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Motor systems energy efficiency supply curves: A methodology for assessing the energy efficiency potential of industrial motor systems

Aimee McKane [a], Ali Hasanbeigi [b,*]

[a] Industrial Energy Analysis, Energy Analysis Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd. MS 90R4000, Berkeley, CA 94720, USA
[b] China Energy Group, Energy Analysis Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd. MS 90R4000, Berkeley, CA 94720, USA

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ABSTRACT

Motor-driven equipment accounts for approximately 60% of manufacturing final electricity use worldwide. A major barrier to effective policymaking, and to more global acceptance of the energy efficiency potential in industrial motor systems, is the lack of a transparent methodology for quantifying the magnitude and cost-effectiveness of these energy savings. This paper presents the results of groundbreaking analyses conducted for five countries and one region to begin to address this barrier. Using a combination of expert opinion and available data from the United States, Canada, the European Union, Thailand, Vietnam, and Brazil, bottom-up energy efficiency supply curve models were constructed to estimate the cost-effective electricity efficiency potentials and CO_2 emission reduction for three types of motor systems (compressed air, pumping, and fan) in industry for the selected countries/region. Based on these analyses, the share of cost-effective electricity saving potential of these systems as compared to the total motor system energy use in the base year varies between 27% and 49% for pumping, 21% and 47% for compressed air, and 14% and 46% for fan systems. The total technical saving potential varies between 43% and 57% for pumping, 29% and 56% for compressed air, and 27% and 46% for fan systems.

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1. Introduction

Motor-driven equipment accounts for approximately 60% of manufacturing final electricity use and are ubiquitous in industrial facilities worldwide. Motor systems, such as compressed air, pumping, and fan systems, represent a largely untapped, cost-effective source for industrial energy efficiency savings that could be realized with existing technologies. Although motor systems have the potential to contribute substantial energy savings, on the order of 2.58 EJ in final energy use, this potential is largely unrealized (IEA, 2007).

A major barrier to effective policymaking, and to more global acceptance of the energy efficiency potential of motor systems, is the lack of a transparent methodology for quantifying this potential based on sufficient data to document the magnitude and cost-effectiveness of these energy savings by country and by region (McKane et al., 2008). It is far easier to quantify the incremental energy savings of substituting an energy efficient motor for a standard motor than it is to quantify energy savings of applying energy efficiency practices to an existing motor system.

This paper and supporting analyses represent an initial effort to address this barrier, thus supporting greater global acceptance of the energy efficiency potential of motor systems, through the construction of a series of motor system efficiency supply curves, by motor system and by country studied. It is important to note, however, the limitations of this initial study. 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 motor system energy efficiency opportunities of a specific site.

This paper was informed by several previous studies. One of the most comprehensive assessments of industrial motor systems to date was conducted by the US Department of Energy (US DOE) and has been used extensively as a foundation for further analysis (US DOE, 2002). Also useful was the US DOE publication of energy footprints describing the energy use of different industrial subsectors (US DOE, 2004). In the European Union, de Almeida et al. (2003) conducted an extensive assessment of energy efficiency potential in industrial motor systems in EU. International Energy Agency (IEA) also roughly estimated the potential for energy efficiency in industrial motor systems (IEA, 2007). The potential for energy saving in the industrial motor systems have also been

* Corresponding author. Tel.: +1 510 495 2479; fax: +1 510 486 6996.
E-mail address: AHasanbeigi@lbl.gov (A. Hasanbeigi).

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presented as a part of broader energy efficiency opportunity studies such as McKinsey and Company (2008) and Fraunhofer ISI (2009).

We used the concept of a ''conservation supply curve'' (CSC) to make a bottom-up model to capture the cost effective as well as the technical potential for energy efficiency and CO_2 emission reduction in the industrial motor systems in countries studied. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy. It was first introduced by A. Rosenfeld and his colleagues at Lawrence Berkeley National Laboratory (Meier, 1982). Later CSCs were used in various studies to capture energy efficiency potentials in different economic sectors (Koomey et al., 1990; Levine and Meier, 1999; Lutsey, 2008; Hasanbeigi et al., 2010). Recently, McKinsey and Company (2008) has also developed greenhouse gas abatement cost curves for different countries using the concept of the conservation supply curve.

The approach used in this study to develop the energy conservation supply curves (in this paper called motor system energy efficiency supply curves) is different from the one often used in prior studies. Because of data limitations for industrial motor systems at the country-level, detailed bottom-up data typically used for developing a CSC was not available. To overcome this problem, an innovative approach was developed that combines available data with expert opinion to develop energy efficiency supply curves for the motor systems. This approach is explained in detail in the next section.

This Phase I analysis is consistent with the level of precision possible with the available data and is meant to be a beginning, not an end unto itself. The authors seek to initiate an international dialogue with other interested researchers to further refine these analyses based on additional data.

2. Methodology

For the Phase 1 analyses, six countries/region were selected that represent varying sizes and levels of industrial development, for which industrial energy use by sector and some information about motor system efficiency practices were available. These initial six are the United States, Canada, the European Union, Thailand, Vietnam, and Brazil.

The first step was a literature review to develop a baseline of information. Next, a data collection framework was developed to obtain expert input to supplement the existing data. Input was sought from a total of seventeen motor system experts known to the authors through prior research and responses were received from thirteen of them. At least four experts responded for each of the three systems analyzed (compressed air, fans, and pumping), with one expert providing input on two systems. A Delphi-type approach was used in which several iterations of expert opinion were used to refine the final inputs to the analyses.

Country-specific data was collected in parallel with the motor system expert consultation. After receiving expert input and completing collection of the country-specific data, the Motor System Energy Efficiency Supply Curves were constructed based on the methodology explained below. For a more detailed explanation of the methodology and data (country-specific and system-specific data) used in the study, refer to United Nations Industrial Development Organization (UNIDO) (2010).

2.1. Experts input

2.1.1. Defining three base case system efficiency scenarios (LOW–MEDIUM–HIGH)

The approach used was to establish three base case energy efficiency scenarios (LOW–MEDIUM–HIGH) for each of three system types – pumping, compressed air, and fan systems – based on the previous research and the experts' opinion. The first step in establishing a base case was to create and test a unique list of system energy efficiency practices representative of each of three efficiency base case scenarios for each system type. Each list was tested and refined based on expert input. Table 1 represents pumping systems base case practices. Similar tables for compressed air and fan systems were developed and published in UNIDO (2010).

2.2. Data preparation and assumptions

The experts were asked to assign system efficiency, expressed as a % over a range, that they would expect to see when assessing a

Table 1
Characteristics of LOW–MEDIUM–HIGH efficiency base case scenarios for *pumping* systems.

