



Moving beyond equipment and to systems optimization: techno-economic analysis of energy efficiency potentials in industrial steam systems in China

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ABSTRACT

The industrial sector dominates China's total energy consumption, accounting for about 70% of primary energy use and 72% of country's CO₂ emissions in 2012. On average, industrial steam systems account for around 30% of manufacturing industry energy use worldwide. The goal of this study is to develop and apply a steam system energy efficiency cost curve modeling framework to quantify the energy saving potential and associated costs of implementation of an array of steam system optimization measures on coal-fired boilers and steam systems in China's industrial sector. 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 1687 PJ and 2047 PJ, respectively. These account for 23% and 28% of the total fuel used in industrial coal-fired steam systems in China in that year, respectively. The CO₂ emission reduction potential associated with the cost-effective and total technical potential is equal to 165.82 MtCO₂ and 201.23 MtCO₂, respectively. By comparison, the calculated technical fuel saving potential for industrial coal-fired steam systems in China is approximately 9% of the total coal plus coke used in Chinese manufacturing in 2012.

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1. Introduction

Steam is used extensively as a means of delivering energy to industrial processes. The use of steam in different industry sub-sectors varies widely. In China, the top five steam-consuming industrial sub-sectors in 2012 were the chemical industry, smelting and pressing of ferrous metals (iron and steel industry), petroleum refining, food and beverage, and textile industry (Calculated based on NBS, 2013).

On average, industrial steam systems account for approximately 30% of manufacturing industry energy use worldwide (Yang and Dixon, 2012). Despite the existence of significant potential for energy efficiency improvement in the steam systems (IEA, 2007), this potential is largely unrealized. The lack of information about the potential savings and its magnitude as well as lack of suitable policy

frameworks and supporting programs 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 energy savings of applying energy efficiency practices to an existing steam system, which goes beyond the boiler itself and which 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 onsite evaluation to maximize system efficiency. Providing a modeling framework for quantifying steam

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system energy efficiency potential that moves beyond case studies of individual applications is needed.

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

The development of such a steam system energy efficiency cost curve modeling 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 modeling framework is used to quantify the energy saving potential and associated cost by implementation of certain steam system optimization measures. The purpose of this research is to provide guidance for national policy makers and is not a substitute for a detailed technical assessment of the steam systems energy efficiency opportunities of a specific plant.

1.1. Overview of boiler and steam systems in China and Chinese industry

In 2009, there were 595,200 in-use boilers 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 tonne of coal, or about 70% of China's total raw coal production of 3.24 billion (Dai and Xiong, 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% and the number of in-use boilers reached 607,000 in 2010 (Dai and Xiong, 2013). In 2012, industrial steam systems accounted for around 25% of the total fuel used in Chinese industry in that year.¹

In 2010, the average capacity of in-use boilers in China was about 3.4 tonne 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% of total coal consumption in industrial boilers in China (Gao and Zhang, 2013). Coal-fired boilers account for around 80%–85%, oil- and gas-fired boilers account for around 15%, and boilers that use other fuels (e.g. electricity, biomass, etc.) account for less than 5% 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, 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% 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 to 5 percent of China's boilers (Gao and Zhang, 2013).

During the 11th FYP period, about 15% 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 program. Two additional projects, the

"Regional Combined Heating and Power Project" and the "Waste Heat & 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 more holistic knowledge and assessment of the system, it will often yield much greater energy saving compare 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 the boiler efficiency. The study presented in this paper adopts such a holistic approach, focusing on steam system efficiency rather than focusing on boilers alone.

2. Methodology

This study focuses on coal-fired boilers and steam systems used in Chinese industry.² The "steam system" boundary analyzed in this study consists of the generation, distribution, and recovery component 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% 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 modeling and evaluation sophistication.

First, a data collection questionnaire was developed to obtain expert input to supplement the existing data. Input was sought from seven steam system experts from the U.S., 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), 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,

¹ See Table 6 for the calculation based on NBS (2013) and U.S. DOE/EIA (2013).

² 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.

analyses, and review 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 2.1.

2.1. 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.

