrates how changes in the discount rate can have a significant effect on cost-effective energy saving potentials, assuming all the other factors, including the coal price, are held constant. It should be noted that non-cost effective measures might not become cost-effective by changing the discount rate, since the unit price of coal also plays a role in determining cost. The "sum of final CCE of all measures" will decrease with the decline in discount rate regardless. The total technical energy saving potentials do not change with the variation of the discount rate.

The choice of the discount rate depends on the purpose of the analysis and the approach (prescriptive versus descriptive) used. A prescriptive approach uses lower discount rates (4 to 8 per cent), especially for long-term issues such as climate change or public sector projects. Low discount rates have the advantage of treating future generations equally to the current generation (see section 1.3.2), but they also may cause relatively certain, near-term effects to be ignored in favour of more uncertain, long-term effects. A descriptive approach, however, uses relatively higher discount rates often between 10 and 30 per cent in order to reflect the existence of barriers to energy efficiency investments (Worrell et al. 2004). The discount rate used for this study is 15 per cent.

Table 12. Sensitivity analysis for cost-effective fuel saving potentials in industrial coal-fired steam systems in China with different discount rates

Discount rate	5%	10%	15%[a]	20%	30%
Cost-effective annual fuel savings potential (PJ/y)	1,851	1,851	1,678	1,346	1,140
Sum of final CCE of all measures (US$/GJ-saved)[b]	19.8	25.2	31.3	37.5	51.7

[a] The 15 per cent discount rate is the base scenario which is used in the main analysis presented in this report.

[b] Sum of final CCE of all measures is included here to illustrate that, although the change in discount rate may not result in a change in cost-effective savings, it will change the CCE in general.

The energy price can also directly influence the cost-effectiveness of energy saving potentials. A higher energy price can result in more energy efficiency measures being cost-effective, as it may cause the CCE to fall below the energy price line for more measures. Table 13 shows how cost-effective energy savings change by the variation of the unit price of coal, keeping the discount rate and other parameters unchanged. As can be seen from the table, in some cases the change in the average unit price of coal for the industry will not change cost-effective energy saving potentials. This is because the change in the coal price in that range will not change the position of the CCE of the measures compared to the coal price line in the steam systems energy efficiency cost curve (figure VIII). In other words, no measures will change their ranking in relation to the average unit price of coal. The technical energy saving potential does not change with the variation in energy price.

Table 13. Sensitivity analysis for cost-effective fuel saving potentials in industrial coal-fired steam systems in China with different coal prices

	Average unit price of coal for industry in 2012 minus 20%	Average unit price of coal for industry in 2012 minus 10%	Average unit price of coal for industry in 2012	Average unit price of coal for industry in 2012 plus 10%	Average unit price of coal for industry in 2012 plus 20%
Average unit price of coal for industry (US$/GJ)	4.3	4.8	5.3	5.8	6.4
Cost-effective annual fuel savings potential (PJ/y)	1,346	1,346	1,687	1,687	1,851

2.3. Uncertainties and limitations

Since this analysis was conducted at the country-level and not at plant-level, assumptions and generalizations had to be made. There is a range for many of the key inputs used in the analysis, but a number was chosen to the best knowledge and judgment of the authors. Some of the main uncertainties of this study are explained below.

First, as mentioned in the methodology section, because of the lack of data needed for this analysis, this study relied significantly on expert input. Although the experts consulted are world renown authorities in the area of steam systems optimization with years of experience in the industry, and two of them with experience in working on steam systems in China, there is uncertainty associated with the data provided by experts (base case efficiencies, energy efficiency improvement potential, cost and lifetime of the efficiency measures, etc.), especially when such data are used for a country and not a particular industrial plant.