No.	**LOW efficiency base case scenario**
1	Few pumping systems have ever been assessed for system energy efficiency
2	Maintenance is limited to what is required to support operations
3	Flow is typically controlled by throttling or bypass
4	Flow in excess of actual system needs is common
5	Variable speed drives are not commonly used
6	Motors of all sizes are routinely rewound multiple times instead of replaced
7	5% Or less of the installed motors are high efficiency—either EPAct or EFF1 equivalent
	MEDIUM efficiency base case scenario
1	~15% Of pumping systems have been assessed for system energy efficiency
2	Maintenance is a routine part of operations and includes some preventative actions
3	System operators take steps to avoid controlling flow via throttling or bypass
4	Efforts are taken to efficiently match supply with demand
5	Variable speed drives are proposed as a solution for flow control
6	Motors $\geq$37 kW are typically rewound multiple times, while smaller motors may be replaced
7	~25% Of the installed motors are high efficiency—either EPAct or EFF1 equivalent
	HIGH efficiency base case scenario
1	~30% pumping systems have been assessed for system energy efficiency
2	Both routine and predictive maintenance are commonly practiced
3	Flow is not controlled by throttling or bypass except in emergencies
4	Fluid is only pumped where and when needed to meet demand
5	Variable speed drives are one of several flow control strategies commonly applied to increase system efficiency
6	Most facilities have a written rewind/replace policy that prohibits rewinding smaller motors (type $<$37 kW)
7	50% Or more of the installed motors are high efficiency—either EPAct or EFF1 equivalent

Table 2
Consolidated system efficiency for LOW–MED–HIGH efficiency base cases.

Motor system type	System efficiency			
	Low end (%)	High end (%)	Average (%)	**Used in our analysis (%)**
Pumping systems				
Low level of efficiency	20.0	40.0	30.0	**20.0**
Medium level of efficiency	40.0	60.0	50.0	**40.0**
High level of efficiency	60.0	75.0	67.5	**60.0**
Compressed Air systems				
Low level of efficiency	2.0	5.0	3.5	**3.5**
Medium level of efficiency	4.8	8.0	6.4	**6.4**
High level of efficiency	8.0	13.0	10.5	**10.5**
Fan systems				
Low level of efficiency	15.0	30.0	22.5	**22.5**
Medium level of efficiency	30.0	50.0	40.0	**40.0**
High level of efficiency	50.0	65.0	57.5	**57.5**

Table 3
Base case efficiencies assigned to each country for each motor system type.

	Pumping	Fan	Compressed air
US	MED	MED	MED
Canada	MED	MED	MED
EU	MED	MED	MED
Brazil	MED	LOW	LOW
Thailand	MED	LOW	LOW
Vietnam	LOW	LOW	LOW

system in an industrial market with the characteristics listed for the LOW–MED–HIGH efficiency base cases. 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. Table 2 consists of the consolidated results of these expert inputs, including the baseline values used in calculating the cost curves. *There was a high degree of agreement among experts for each system type regarding the range of system energy efficiency that would be expected to result from the list of characteristics assigned to the three base case scenarios.* Average values (of low to high ranges) were used for compressed air and fan systems. However, low end of the range was used for pumping systems because these values provided an outcome more consistent with experts' opinions for each of the base cases than the average values. This helped to compensate for lack of interactivity between measures in the analysis, which seemed to be a particular issue for the pumping system measures.

After defining efficiencies for each motor system, we assigned a base case efficiency to each country of study (Table 3) for the purpose of providing a reference point for the current (pumping, compressed air, or fan) system performance in that country. Expert judgment was used for this purpose. While it is important to acknowledge that this approach blurs the real variations that may exist in system performance from one industrial sector to another within a country, it is consistent with the level of precision possible with the available data.

2.2.1. *Determining the impact of energy efficiency measures*

A list of potential measures to improve system energy efficiency was developed for each system type and sent to the experts for review. Ten energy-efficiency technologies and measures for pumping systems (US DOE, 2006), ten measures for the fan systems (US DOE, 2003), and sixteen measures for compressed air systems (Compressed Air Challenge and the US Department of Energy, 2003) were analyzed. For each group of measures, we asked experts to provide their opinion on 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 percentage efficiency improvement by the implementation of each measure decreases as the base case moves from LOW to HIGH. For instance, since the LOW base case is defined by limited maintenance, the % improvement from maintenance-related measures would be expected to be greater than that of the HIGH base case, for which both routine and predictive maintenance are common.

The experts were also asked to critique the list of measures. Based on the responses received, edits were made to the list of measures, requiring a second round of review to validate the % efficiency improvement values.

In some instances, the initial list of measures included several measures that would be unlikely to be implemented together—it is more likely that one would be selected. For example, it is likely that matching pumping system supply to demand would include one of the measures below, rather than all three.

Measure A—trim or change impeller to match output to requirements.
Measure B—install pony pump.
Measure C—install new properly sized pump.

For this reason, in situations for which there appear to be groupings of several proposed solutions to address a specific problem, during the second round of review, the experts were asked whether the measures would be undertaken together, and if not, to select which one was the most typical or common.

For compressed air systems, heat recovery can be extremely beneficial to improving the energy efficiency of the system by recovering the energy lost through heat of compression (typically 80% of input energy), if a suitable use can be found for the resulting low grade heat. Because compressed air system heat recovery would need to be added to the base case rather than applied as a % improvement and consensus could not be reached concerning its potential across countries and climates, the measure was not included in the final analyses.

The experts were also asked to provide cost information for each measure, disaggregated by motor size range. The size ranges were selected based on categories developed for the most detailed motor system study available (US DOE, 2002). For the purpose of this study, the term "motor system size" refers to the aggregate motor HP or kW for that system. In addition to the energy efficiency improvement cost, the experts were also asked to provide the useful lifetime of the measures, disaggregated into two categories of operating hours (between1000 h and 4500 h per year and more than 4500 h per year). Finally, the experts were asked to indicate the degree to which the energy saving achieved by each measure is dependent on the future maintenance practices (limited, moderately, or highly dependent).

While the installed cost of any given measure is highly dependent on site conditions, the "typical" cost data given by experts was reasonably well correlated for most measures and system sizes, with the exception of very large systems (large than 1000 hp or 745 kW). For these systems, costs estimates varied widely—possibly due to their customized requirements. Because wide variations in cost

Table 4
Expert Input: energy efficiency measures, efficiency improvement and cost for *pumping* systems.