2.1.1. 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 1–3 provide the list of practices defined for each base-case efficiency level.

The efficiency of the steam system was defined as:

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

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 %) 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 implementation of a list of measures and technologies identified in this study.

2.1.2. 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 implementation of each measure, taken as an independent action, expressed as a % improvement over each of the LOW-MED-HIGH base cases. The experts provided a % improvement for each measure over the base case scenarios using a 0–100% scale. For example, if an energy efficiency measure improves the efficiency by 10% in a steam system operating with 60% efficiency,

the new system would have 66% 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 1), the % 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 3).

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 %) 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 U.S. 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 (tonne 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 labor 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 U.S. This adjustment was necessary because there is a large gap between labor costs in the U.S. and China.

Table 1
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 oil fired 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 program
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% of the items listed in the table are in poor condition as noted in Table 1.

Table 2
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

A manufacturing labor cost of \$36/h was assumed in the U.S. based on U.S. BLS (2012) and \$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.

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 implementation cost of the measure in US\$ 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.

Table 3
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 program
	Recovery
9	High level of condensate recovery
10	High level of flash-steam is recovered

2.2. Data preparation and assumptions

2.2.1. Expert input consolidation

The experts were asked to assign system efficiency, expressed as a range, for the LOW-MED-HIGH efficiency base cases. Table 4 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.

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 5 shows the consolidated experts input data for the typical % 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.

2.2.2. Steam systems energy use by industry sub-sector

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 the fuel use by industrial steam systems in China.³ 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 sub-sector level calculation as follows. In the U.S., 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.

The 2010 U.S. 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 6. 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 6 shows that the total fuel used in Chinese industrial steam systems in 2012 was 8850 petajoules (PJ). Since this study focuses on coal-fired steam systems, which account for 80%–85% 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% of total industrial boilers in China, the total fuel used in coal-fired industrial steam systems in China in 2012 is estimated to be 7301 PJ.

Although it should be noted that the structure within industrial subsectors might vary between China and the U.S., 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.

As can be seen from Table 6, 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

³ The calculation procedure is explained in more detail in Section 2.3.2.

Table 4
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%

products (48%), smelting and pressing of ferrous metals (17%), petroleum refining and coking (13%), food, beverage and tobacco (6%), and the textile, apparel, chemical fibers, leather, fur industry (5%).

2.3. Construction of a steam systems energy efficiency cost curve

Fig. 1 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 sub-sections.

2.3.1. 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 Eq. (2).

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

The annualized capital cost can be calculated from Eq. (3).

$$\text{Annualized capital cost} = \text{Capital Cost} \times \frac{d}{1 - (1 + d)^{-n}} \quad (3)$$

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. In this study, a real discount rate of 15% was assumed for the analysis.

2.3.2. 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:

- 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)
- For each energy efficiency measure, the experts provided a typical % improvement in steam system energy efficiency over the base case efficiency
- Fuel use in coal-fired industrial steam systems in China in 2012 (calculated as explained in Section 2.2.2)

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:

- Annual Input energy for coal-fired industrial steam systems in 2012 (TJ/yr) = Industrial coal-fired steam systems fuel use in China in 2012
- 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]
- 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]
- 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]
- 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)]
- 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 (7301 PJ) calculated in Section 2.2.2. 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 Input energy use (step 2). Since the system efficiency is always lower than 100%, 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.

- Annual Input energy for coal-fired industrial steam systems in 2012 (TJ/yr) = Industrial coal-fired steam systems fuel use in China in 2012
- 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]
- Cumulative New system efficiency after the implementation of an energy efficiency measure = [Base case efficiency of steam

Table 5

Energy efficiency measures, % 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 <u>China</u> by system size when the measure is implemented over <u>LOW</u> efficiency base case (US\$) ^c					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. ^a	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. ^a	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. ^a	Excess air management: Upgrade from standard oxygen trim to oxygen trim with CO tuning ^b			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	1800	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 program	2.2%	1.1%	0.4%	7	8100	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 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.

