Costs and Benefits of Energy Efficiency Improvement in Ceiling Fans

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Abstract

Ceiling fans contribute significantly to residential electricity consumption, especially in developing countries with warm climates. The paper provides analysis of costs and benefits of several options to improve the efficiency of ceiling fans to assess the global potential for electricity savings and green house gas (GHG) emission reductions. Ceiling fan efficiency can be cost-effectively improved by at least 50% using commercially available technology. If these efficiency improvements are implemented in all ceiling fans sold by 2020, 70 terawatt hours per year could be saved and 25 million metric tons of carbon dioxide equivalent (CO_2-e) emissions per year could be avoided, globally. We assess how policies and programs such as standards, labels, and financial incentives can be used to accelerate the adoption of efficient ceiling fans in order to realize potential savings.

Introduction

This report presents the results of an analysis of ceiling fan efficiency, prepared in support of the Super-efficient Equipment and Appliance Deployment (SEAD) initiative.[1] SEAD aims to transform the global market through increasing availability of efficient equipment and appliances. The objective of this analysis is to provide the background technical information necessary to improve the efficiency of ceiling fans and to provide a foundation for the voluntary market transformation activities of SEAD participating countries.

Ceiling fans contribute significantly to residential electricity consumption in warm climates and especially in developing countries. For example, in India, ceiling fans alone accounted for approximately 6% of residential energy use in 2000. This figure is expected to grow to 9% in 2020 [1], an increase that is equivalent to the energy output of 15 mid-sized power plants.[2] In addition, ceiling fan ownership rates have been shown to significantly increase in low-income Indian households as income levels increase [1]. Although ceiling fan standards and labeling programs are specified for every major economy in the world, these programs only discourage the use of highly inefficient fans [8]. In developed countries and countries with milder climates, a smaller fraction of electricity consumption is attributable to ceiling fans. Nevertheless, ceiling fans account for as much as 5% of residential electricity use in the U.S., although this varies greatly by region [12]. Even in those areas where they do not constitute a significant fraction of electricity demand, ceiling fans can reduce energy consumption by reducing the use of other cooling devices. Fans are well known to be a cost-effective option for reducing the electricity demand of air conditioners [13], [14]. Air conditioners are responsible for approximately 16% of residential electricity consumption in the U.S. In addition, ceiling fans are essential features in passive cooling systems aimed at achieving energy-efficient thermal comfort [15], [16].

This study assesses the potential for global ceiling fan energy-efficiency improvement. We analyze the cost-effectiveness of ceiling fan efficiency improvements while estimating the global potential for both energy consumption and CO_2-e emission reductions. We utilize the Bottom-Up Energy Analysis System

[1] An initiative of the Clean Energy Ministerial (CEM) and a task within the International Partnership for Energy Efficiency Cooperation (IPEEC), SEAD seeks to engage governments and the private sector to transform the global market for energy-efficient equipment and appliances. As of October 2012, the governments participating in SEAD are: Australia, Brazil, Canada, the European Commission, France, Germany, India, Japan, Korea, Mexico, Russia, South Africa, Sweden, the United Arab Emirates, the United Kingdom, and the United States. More information on SEAD is available from its website at http://www.superefficient.org/ .

[2] For this estimate we assume an increase in BAU power consumption of ~20TWh, as outlined in the section titled " Energy Savings Potential". We also conservatively estimate that one-tenth of ceiling fans are used during the peak hour and that a mid-sized power plant has a 500-megawatt capacity and runs at 70% efficiency (as described in [11]). However, currently installed power plants in India have a much lower average efficiency [1].

(BUENAS) to make these estimates [11]. First we present a technological economic analysis of fan efficiency improvement options followed by global energy savings estimates. Finally we discuss implications for design of market transformation programs, and conclude the paper.