No.	Energy efficiency measure	Typical % improvement in energy efficiency over current *pump* system efficiency practice			Expected useful life of measure (years)	Typical capital cost (US$)				
		% Improvement over LOW eff. base case (%)	% Improvement over MED eff. base case (%)	% Improvement over HIGH eff. base case (%)		$\leq$ 50 hp	$>$ 50 hp $\leq$ 100 hp	$>$ 100 hp $\leq$ 200 hp	$>$ 200 hp $\leq$ 500 hp	$>$ 500 hp $\leq$ 1000 hp
						$\leq$ 37 kW	$>$ 37 kW $\leq$ 75 kW	$>$ 75 kW $\leq$ 150 kW	$>$ 150 kW $\leq$ 375 kW	$>$ 375 kW $\leq$ 745 kW
1.1	**Upgrade system maintenance**									
1.1.1	Fix Leaks, damaged seals, and packing	3.5	2.5	1.0	5	$1000	$1500	$2000	$2500	$3000
1.1.2	Remove scale from components such as heat exchangers and strainers	10.0	5.0	2.0	4	$6000	$6000	$9000	$12,000	$15,000
1.1.3	Remove sediment/scale buildup from piping	12.0	7.0	3.0	4	$3500	$3500	$7000	$10,500	$14,000
1.2	**Eliminate unnecessary uses**									
1.2.1	Use pressure switches to shut down unnecessary pumps	10.0	5.0	2.0	10	$3000	$3000	$3000	$3000	[a]
1.2.2	Isolate flow paths to nonessential or non-operating equipment	20.0	10.0	5.0	15	$0	$0	$0	$0	$0
1.3	**Matching Pump System Supply to Demand**									
1.3.1	Trim or change impeller to match output to requirements	20.0	15.0	10.0	8	$5000	$10,000	$15,000	$20,000	$25,000
1.4	**Meet variable flow rate requirement w/o throttling or bypass** [b]									
1.4.1	Install variable speed drive	25.0	15.0	10.0	10	$4000	$9000	$18,000	$30,000	$65,000
1.5	**Replace pump with more energy efficient type**	25.0	15.0	5.0	20	$15,000	$30,000	$40,000	$65,000	$115,500
1.6	**Replace motor with more energy efficient type**	5.0	3.0	1.0	15	$2200	$4,500	$8000	$21,000	$37,500
1.7	**Initiate predictive maintenance program**	12.0	9.0	3.0	5	8000	$8000	$10,000	$10,000	$12,000

[a] This measure is not typical for large pumps, but it is a good practice for all pumps in parallel applications.
[b] For pumping systems dominated by static head, multiple pumps may be a more appropriate way to efficiently vary flow.

imposed additional uncertainty on the final results, systems larger than 1000 hp (745 kW) were excluded from the final analysis. This reduced the total energy savings potential estimated in some instances, most notably for compressed air systems in the US A more extensive dialogue with experts on the cost drivers of larger systems might result in sufficient disaggregation to permit their inclusion in future analyses.

Because the goal of the analysis is to *assess the total potential* for energy efficiency in industrial motor systems in the base year, the estimated *full cost* of the measures analyzed was used rather than the *incremental cost* for energy efficient measures. Therefore, the energy savings is based on the assumption that all the measures are installed in the base 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.

Experts input for motor system characteristics described above were reduced to a single value for each characteristic based on an analysis of average and median values. These consolidated values were further validated through one more round of expert review before being included in the analyses. Table 4 depicts the final values for typical % improvement in efficiency over each base case efficiency (LOW–MED–HIGH) as well as an estimated typical capital cost of the measure, differentiated by system size for the pumping system.

The similar tables for compressed air and fan systems can be found at UNIDO (2010). The base year for all countries/region except the EU was 2008. For the EU, year 2007 was used as the base year based on industrial energy use data availability. Country-specific data was collected from various sources.

Data from three sources – US DOE (2002), US DOE (2004) and de Almeida et al. (2003) – were used to construct a preliminary table of motor system use by industrial sector. The experts were then asked to estimate (a) the system electricity use as % of overall electricity use in the sector, or (b) system electricity use as % of motor system electricity use in the sector

The results from the experts were compared with the three studies and final estimates were developed for (1) the motor systems electricity use as a % of total electricity use in each industrial sector and (2) for each system (pump, compressed air, and fan), the electricity use as % of overall motor system electricity use in the sector. These values were then applied to the electricity use data for each country. The data were mapped using the US classifications (US DOE, 2002) in a way that best represented the industry sectors given for these countries.

2.3. Construction of Motor System Efficiency Supply Curves

The conservation supply curve (CSC) used in this study is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy (Meier, 1982). The Cost of Conserved Energy can be calculated from Eq. (1).

$$\text{Cost of Conserved Energy} = \text{annualized capital cost} + \text{annual change in O\&M costs}/\text{annual energy savings} \quad (1)$$

The annualized capital cost can be calculated from Eq. (2):

$$\text{annualized capital cost} = \text{capital cost} * (d/(1-(1+d)^{-n}) \quad (2)$$

d is the discount rate, n the lifetime of the energy efficiency measure.

After calculating the Cost of Conserved Energy for all energy efficiency measures, the measures are ranked in ascending order of Cost of Conserved Energy against an energy price line. All measures that fall below the energy price line are identified as “cost-effective”. That is, saving a unit of energy for the cost-effective measures is cheaper 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 10% was assumed for the analysis. Since it is one of the key variables used in the cost of conserved energy calculation, we conducted a sensitivity analysis of the final results with varying discount rates. A sensitivity analysis was also conducted for the unit price of electricity because it can vary within the country/region, especially in the US and EU. The results of these analyses can be found in UNIDO (2010).

Fig. 1 shows the schematic of calculation process for the construction of motor systems efficiency supply curves. The details of each step are explained in next sections.

2.3.1. Calculation of the annual energy savings

The calculation and data analysis methodology used was the same for all three motor system types included in these analyses (i.e. pumping, fan, and compressed air systems). The example provided here for pumping systems is also illustrative of the methodology used for the other two systems.

For the calculation of energy saving achieved by the implementation of each efficiency measure for the pumping system, the following inputs were available:

- The efficiency base case scenarios for pumping systems (LOW, MED, and HIGH), as developed from expert input. As previously described, each country was then assigned a base case efficiency for pumping systems, based on the authors' judgment and expert consultation.
- For each pumping system measure, the experts provided a typical % improvement in energy efficiency over each base case efficiency scenario.

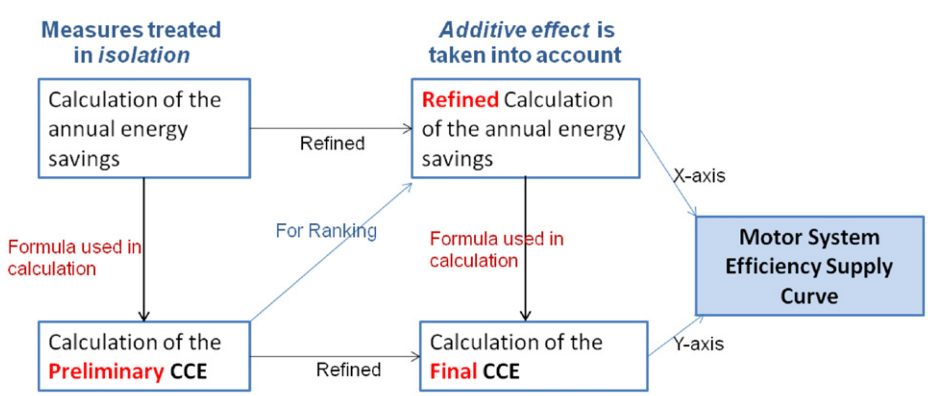

Fig. 1. Schematic of calculation process for the construction of motor systems efficiency supply curves.

- Electricity use in the manufacturing sectors of each country.
- The percentages of the pump system electricity use as compared to the total electricity use in each industrial sector studied. Using these percentages and the electricity use of each sector, the total electricity use by the pump system in each sector was calculated. The total value of all the electricity use for the industrial sectors studied in the given country could then be calculated and used to calculate the potential electricity savings for this system type.
- From the above information, the annual electricity saving from the implementation of each individual efficiency measure for the pumping system was calculated following the steps given in Box 1, *assuming that measures are treated individually and can be implemented regardless of the implementation of other measures.*

In the procedure explained above, input energy use is the energy that is supplied to the system. The Useful energy use, however, is the energy that is converted to the actual service through the system—it is the energy that does the work of the system at the end use. Useful energy use is calculated by multiplying the Input energy use by the system efficiency, which is always less than 100%.