Second, there are no official data available on steam systems fuel use in Chinese industry and by subsector. Hence, these data had to be estimated by using the share of steam system fuel use from total fuel use of each manufacturing subsector in the United States provided by U.S. DOE/EIA (2013a) applied to the industrial subsector fuel use in China in 2012 provided by NBS (2013) in order to calculate the fuel used in steam systems in Chinese manufacturing. While there is uncertainty associated with this calculation, we believe that the estimated number for the total fuel use in Chinese industrial steam system in 2012 (table 7) has a high accuracy since it is calculated using industry subsector level data.

Thirdly, in the proposed approach a LOW efficiency base case was assigned to industrial steam systems in China. While based on the available information and experts consultation, a LOW base case efficiency is a good representative for the entire Chinese industry, there are perhaps many plants in China with steam system efficiency equal to MED or even HIGH base case efficiency. Thus, the results of this study are in line with the limitations of this study.

This study shows the complexity of quantifying cost benefits for steam system optimization and provides an initial methodological approach that can be further developed as better data may become available or are collected. The aforementioned uncertainties and limitations should be considered when reviewing the results of the analysis presented in this report.

2.4. Policy implications

Several policy implications can be drawn from this study as follows:

1. The steam systems energy efficiency cost curve for Chinese industry calculated in this study documents that under current market conditions over 80 per cent of the calculated energy saving potential for industrial steam systems in China is cost-effective. Many cost-effective opportunities for energy efficiency improvement in steam systems have been identified but frequently are not adopted, leading to what is called an "efficiency gap" (Jaffe and Stavins, 1994). This is explained by the existence of various obstacles, especially non-monetary barriers to energy efficiency improvement such as lack of information and knowledge in companies, especially in small and medium enterprises (SMEs), management concerns about other matters especially production rather than energy efficiency, lack of financial resources especially in SMEs which makes it difficult to adopt even cost-effective measures/technologies, lack of top management commitment and understanding, uncertainty about new technologies and the fear of production disruption, lack of incentives by government and lack of enforcement for government regulations, etc. (Hasanbeigi et al. 2010).

Policies such as information dissemination and training programmes for energy efficiency improvement and steam systems optimization, top management awareness-raising programmes, financial incentives, especially for SMEs, provision of steam systems assessment tools and guidelines, etc. are some of the programmes that can address the aforementioned non-monetary barriers.

2. As can be seen from the steam systems energy efficiency cost curve for Chinese industry, measure 8: Flash-steam recovery and measure 9: Loss on ignition (LOI) optimization are not cost-effective but they result in significant savings. For these measures and any other measures/technologies that are not covered in this study and are not cost-effective, fiscal policies can be used to support their deployment. However, it should be noted that, based on the steam system efficiency cost curve, the amount of financial incentives needed for measures 8 and 9 should be only large enough to make these two measures cost-effective. In other words, the financial incentives need to bring the CCE of these two measures below the unit price of coal (5.3 US$/GJ). After that, to ensure these measures will be fully adopted within a period of time, the non-monetary barriers mentioned above should also be addressed.

3. The steam systems energy efficiency cost curve for Chinese industry shows the large magnitude for fuel savings potential that exists only through industrial steam systems optimization. This should give policymakers an extra incentive to design system specific policies and programmes to improve energy efficiency in industrial steam systems in China. The nature of the barriers, issues and requirements as well as some of the target groups to reach out to in order to advance steam systems performance is different from those for other energy systems (e.g. motor systems). Hence, focused and targeted policies and programmes for industrial steam systems could be more effective and cost-efficient.

4. The traditional approach in many countries, including China, is to focus on boilers only and not on the entire steam systems that include steam generation (boilers), distribution, recovery systems, and even steam end use. While the use of more efficient boilers results in energy savings, optimization of the entire steam system will result in much larger energy savings. In developed countries, more attention is being paid to system optimization rather than individual equipment efficiency. In China, there is a need for this shift of paradigm to focus on system efficiency. If Chinese policymakers design programmes and policies that are targeted to steam systems and not boilers alone there is greater potential for energy savings and CO_2 emissions reductions.

5. China already has a series of standards for boilers. While there is room to refine and improve existing boiler standards and technical regulations, China can also move towards the development of system-based standards and norms for steam systems. While this might be a challenge, the impact of such system-based standards can be much larger than equipment-based standards.