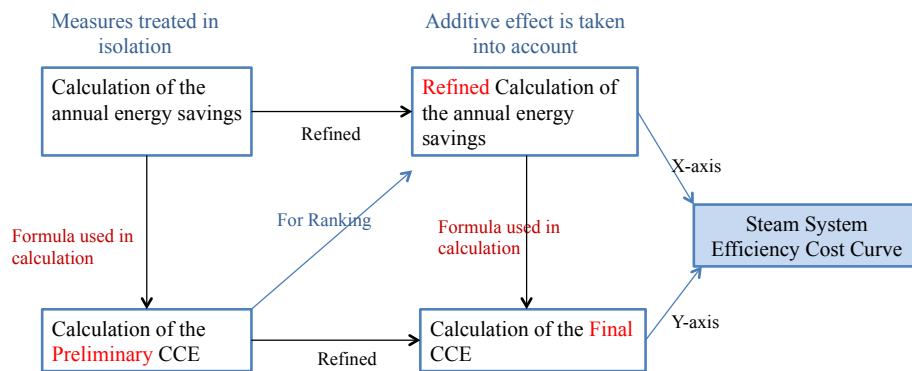
^b For measures 1.2 and 1.3, based on the above note, cost data are for when the measure is implemented over the MED and HIGH efficiency base case, respectively.

^c The installed cost data in the table are rounded to the nearest 100 US\$.

Table 6

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

No.	Industry sub-sector	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 Fibers, Leather, Fur	758,400	57%	429,283
3	Timber, Wood, Bamboo, etc.	94,215	15%	14,132
4	Furniture	15,926	7%	1138
5	Paper and Paper Products	573,659	72%	411,519
6	Printing and Publishing	42,318	20%	8464
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).**Fig. 1.** Schematic of calculation process for construction of a steam systems energy efficiency cost curve.

systems]*[1 + **Sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented**]

- 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]
- 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)]
- 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 % Efficiency improvement by the implementation of measures 1, 2, and 3* is used in the above calculation.

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 % 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.

2.3.3. 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 5), 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 5 were used for calculating the CCE and annual energy savings. The CCE was calculated following the steps described below:

- 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 Table 7.
- The annualized installed cost of implementing each measure on one system was calculated using the cost data in Table 5 and Eq. (3) given in Section 2.3.1.
- A real discount rate of 15% was assumed for this analysis. The lifetime of the measures were provided by the experts for each efficiency measure (Table 5).
- 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 improvement in maintenance practices. Therefore, the CCE can be calculated from the following formula:

$$\text{CCE (US\$/GJ - saved)} = \frac{\text{Annualized installed cost (US\$)}}{\text{Annual Input energy savings (GJ)}} \quad (4)$$

- 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 & Research Institute (CSEI, 2013). Table 8 shows the values used in the analysis for these parameters.
- 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:

- 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 8.

Table 7

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

- 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]
- 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]
- Annual Useful energy used in one system with NEW system efficiency (GJ/y) = [Annual Input energy for one system (GJ/y)]*[New system efficiency]
- 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]
- 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]
- Once the annual cost and annual energy savings are calculated for one system, the CCE can be calculated for each representative system size (5 CCEs for 5 sizes).
- 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 U.S. 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, we can calculate the Final CCE from the followings.

- Annual *Input* energy for one steam system (GJ/y) = [Steam gen capacity (t/h)]*[Specific enthalpy of steam (GJ/t)]*[Typical annual operation hours (hr/y)]/[Typical boiler efficiency in Chinese industry (%)]
- 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 (Fig. 2). 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 Final CCE. For the calculation of 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:

Table 8

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 evaporation (enthalpy of steam – enthalpy of feedwater) (kJ/kg)	Annual fuel use by one steam system (GJ/y)
4	70%	1.0	2150	2287	26,512
12	73%	10.3	6065	2361	225,552
29	77%	20.7	7412	2378	652,517
66	78%	27.6	7412	2810	1,762,658
94	79%	55.2	7412	3029	2,680,819

3. *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)]*
4. *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)]*
5. *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)]*
6. *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)]*
7. *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 2.3.2. 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.

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 the 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 savings 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.