In practice, the implementation of one measure can influence the efficiency gain by the next measure implemented because the second measure is implemented against an improved base case efficiency. Therefore, the efficiency improvement by the second measure will be less than if the second measure was implemented first or was considered alone. The refined methodology treats measures in relation with each other (as a group). *Using this refined approach, the efficiency improvement by the implementation of one measure depends on the efficiency improvement achieved by the previous measures implemented* and can be described as shown in Box 2.

In this method, the *Cumulative* electricity saving is calculated by taking into account the additive effect of the measures, rather than treating the measures completely in isolation from each other.

As might be anticipated, the ranking of the measures significantly influences the energy saving achieved by each measure. *The higher the rank of the measure, the larger the energy saving contribution of that measure to the cumulative savings*. To define the ranking of the efficiency measures before calculating the cumulative energy saving from the method described above, the Preliminary Cost of Conserved Electricity (CCE) was calculated (see below for the explanation on 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.

Box 1–Annual electricity savings calculation: pumping system measures treated in isolation.

1. Annual input energy for the pumping system (MWh/yr) = pump system energy use in industry in the base year.
2. Annual useful energy used in the pumping system with *base case* efficiency = annual input energy for the pump (MWh/yr)*baseline efficiency of the pumping system.
3. New system efficiency after the implementation of the efficiency measure = base case efficiency of the pumping system*(1+ % system efficiency improvement by the implementation of the measure).
4. Annual useful energy used in the pumping system with *NEW* efficiency = annual input energy for the pumping system (MWh/yr)*new system efficiency.
5. Annual useful energy saving = annual useful energy used in the pumping system with *NEW* efficiency − annual useful energy used in the pumping system with *base case* efficiency.
6. Annual input energy saving = annual Useful energy saving/*new* system efficiency after the implementation of the efficiency measure.

Box 2–*Cumulative* annual electricity savings calculation: pumping system measures treated in relation to each other.

1. Annual input energy for the pump system (MWh/yr) = pumping system energy use in industry in the base year.
2. Annual useful energy used in the pumping system with *baseline* efficiency = annual Input energy for the pump (MWh/yr)*baseline efficiency of the pumping system.
3. *Cumulative* new system efficiency after the implementation of the efficiency measure = base case efficiency of the pumping system*(1+sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented).
4. *Cumulative* annual useful energy used in the pumping system with *NEW* efficiency = annual input energy for the pumping system (MWh/yr)*cumulative* new system efficiency.
5. *Cumulative* annual useful energy saving = annual useful energy used in the pumping system with *NEW* efficiency − annual useful energy used in the pumping system with *base case* efficiency.
6. *Cumulative* annual input energy saving = *cumulative* annual useful energy saving/*cumulative New* system efficiency after the implementation of the efficiency measure.

2.3.2. Calculation of the Cost of Conserved Electricity

Since the capital cost data received from the experts was for the implementation of only one unit of each measure/technology, the Cost of Conserved Electricity (CCE) was calculated assuming the implementation of only one unit of each measure under each efficiency base case, taken separately. Calculations were performed separately for each base case (LOW, MED, and HIGH). Later, the CCE was calculated under the base case scenario assigned to each country (see Table 3) and the system was used in developing the corresponding efficiency supply curve. The CCE is calculated as follows:

- Capital cost data was provided in five bins based on a range of motor sizes, expressed in horsepower (hp) UNIDO (2010). The average hp 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 Annualized capital cost of implementing one unit of each measure could then be calculated using the Eq. (2).
- The discount rate of 10% was assumed for the analysis, as previously discussed. The lifetime of the measures were provided by the experts for each efficiency measure.

Because only one type of cost (capital cost) was available for each measure, the capital 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 cost of conserved energy can be calculated from the following formula:

$$\text{Cost of Conserved Energy} = \frac{\text{annualized capital cost}}{\text{annual input energy savings}} \quad (3)$$

- For calculating the energy saving achieved by the implementation of one unit of each measure, the information concerning the cost of implementing one unit of each measure was combined with some assumptions for the load and operation hours for the motor systems for each representative size for which the CCE is calculated.
- For the hours of operation, the values for each motor system type and power range from US DOE's motor market assessment report were used (US DOE, 2002).
- For the load factor, the experts were asked to provide the *Distribution of Industrial Motors by Part Load* (part loads: 25%, 50%, 75%, and 100%) for each motor system type UNIDO (2010).
- The annual energy saving for *one unit* of each measure under each base case scenario was calculated (separately) using the procedure shown in Box 3.
  Having the annual cost and annual electricity saving calculated above for one unit of the system, the Cost of Conserved Electricity (CCE) could be calculated for each representative motor size (5 CCE for 5 motor sizes).
- Only one CCE value can be displayed on the supply curve, therefore, the CCEs calculated for different motor sizes were consolidated. For each measure, the motor system energy use (GWh/yr) by Horsepower (for each type of system, i.e. pumping, fan, compressed air) was used to calculate the weighted average CCE. One CCE resulted for each efficiency measure under each base case scenario. 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.

Box 3–Calculation of the annual energy saving for *one unit* of each measure under each base case scenario.

1. Annual input energy for one unit of system (MWh/yr) = (hp∗hours used per year∗load∗0.746/1000)/motor efficiency.
2. Annual useful energy used in one unit of system with *base case* efficiency = annual input energy for one unit of system (MWh/yr)∗base case efficiency of the pumping system.
3. New system efficiency after the implementation of the efficiency measure = base case efficiency of the pumping system∗(1+ % system efficiency improvement by the implementation of the measure).
4. Annual useful energy used in one unit of system with *NEW* efficiency = annual input energy for one unit of system (MWh/yr)∗new system efficiency.
5. Annual Useful energy saving for one unit of system = annual useful energy used in one unit of system with *NEW* efficiency − annual useful energy used in one unit of system with *base case* efficiency.
6. Annual Input energy saving for one unit of system = annual useful energy saving for one unit of system/ *New* system efficiency after the implementation of the efficiency measure.

Once the measures are ranked based on the Preliminary CCE, we can calculate the Final CCE from the calculation shown in Box 4.

The final CCE is used for the construction of Motor Systems Efficiency Supply Curve along with the *Cumulative* Annual Input Energy Saving explained in the previous section.

Box 4–Final CCE calculation.