Techno-Economic Assessment of Efficiency Improvement Options in Ceiling Fans

Ceiling fan energy performance is typically measured in units of meters cubed per minute per Watt (m^3/min/W). This represents the ratio of air delivery to power input. The term “efficiency” is commonly used to represent the ratio of mechanical-output to electrical-input power. In this paper, we follow the example of earlier studies [17]. The term “efficacy” refers to fan performance, while the term “efficiency” is used as a general performance descriptor and when discussing the performance of motors.

Note: In Europe and India the term “Service Value” is used to refer to efficacy.

Table 1. Summary of characteristics used in various standards and labeling programs

Country	Agency	Standard/ Label Type		Speed	Size category	Rating type
India	BIS	Standard	Voluntary		Yes	Specifies minimum efficacy for various fan sizes
India	BEE	Label	Voluntary		Only 1200 mm	Assigns star ratings to fans meeting minimum efficacy requirements
China	NDRC, AQSIQ	Standard	Mandatory		Yes	Assigns ratings based on efficacy, to fans classified by size
U.S.	EPA	Label	Voluntary	Yes		Specifies minimum efficacy for fans classified by operating speed
Europe	Ecodesign Forum	Standard	Mandatory		Yes	Specifies a minimum efficacy for various fan sizes

Standards and labeling programs for ceiling fans are typically designed to ensure a specified level of efficacy. Specifications include sub-categories that are classified by characteristics such as fan size, operating speed, or airflow. Fans have higher efficacy at lower speeds meaning standards and labeling programs categorize fans by operating speed [17]. Fan efficacy can be increased through increasing blade length because power consumption decreases with as blade length increases assuming constant airflow. Accordingly, some programs categorize fan standards and labels by fan size or sweep. Table 2 summarizes fan standards and labeling frameworks in various countries. In the U.S., the ENERGY STAR program specifies minimum ceiling fan efficacy rankings for three different airflow levels [3]. Similarly, the Indian standard IS-374 defines minimum efficacy levels for five different ceiling fan size categories [10]. In addition to this, the Indian Bureau of Energy Efficiency (BEE) maintains a star rating system based on fan efficacy [4]. However, the Indian star rating system is applicable to only one size of fan (1200 mm) and does not vary by fan speed.

Efficiency Improvement Options for Ceiling Fan Systems

The ceiling fan system consists of multiple components that together determine the fan’s overall energy consumption. We focus on engineering improvements that are easily quantifiable such as changes to fan motors and blades that improve ceiling fan efficiency.

Fan Motors

Historically ceiling fans have utilized AC induction motors because these motors are durable, easy-to-construct, and relatively inexpensive to manufacture. Permanent split-capacitor motors are prevalent in ceiling fans manufactured in India, and shaded-pole motors are prevalent in ceiling fans manufactured in the U.S. and Europe [20]. However, these AC induction fan motors are relatively inefficient because of the slip[3] associated with single-phase induction motors. Brushless DC (BLDC) motors have become increasingly common in appliances in recent decades due to developments in electronic commutation and the availability of inexpensive and high-performing magnetic materials [21]. Such motors are more efficient than brushed DC motors because they do not have the friction loss associated with mechanical commutation. Induction motors are inefficient because their rotors do not rotate synchronously with the magnetic field that induces rotor motion which results in slip. BLDC motors alleviate these issues because the rotor moves synchronously with the rotating AC magnetic field produced by electronic commutation. For instance, a 75 W BLDC motor has been estimated to have an efficiency of up to about 90% whereas the average new 75-W AC induction motor has an efficiency of around 75% [21]. Table 2 shows these efficiencies along with those of other 75-W motors.