6. Many of the steam systems optimization measures involve improved operational and maintenance practices, which can be undertaken within a continuous improvement approach within industries. Hence, the adoption of energy management systems such as the International Organization for Standardization (ISO) 50001- Energy Management Systems can aid in the implementation of such measures in a more systematic manner. In addition, energy management systems can provide a framework that helps to ensure that energy savings from steam systems optimization measures are sustainable and do not diminish over time. A principal goal of the ISO 50001 standard is to foster continual and sustained energy performance improvement through a disciplined approach to operations and maintenance practices. Therefore, it is crucial for policymakers in China to promote and incentivize the adoption of ISO 50001 or other energy management systems in industrial plants.

3

Conclusions

This report represents an initial effort to provide a transparent methodology for quantifying the energy efficiency potential of steam systems based on sufficient data to document the magnitude and cost-effectiveness of the resulting energy savings for China. As such, this analysis addresses a major barrier to effective policymaking and to more global acceptance of the energy efficiency potential of steam systems. This study demonstrates the complexity of quantifying the costs and benefits of steam system optimization.

In this assessment, an energy efficiency cost curve was developed for industrial coal-fired steam systems in China. The purpose of the analysis was to determine the potentials and costs of improving the energy efficiency of these industrial steam systems in China by taking into account the costs and energy savings of different energy efficiency measures. Many cost-effective opportunities for energy efficiency improvement in industrial steam systems have been identified but frequently are not adopted, leading to what is called an "efficiency gap" (Jaffe and Stavins, 1994). This is explained by the existence of various obstacles–especially non-monetary barriers–to energy efficiency improvement.

Nine energy efficiency technologies and measures for steam systems were analysed. The cost-effective fuel saving potentials for industrial steam systems were estimated for China using an innovative approach to develop a bottom-up energy efficiency cost curve model. Total technical fuel savings potentials were estimated for 100 per cent penetration of the measures in the base year. Using the CO_2 emission factor of coal, the CO_2 emission reduction associated with the fuel saving potentials was also calculated.

The total cost-effective and technical fuel savings potential in industrial coal-fired steam systems in China in 2012 was estimated to be 1,687 PJ and 2,047 PJ, respectively, which account for 23 and 28 per cent of the total fuel used in industrial coal-fired steam systems in China in 2012, respectively. By comparison, the calculated technical fuel saving potential for industrial coal-fired steam systems in China is around 9 per cent of the total coal plus coke used in Chinese manufacturing in 2012 and is greater than the total 2010 primary energy use of over 160 countries and territories in the world.

In general, the cost of conserved energy has a direct proportional relationship with the discount rate. Reductions in the discount rate will produce corresponding reductions in the cost of conserved energy, which will increase the cost-effective energy saving potential (depending on the energy price). A sensitivity analysis was conducted for a range of discount rates to illustrate these relationships.

A sensitivity analysis was also conducted for the unit price of coal because it varies within China depending on the region and industry. The energy price can also directly influence the cost-effectiveness of energy saving potentials. A higher energy price will result in more energy efficiency measures being cost-effective, as it may cause the cost of conserved energy to fall below the energy price line in more cases.

It should be further noted that some energy efficiency measures provide other benefits in addition to energy savings such as productivity and reduced environmental impact, but it is difficult to quantify those benefits. Including estimates of these other co-benefits can decrease the cost of conserved energy and, thus, increase the number of cost-effective efficiency measures. This could be the subject of further research.

The approach used in this study and the model developed should be viewed as a screening tool to present energy efficiency measures and capture the energy saving potential in order to help policymakers understand the potential of savings and design appropriate energy efficiency policies. However, the energy saving potentials and the cost of energy-efficiency measures and technologies will vary in accordance with country- and plant-specific conditions. Finally, effective energy efficiency policies and programmes are needed to realize the cost-effective potentials and to exceed those potentials in the future.

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