1. Annual input energy for one unit of system (MWh/yr) = (hp∗hours used per year∗load∗0.746/1000)/motor efficiency.
   We assumed the average motor efficiency of 93% across all sizes.
2. *Cumulative* new system efficiency after the implementation of the efficiency measure = base case efficiency of the pumping system∗(1+**sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented**).
   However, unlike the energy saving that is shown as cumulative saving on the supply curve (*x*-axis), the CCE for each individual measure is shown separately on the supply curve. In other words, the *y*-axis on the supply curve shows the CCE for the individual measure. Therefore, the *cumulative* input energy saving for one unit of 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 saving for one unit of system for each measure. This is done, for example for measure number (*i*) from the following procedure:
3. *Cumulative* Annual Useful energy used in one unit of system with *Cumulative* new efficiency after the implementation of the efficiency measure (*i*) = annual Input energy for one unit of system (MWh/yr)∗*cumulative* new system efficiency after the implementation of the efficiency measure (*i*).
4. *Cumulative* annual useful energy used in one unit of system with *cumulative* new efficiency after the implementation of the efficiency measure ($i-1$) = annual Input energy for one unit of system (MWh/yr)∗*cumulative* new system efficiency after the implementation of the efficiency measure ($i-1$).
5. *Individual* annual useful energy saving for one unit of system for measure (*i*) = *cumulative* annual useful energy used in one unit of system with *cumulative* new efficiency after the implementation of the efficiency measure (*i*) − *cumulative* annual useful energy used in one unit of system with *cumulative* new efficiency after the implementation of the efficiency measure ($i-1$).
6. *Individual* annual input energy saving for one unit of system measure (*i*) = *individual* annual useful energy saving for one unit of system/*cumulative* new efficiency after implementation of the efficiency measure (*i*).
7. Final Cost of Conserved Electricity of measure (*i*) = annualized capital cost of measure (*i*)/*individual* annual input energy saving for one unit of system for measure (*i*).

2.3.3. Labor adjustment factor for the cost of measures

The typical capital costs of installing the selected measures provided by the experts were more typical of the US, Canada, and European countries. Since a significant proportion of the installed cost of many system improvement measures is the labor, a labor adjustment factor (LAF) was calculated for each energy efficiency measure for the three developing countries/emerging economies, i.e. Thailand, Vietnam, and Brazil. This resulted in lower CCEs for the measures in the three developing countries compared to that of the developed countries (see UNIDO, 2010 for further details).

3. Results and discussion

It should be noted that the energy saving potentials are the total existing potentials for the energy efficiency improvement in the studied motor systems in the base year, and would only be possible over a period of time. Conducting the scenario analysis by assuming different penetration rates for the energy efficiency measures would be an excellent subject for further study.

3.1. Pumping System Efficiency Supply Curves

Fig. 2 presents the Pumping System Efficiency Supply Curves for the US Similar figures and tables for the industrial pumping systems in other countries studied can be found in UNIDO (2010). The name of the measures related to each number on the supply curve is given in Table 5 along with the cumulative annual electricity saving potential, final CCE of each measure, cumulative annual primary energy saving potential, and cumulative CO_2 emission reduction potential.

In Table 5, the energy efficiency measures that are above the bold line are cost-effective (i.e. their CCE is less than the unit price of electricity) and the efficiency measures that are below the bold line in the tables and are shaded in gray are not cost-effective. The results of Pumping System Efficiency Supply Curves show that in the developed countries (US, Canada, and EU) out of 10 energy efficiency measures, from 3 to 5 measures are cost effective, i.e. their cost of conserved energy is less than the average unit price of electricity in those countries. On the other hand, in the developing countries, more energy efficiency measures fall below the electricity price line (7–9 measures), primarily due to the impact of the labor adjustment factor. Table 6 shows the summary of the results for the U.S. pumping system.

Table 7 illustrates that in all countries studied except Vietnam, the total technical energy saving potential is around 45% of the total pumping system energy use in the base year for the industries analyzed. The reason for this similarity is that all countries except Vietnam fall into the MEDIUM base case efficiency (see Table 3). Because Vietnam falls into LOW base case efficiency, the share of total technical energy efficiency potential

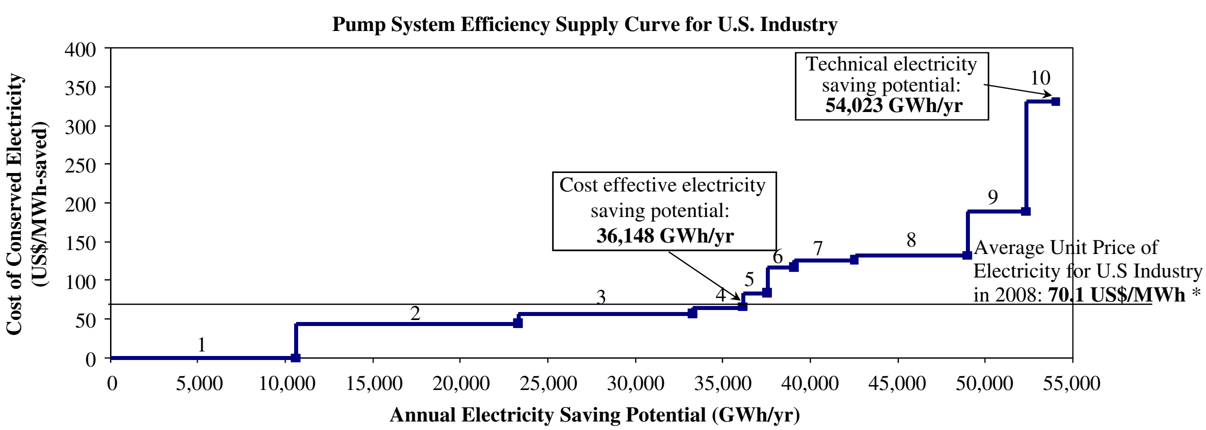

Fig. 2. US Pumping System Efficiency Supply Curve. *Note*: This supply curve is intended to provide an indicator of the relative cost-effectiveness of system energy efficiency measures at the national level. The cost-effectiveness of individual measures will vary based on site-specific conditions.

Table 5
Cumulative annual electricity saving and CO_2 emission reduction for pumping system efficiency measures in US ranked by their final CCE.

No.	Energy efficiency measure	Cumulative annual electricity saving potential in industry (GWh/yr)	Final CCE (US$/MWh-saved)	Cumulative annual primary energy saving potential in industry (TJ/yr)	Cumulative annual CO_2 emission reduction potential from industry (kton CO_2/yr)
1	Isolate flow paths to nonessential or non-operating equipment	10,589	0.0	116,265	6382
2	Install variable speed drive	23,295	44.5	255,784	14,040
3	Trim or change impeller to match output to requirements	33,279	57.0	365,405	20,057
4	Use pressure switches to shut down unnecessary pumps	36,148	65.7	396,905	21,786
5	Fix Leaks, damaged seals, and packing	37,510	84.1	411,855	22,607
6	Replace motor with more energy efficient type	39,084	116.9	429,138	23,555
7	Remove sediment/scale buildup from piping	42,523	126.3	466,906	25,628
8	Replace pump with more energy efficient type	48,954	132.2	537,516	29,504
9	Initiate predictive maintenance program	52,302	189.0	574,280	31,522
10	Remove scale from components such as heat exchangers and strainers	54,023	330.9	593,171	32,559

compared to the total pumping system energy use is higher than that of the other five countries/region, at approximately 57%.