Multiple engineering studies have estimated the potential for reducing energy consumption through the use of BLDC motors. One experimental Taiwanese study shows that the energy consumption of a ceiling fan with a BLDC motor is about 50% that of a fan with a split-phase induction motor [22]. An experimental study from Australia shows that BLDC motors decreases ceiling fan energy consumption by a factor of three at low speeds and a factor of two at high speeds [23]. Industry experts indicate that using a BLDC motor can reduce energy consumption by an estimated 60% in the U.S. and 50% in India [24],[20]. In addition to the potential energy efficiency improvements achieved with BLDC motors, some fans in India incorporate a combination of elements that affect AC induction motor efficiency. These fans consume significantly less energy than normal [20],[25]. At high speeds, these fans can reduce power consumption from 70-75 W to about 45-50 W. The elements that [20] cites as influencing AC induction motor efficiency in these fans are increased amount of “active” material (such as lamination steel and copper), reduced air gap between stator and rotor and incorporation of standard-grade aluminum for die-cast rotors.

Table 2. Efficiency data for various 75-W motor types in the U.S.

Motor type	**Efficiency**
NovaTorque[4]	90%
Practical Limits BLDC[6]	87%
Practical Limits AC Induction	84%
Average New Production	75%
Average Installed Base	60%

Source: Desroches & Garbesi 2011 [21]

Fan Blades

Improving fan blade design has been shown to have significant influence on fan efficiency. Efficiency improvements have been achieved by multiple approaches. Incorporation of aerodynamic attachments for conventional blades [26]; a decrease in the angle of attack through the use of twisted, tapered (TT) blades [27]; and use of TT blades with an air foil [28]. We focus on the last of these options due to wide use of this type of blade and the potentially large energy savings that are associated with this design.

[3] The slip is the difference between the speed of the rotor and the magnetic field in an AC induction motor.

[4] The company Novatorque has incorporated technical improvements to push efficiency further beyond the so-called “practical limits” of a BLDC motor.

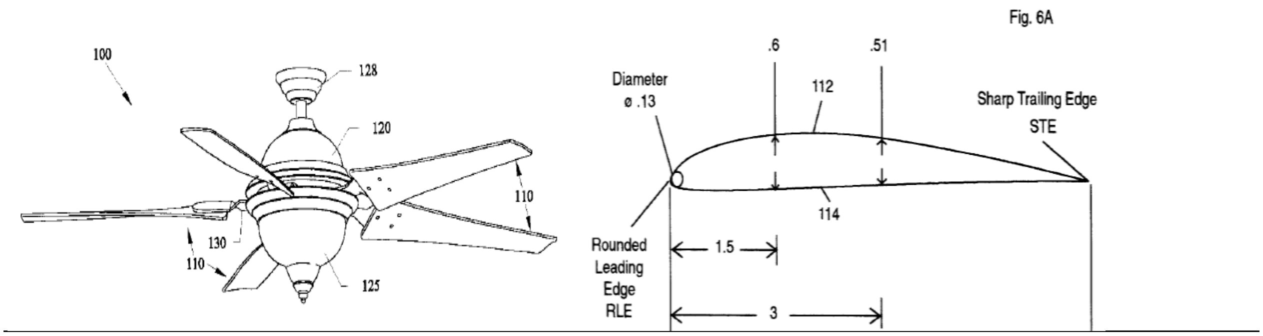

Figure 1. Design drawings from a patent for a ceiling fan with twisted, tapered blades with an airfoil. [5] Source: Parker et al. [40]

TT blades with an airfoil increase efficiency by reducing energy lost to turbulence and flow-separation as shown in Figure 1 [29]. Optimal blade design requires a balance between multiple objectives including maximization of air speed, uniform air speed along the fan radius, and maximization of airflow coverage. A test of one such patented blade design indicates that the subject invention has an efficacy 86%-111% higher than that of a conventional flat blade, indicating remarkable potential for energy-efficiency improvements from changes in fan blade design [30]. These blades can also be used to reduce motor size and cost, and the resulting device will still outperform a conventional fan [30]. Some efficient blade designs have been adapted for aesthetic purposes to appear like traditional blades from the bottom-side while being aerodynamic on the top-side, thus improving efficiency 10%- 26% when compared to conventional designs [31]. The blade has been designed to meet a market preference by some consumers for energy-efficient fans with a traditional appearance.