3. Results and discussions

Based on the methodology explained above, a steam systems energy efficiency cost curve was constructed for the industrial sector in China, to separately capture the cost-effective and total technical potential for energy efficiency improvement in industrial steam systems. Furthermore, the CO₂ emissions reduction potential associated with the fuel savings was calculated using the CO₂ emissions factor of 98.3 kgCO₂/GJ for coal used in industrial boilers

(IPCC, 2006). On the cost curve, the average unit price of bituminous coal⁴ 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% penetration rate. It is acknowledged that a 100% 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.

Fig. 2 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 9 along with the cumulative annual fuel saving potential, final CCE of each measure, and cumulative CO₂ 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 7 out of 9 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. Fig. 2 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.

Table 10 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 1687 PJ and 2047 PJ, respectively which account for 23% and 28% of the total fuel used in industrial coal-fired steam systems in China in 2012, respectively. The CO₂ emission reduction potential associated with the cost-effective and total technical potential is estimated to be 165,817 ktCO₂ and 201,231 ktCO₂, respectively. Hence, it is clear that a significant portion of the energy savings 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.

By comparison, the total technical fuel savings potential in industrial coal-fired steam systems in China calculated in this study is around 17% of the total coal and 9% 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 CO₂ 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 CO₂ emissions reduction potential in Chinese steam systems. First, there are additional steam systems optimization measures that are not

⁴ The average net calorific value of dominant bituminous coal used in China is around 20.9 GJ/t.

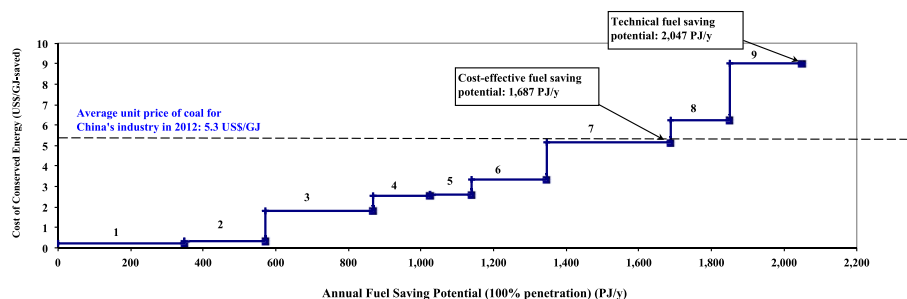


Fig. 2. Steam systems energy efficiency cost curve for Chinese industry.

Table 9

Cumulative annual fuel saving and CO₂ 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	1025	2.6	100,769
5	Implementation of an effective steam trap maintenance program	1140	2.6	112,049
6	Optimization of condensate recovery	1346	3.4	132,304
7	Flue gas thermal energy recovery (Economizer and/or air heater)	1687	5.1	165,817
8	Flash-steam recovery	1851	6.3	181,953
9	Loss On Ignition (LOI) optimization	2047	9.0	201,231

Table 10

Total annual cost-effective and technical energy savings and CO₂ 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)	1687	2047
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

included in this study for various reasons, some of which are discussed in Section 2. Second, this study only focuses on industrial coal-fired boilers, which account for 80%–85% of industrial boilers in China, and does not include boilers that burn other fuels (e.g. natural gas, biomass, etc.). Therefore, the actual energy savings 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 savings potential. Finally, combined heat and power systems are not addressed in this study. These areas could be the subject of future analyses.

In addition, 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).

Overall, the relative cost-effectiveness of the steam systems energy efficiency measures presented in Fig. 2 are generally consistent with what could be expected based on field experiences. However, because of the uncertainties and limitations of this analysis 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.

4. Conclusions

This paper represents an initial effort 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. 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.

Nine energy-efficiency technologies and measures for steam systems were analyzed. The cost-effective fuel saving potentials for the 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% penetration of the measures in the base year. Using the CO₂ emission factor of coal, the CO₂ 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 1687 PJ and 2047 PJ, respectively which account for 23% and 28% 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% 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.

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 policy makers 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 programs are needed to realize the cost-effective potentials and to exceed those potentials in the future.

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