For cost-effective potential, however, the story is different. The three developed countries have the cost-effective potential of 27–29% of the total pumping system energy use in the base year for the industries analyzed. Although Thailand and Brazil have a MEDIUM base case efficiency (similar to the developed countries), their cost-effective potential is higher – equal to 36% and 43%, respectively – due to the application of a labor adjustment factor in the calculation of CCE. For Vietnam, the cost-effective potential is much higher than other countries (49%) due to the combination of a LOW efficiency baseline and the application of labor adjustment factor.

The relative cost-effectiveness of the pumping system energy efficiency measures across all countries are generally consistent with what could be expected based on field experience. There are some interesting findings. For example, replacing either the pump or the motor with a more energy efficient type, a commonly implemented measure, is frequently not cost-effective on the supply curves. There are two notable findings that are not consistent with what one might expect based on field experience. First, the relative cost-effectiveness of a preventive maintenance program is much lower for pumping systems than for compressed air or fan systems, which may warrant further investigation. Second, relatively low cost effectiveness result for removing scale from heat exchangers, which in reality, is often cost-effective for cooling loops, a common pumping application. While this lack of granularity may be suitable to support policymaking needs, it is not a substitute for individualized assessments of motor system efficiency opportunities.

Table 6
Total annual cost-effective and technical energy saving and CO_2 emission reduction potential for US industrial pumping systems.

	Cost effective potential	Technical potential
Annual electricity saving potential for pumping system in US industry (GWh/yr)	36,148	54,023
Share of saving from the total pumping system energy use in studied industries in US in 2008 (%)	29	43
Share of saving from total electricity use in studied industries in US in 2008 (%)	4	6
Annual primary energy saving potential for pumping system in US industry (TJ/yr)	396,905	593,171
Annual CO_2 emission reduction potential from US industry (kton CO_2/yr)	21,786	32,559

Table 7
Total annual cost-effective and technical energy saving potential in pumping systems in studied countries.

Country	Annual electricity saving potential in industrial *pumping* system (GWh/yr)		Share of saving from total *pumping* system energy use in studied industries in 2008	
	Cost effective	Technical	Cost effective (%)	Technical* (%)
US	36,148	54,023	29	43
Canada	9929	16,118	27	45
EU	26,921	38,773	30	44
Thailand	2782	3459	36	45
Vietnam	1693	1984	49	57
Brazil	4439	4585	43	45

* In calculation of energy savings, equipment 1000 hp or greater are excluded.

3.2. Compressed Air System Efficiency Supply Curves

Fig. 3 presents the Compressed Air System Efficiency Supply Curves for the US Tables 8 and 9 summarize the results for the US. Similar figures and tables for the industrial compressed air systems in other countries studied can be found in UNIDO (2010). The Compressed Air System Efficiency Supply Curves for the six countries/region showed that "Fix Leaks, adjust compressor controls, establish ongoing plan" and "Initiate predictive maintenance program" are the top two most cost-effective measures for the compressed air system across studied countries, except for the EU for which "Install sequencer" displaces "Initiate predictive maintenance program" in the top two. On the other hand, "Size replacement compressor to meet demand" is ranked last with the highest CCE across all countries studied.

Table 10 shows that for Canada and the EU, each with a MEDIUM base case efficiency, the total technical energy saving potential is well-aligned at 41% and 38%, respectively, of the total compressed air system energy use in the base year for the industries analyzed. Although the US base case efficiency for compressed air systems is also MEDIUM, the total technical potential is only 29% of the total compressed air system energy use for the industries analyzed based on 2008 data. A major reason for this difference seems to be in the relative share of energy use by compressed air system larger than 1000 hp, *excluded* from these analyses, as compared to the total energy use of compressed air systems, which *includes* these larger

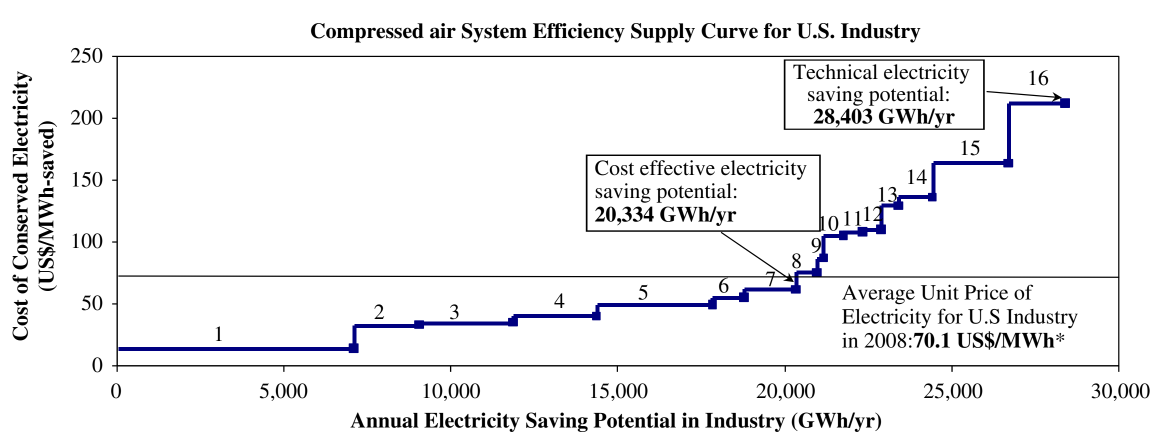

Fig. 3. US Compressed Air System Efficiency Supply Curve. *Note*: this supply curve is intended to provide an indicator of the relative cost-effectiveness of system energy efficiency measures at the national level. The cost-effectiveness of individual measures will vary based on site-specific conditions.

Table 8
Cumulative annual electricity saving and CO_2 emission reduction for compressed air system efficiency measures in US ranked by their Final CCE.

No.	Energy efficiency measure	*Cumulative* annual electricity saving potential in industry (GWh/yr)	Final CCE (US$/MWh-saved)	Cumulative annual primary energy saving potential in industry (TJ/yr)	Cumulative annual CO_2 emission reduction potential from industry (kton CO_2/yr)
1	Fix Leaks, adjust compressor controls, establish ongoing plan	7073	14.4	77,658	4263
2	Initiate predictive maintenance program	9037	33.4	99,230	5447
3	Install sequencer	11,862	35.3	130,239	7149
4	Improve end use efficiency; shut-off idle equip, engineered nozzles, etc.	14,353	40.4	157,600	8651
5	Eliminate inappropriate compressed air uses	17,832	49.9	195,796	10,747
6	Address restrictive end use drops and connections, faulty FRLs	18,783	55.7	206,242	11,321
7	Eliminate artificial demand with pressure optimization/control/storage	20,334	62.0	223,267	12,255
8	Replace existing condensate drains with zero loss type	20,958	75.7	230,116	12,631
9	Correct compressor intake problems/replace filter	21,161	87.3	232,343	12,753
10	Correct excessive pressure drops in main line distribution piping	21,755	105.5	238,864	13,111
11	Install dedicated storage with metered recovery	22,328	108.8	245,156	13,457
12	Reconfigure branch header piping to reduce critical pressure loss	22,881	110.9	251,229	13,790
13	Correct excessive supply side pressure drop; i.e., treatment equipment	23,415	129.7	257,095	14,112
14	Match air treatment to demand side needs	24,431	136.6	268,248	14,724
15	Improve trim compressor part load efficiency; i.e. variable speed drive	26,699	164.1	293,156	16,091
16	Size replacement compressor to meet demand	28,403	212.7	311,865	17,118

Table 9
Total annual cost-effective and technical energy saving and CO_2 emission reduction potential for US industrial compressed air systems *(systems < 1000 hp excluded from the analysis)*.