Fan Efficiency Improvement Opportunities: Empirical Evidence from the US Market

Figure 2 shows ENERGY STAR market data for qualifying fans being sold in the U.S. and Canada [3]. The information regarding motor and blade type was obtained from product catalogs and phone calls with representatives from ceiling fan manufacturers producing fans with the highest efficacies. These companies include Monte Carlo, Fanimation, Regency, and Emerson [32]. The data in the figures are comparable to the performance of the most efficient fans being introduced in U.S. and Canadian markets. For instance, the Emerson Midway Eco fan is advertised as having a 75% reduction in energy consumption due to the Emerson EcoMotor ™ [9].

[5] We note that most fans sold in India have 3 blades as opposed to the 5 pictured here. However, to be consistent with the patent filed by Parker (2003), we have pictured the 5 bladed design from the patent. The blade improvements will be similar for a fan with 3 blades.

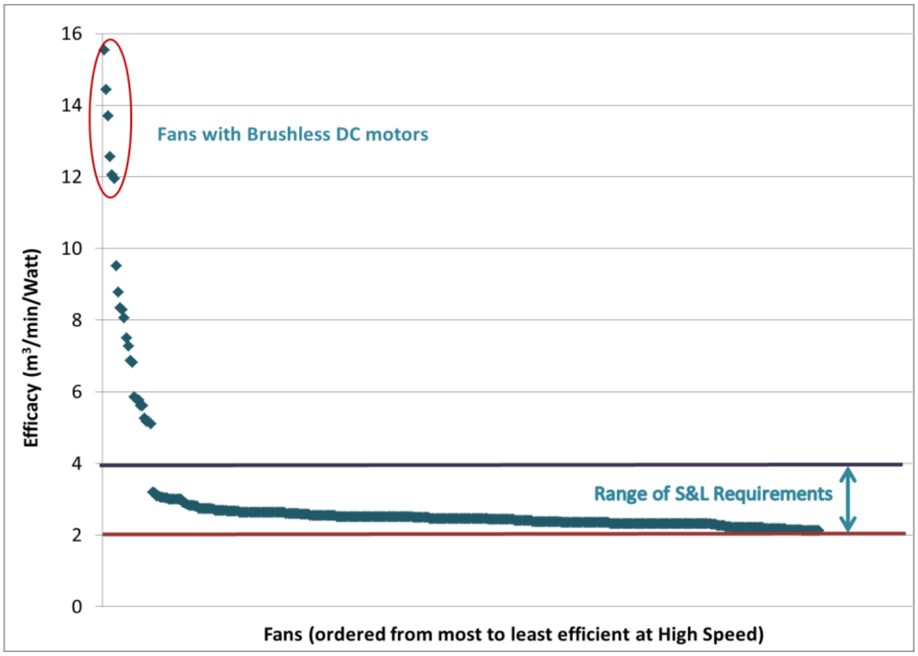

Figure 2. Efficacies for ENERGY STAR ceiling fans (fan only, without lights) at high speed[6]

Source: ENERGY STAR [33]

The figure shows that fans with BLDC motors have far higher efficacies than the current ENERGY STAR high-speed standard requires (2 m^3/min/W). This data indicates that engineering improvements, such as those previously discussed, can be used for purposes other than increasing efficacy. Other purposes include reducing motor size or material quality to reduce manufacturing costs in the absence of policy intervention to improve efficiency. To the authors' knowledge, there are no fans with BLDC motors in these figures other than those highlighted, although this is unconfirmed as we were not able to contact every fan manufacturer.

Technical and Economic Analysis of Efficiency Improvement Options

Here we estimate the costs of efficiency improvement of ceiling fans using the options previously described. We estimate the cost of conserved electricity (CCE) to assess the cost-effectiveness of these efficiency improvements. Due to data constraints, we only cite costs from a few countries while estimating the CCE.