	Cost effective potential	Technical potential
Annual electricity saving potential for compressed air system in US Industry (excludes systems larger than 1000 hp) (GWh/yr)	20,334	28,403
Share of saving from the total compressed air system energy use in studied industries in US in 2008 (%)	21	29
Share of saving from total electricity use in studied industries in US in 2008 (%)	2	3
Annual primary energy saving potential for compressed air system in US Industry (TJ/yr)	223,267	311,865
Annual CO_2 emission reduction potential from US Industry (kton CO_2/yr)	12,255	17,118

Table 10
Total annual cost-effective and technical energy saving potential in compressed air systems in studied countries.

Country	Annual electricity saving potential in industrial *compressed* air system (GWh/yr)		Share of saving from the total *Compressed* air system energy use in studied industries in 2008	
	Cost effective	Technical	Cost ffective (%)	Technical* (%)
US	20,334	28,403	21	29
Canada	4707	7498	26	41
EU	18,519	24,857	28	38
Thailand	3741	4381	47	55
Vietnam	1609	1970	46	56
Brazil	6069	6762	42	47

* In calculation of energy savings, equipment 1000 hp or greater are excluded.

systems. This share in the US is 44%, whereas in Canada and EU they are only 22% and 19%, respectively.

For Thailand, Vietnam, and Brazil with LOW base case efficiency (see Table 3), the share of total technical energy efficiency potential for industrial compressed air systems relative to total compressed air energy use is higher than that of developed countries. Within this group, Brazil has a lower share, most likely because for the same reason given above for the US The three developed countries have the cost-effective potential of 21–28% of the total compressed air system energy use in the base year for the industries analyzed compared to the three developing countries with a cost-effective potential of 42–47%. These results can be attributed the difference in efficiency base cases and the labor adjustment factor.

As expected, most of the compressed air system energy efficiency measures identified as cost effective require limited capital investment. Leaks are routinely cited as the most cost-effective measure among compressed air system experts, but it must be noted that (1) the energy savings for this measure are contingent on the adjustment of compressor controls once the leaks are fixed and (2) the useful life of this measure is based on the implementation of an ongoing leak management program.

As with pumping systems, there are limitations of these analyses, which are by necessity based on a generalization of the benefits of each energy efficiency measure across a wide variety of system type and operating conditions. For instance, there are situations in which correcting a pressure drop across compressed air treatment equipment or replacing a compressor intake filter can be highly cost-effective and may result in the ability to turn off a compressor or the avoidance of premature equipment failure. While this lack of granularity may be suitable to support policymaking needs, it is not a substitute for individualized assessments of motor system opportunities.

3.3. Fan System Efficiency Supply Curves

Fig. 4 shows the Fan System Efficiency Supply Curves for the US Tables 11 and 12 summarize the results for the US. The similar figures and tables for the industrial compressed air systems in other countries can be found in UNIDO (2010). The Fan System Efficiency Supply Curves showed that "Correct damper problems", "Fix Leaks and damaged seals", and "Isolate flow paths to nonessential or non-operating equipment" are the top three most cost-effective measures for fan systems across the studied countries. "Replace motor with more energy efficient type" and "Replace oversized fans with more efficient type" are the least cost-effective across all countries studied.

Table 13 shows that US, Canada, and EU with MEDIUM base case efficiency have a total technical energy saving potential of 27 –30% as compared with total fan system energy use in the base year for the industries analyzed. Thailand, Vietnam, and Brazil, with LOW base case efficiency have a higher percentage of total energy saving technical potential of 40% –46%.

The three developed countries also have a lower cost-effective potential of 14–28% of total fan system energy use in the base year for the industries analyzed, as compared to the cost-effective potential of 40–46% for the developing countries, for the same reasons previously cited for pumping and compressed air systems.

Another point to highlight is the difference between the cost-effective energy saving potential for fan systems in the US and Canada. The main reason for this is that the cost-effectiveness of measure number 8 (install variable speed drive or VSD), which has the highest energy saving potential, is marginally

Table 12
Total annual cost-effective and technical energy saving and CO_2 emission reduction potential for US Industrial fan systems.

	Cost effective potential	Technical potential
Annual electricity saving potential for fan system in US Industry (GWh/yr)	15,432	18,451
Share of saving from the total fan system energy use in studied industries in US in 2008 (%)	25	3
Share of saving from total electricity use in studied industries in US in 2008 (%)	2	2
Annual primary energy saving potential for fan system in US Industry (TJ/yr)	169,438	202,592
Annual CO_2 emission reduction potential from US Industry (kton CO_2/yr)	9300	11,120

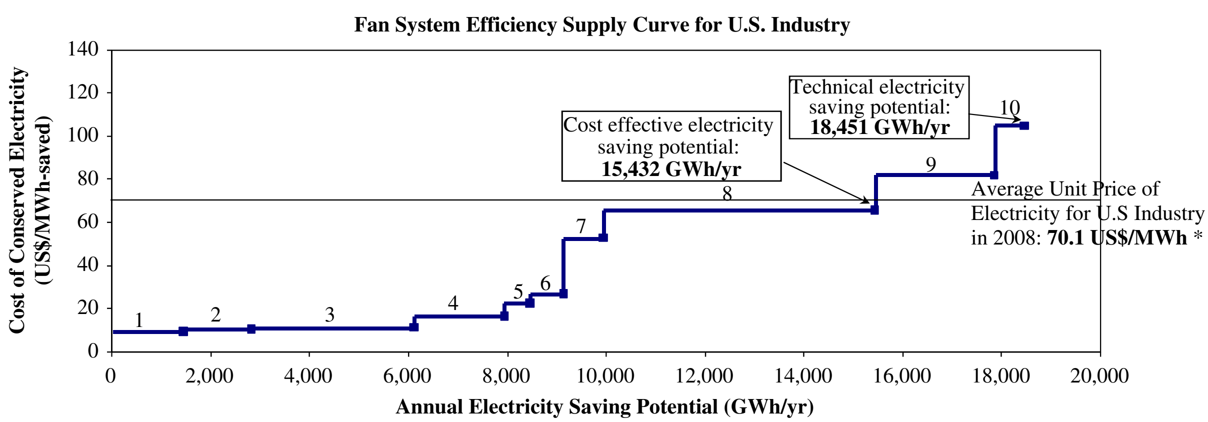

Fig. 4. US Fan System Efficiency Supply Curve. *Note*: This supply curve is intended to provide an indicator of the relative cost-effectiveness of system energy efficiency measures at the national level. The cost-effectiveness of individual measures will vary based on site-specific conditions.

Table 11
Cumulative annual electricity saving and CO_2 emission reduction for fan system efficiency measures in US ranked by their Final CCE.

No.	Energy efficiency measure	*Cumulative* annual electricity saving potential in industry (GWh/yr)	Final CCE (US$/MWh-saved)	Cumulative annual primary energy saving potential in industry (TJ/yr)	Cumulative annual CO_2 emission reduction potential from industry (kton CO_2/yr)
1	Correct damper problems	1448	9.5	15,902	873
2	Fix Leaks and damaged seals	2815	10.6	30,904	1696
3	Isolate flow paths to nonessential or non-operating equipment	6106	11.3	67,049	3680
4	Correct poor airflow conditions at fan inlets and outlets	7939	16.7	87,171	4785
5	Remove sediment/scale buildup from fans and system surfaces	8459	22.5	92,882	5098
6	Initiate predictive maintenance program	9133	26.9	100,280	5504
7	Repair or replace inefficient belt drives	9945	52.9	109,193	5994
8	Install variable speed drive	15,432	65.6	169,438	9300
9	Replace oversized fans with more efficient type	17,850	81.9	195,988	10,758
10	Replace motor with more energy efficient type	18,451	104.9	202,592	11,120

cost-effective in the US but not cost-effective in Canada. This variation is the result of the difference in average electricity price for industry in these two countries. While field experience in Canada would support the cost-effectiveness of VSDs in specific industrial facilities, studying this measure using national averages illustrates the important role of the electricity price in cost-effectiveness of a measure both within and across countries.

Most fan system measures analyzed are cost-effective in all countries studied. In addition, for Thailand and Brazil all fan system measures are cost-effective. Potential causes for this outcome is combination LOW base case, the application of labor adjustment factor, and relatively high electricity costs.

4. Conclusion

Energy Efficiency Supply Curves were constructed for this paper for pumping, fan, and compressed air systems in the US, Canada, EU, Thailand, Vietnam, and Brazil. Using the bottom-up energy efficiency supply curve model, the cost-effective as well as total technical electricity efficiency potentials for these motor systems were estimated for the six countries in the analyses. Fig. 5 shows the share of energy savings for each motor system as a share of total electricity use in the base year for industries studied in the six selected countries/region.

The share of *total technical* electricity saving potential for pumping systems as compared to the total pumping system energy use in studied industries for the base year varies between 43% and 57%. The share of total technical electricity saving potential for compressed air systems as compared to the total compressed air system energy use in studied industries for the base year varies between 29% and 56%. The share of total technical electricity saving potential for fan systems as compared with the total fan system energy use in studied industries in the base year varies between 27% and 46%.

The share of cost-effective electricity saving potential as compared to the total motor system energy use in the base case varies between 27% and 49% for the pumping system, 21% and 47% for the compressed air system, and 14% and 46% for the fan system. Overall, Thailand, Vietnam and Brazil have a higher percentage for cost-effective potential as compared to total motor systems energy use due to a LOW efficiency base case and application of a labor adjustment factor. Table 14 shows the total annual cost-effective and technical energy saving potential in the industrial motor systems in studied countries/region

A further study was conducted for the relative dependence on regular maintenance of energy savings from the measures studied and this result was compared to the cost-effectiveness of these measures. The dependence of many of the cost effective motor system energy efficiency measures on effective maintenance is one indicator of the potential benefits from implementing an energy management system (McKane et al., 2005), and hints at

Table 13
Total annual cost-effective and technical energy saving potential in fan systems in studied countries.

	Annual Electricity Saving Potential in Industrial *fan* system (GWh/yr)		Share of saving from the total *fan* system energy use in studied industries in 2008	
	Cost effective	Technical	Cost effective (%)	Technical[a] (%)
US	15,432	18,451	25	30
Canada	1825	3386	14	27
EU	12,590	13,015	28	29
Thailand	1819	1819	46	46
Vietnam	750	832	41	45
Brazil	3327	3327	40	40

[a] In calculation of energy savings, equipment 1000 hp or greater are excluded.

Table 14
Total annual cost-effective and technical energy saving potential in the industrial motor systems in studied countries/region.

Country	Total annual electricity saving potential in industrial *pumping, compressed air*, and *fan* systems (GWh/yr)		Share of saving from electricity use in *pumping, compressed air*, and fan systems in studied industries in 2008	
	Cost effective	Technical	Cost effective (%)	Technical[a] (%)
US	71,914	100,877	25	35
Canada	16,461	27,002	25	40
EU	58,030	76,644	29	39
Thailand	8343	9659	43	49
Vietnam	4026	4787	46	54
Brazil	13,836	14,675	42	44
Total (sum of 6 countries)	**172,609**	**233,644**	**28**	**38**

[a] In calculation of energy savings, equipment 1000 hp or greater are excluded.

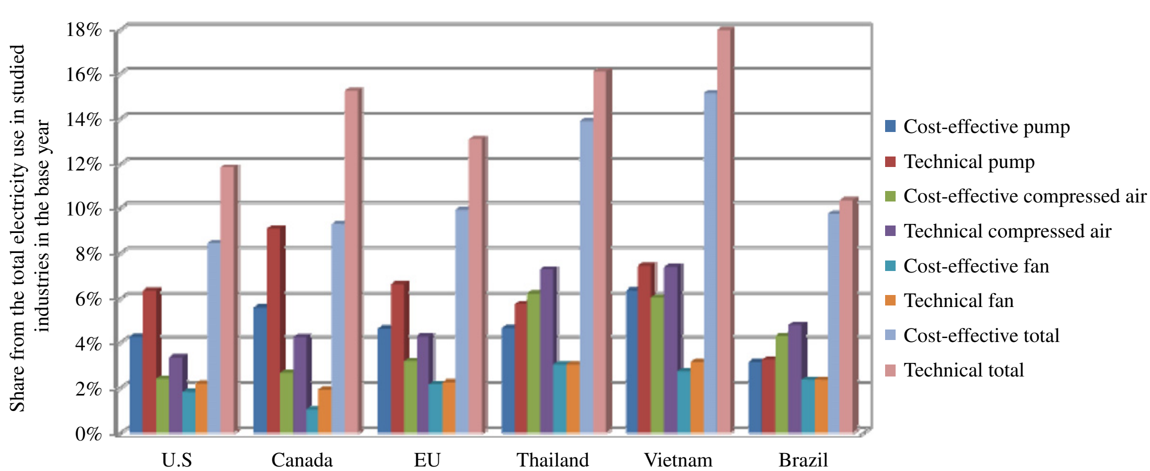

Fig. 5. Energy savings by motor system as a share of total electricity use in the base year for industries studied in the six selected countries.

the potential impact from implementation of the future International Organization for Standardization (ISO) 50001- Energy Management Systems. 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.

This study was planned as a two phase project. The goal of Phase I, which is presented in this paper, was to develop an analysis methodology and apply it to six countries/region for which we had acceptable data on industrial energy use and at least data on motor systems. The purpose of Phase II is to engage wider participation from industrial energy efficiency experts from the countries studied and from 6 to 10 additional countries. These experts will be invited to provide data and to test and refine the Phase I methodology.

Finally, it should be noted that some energy efficiency measures provide productivity, environmental, and other benefits in addition to energy savings, but it is difficult to quantify those benefits. Including quantified estimates of other benefits can decrease the cost of conserved energy and, thus, increase the number of cost-effective efficiency measures (Worrell et al., 2003).

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