Fan Motors

Based on data collected from industry experts we estimate the incremental cost of efficiency improvements of motors typically used in ceiling fans. We consider two types of efficiency improvement options. First, given that BLDC motors are significantly more efficient than induction motors, we estimate the incremental cost of BLDC motors of the same size and performance specifications over the typical induction motor. Second, we consider the cost of improving the efficiency of the induction motor itself, where the efficiency improvements are smaller and less costly compared to those achieved by a BLDC motor. BLDC motors are typically more expensive when compared to induction motors primarily because of the extra cost of the controller. Note that induction motors and BLDC motors have similar materials costs (excluding the BLDC motor controller). This is primarily because the extra cost of permanent magnets in a BLDC motor is compensated by reduction in costs due to less copper and steel (See [36] and [21] for a detailed discussion). Desroches & Garbesi find that that the global cost of materials for a 750-W (note that fan motors are typically much smaller, < 75W) induction motor is about US$43.80, and, for a BLDC motor, the materials cost ranges from US$24.20 to US$36.74, as of 2011 [21]. This indicates

[6] In 2010 and 2011, the market penetration of ENERGY STAR qualified ceiling fans was 18% and 13%, respectively [34] [35].

that the *materials* cost of a smaller BLDC motor, such as would be used in ceiling fans, should also range from a little less than to about equal to that of a comparable AC induction motor. Therefore, the incremental cost of the BLDC motor over an induction motor is essentially the cost of the controller. A BLDC motor controller is estimated to have a manufacturing cost between INR300-700 in India [20], [25]. The same controller would cost between US$3.2 to US$22.5 in the US [36]. We assume the incremental cost of a BLDC motor that replaces a typical ceiling fan induction motor of 75 W to be approximately US$10.50 for the purposes of this report.

Fan Blades

The cost of manufacturing efficient ceiling fan blades in the U.S. is estimated to be about US$2.25, versus US$0.25 per conventional flat blade [31], [30]. The incremental cost of manufacturing an efficient blade versus a conventional blade in India is about INR60 for 3 blades i.e. US$0.36/blade [20]. Although these appear to be significant cost increases for these components, they are not very large (~5%) compared to the total retail price of a ceiling fan. An important point to mention in the case of efficiency improvement through blade design is that blade design and manufacturing are driven by aesthetic considerations rather than just efficiency. This is also reflected in *divergent* estimates of the costs of manufacturing depending on the design, material, manufacturing, and treatment/finishing processes. The significance of aesthetic considerations in blade manufacture implies that *mandating* more efficient blades through minimum energy performance standards (MEPS) is not likely to be a practical or desirable option. However, given that some fans may be designed to meet energy efficiency policy specifications by using more efficient blades, it is still useful to estimate the costs of efficiency improvement through more efficient blades, particularly for labeling and incentive programs. Table 3 reports these costs in dollar terms along with average numbers, which are used as the input for the cost effectiveness calculation.

Table 3. Summary of reported manufacturing costs in dollars of efficiency improvement options[7]

Efficiency Improvement Option	**India**		**US**		Average($)
	[20]	[25]	[36]	[31]	
Improved AC Induction Motor	$1.09	$1.82			$1.5
BLDC Motor	$5.45	$10.91	$3.2-$22.5		$10.5
Efficient Blades	$1.09			$6.00	$3.5

Cost of Conserved Electricity

This section presents the CCE in India for motor and blade improvements described above, using the efficiency assumptions discussed earlier along with corresponding cost assumptions. Two kinds of CCEs are calculated as follows: the manufacturing cost of conserved electricity (CCE_m) which considers the incremental cost of the higher efficiency fan to the manufacturer and the cost to the consumer of conserved electricity (CCE_c) which considers the incremental cost of the higher efficiency model to the consumer. The former metric (CCE_m) is lower than the latter (CCE_c) as it does not include markups or taxes. Therefore, CCE_m can be used to measure the cost-effectiveness of a market transformation program, such as an upstream incentive program, while CCE_c can be used to measure the cost effectiveness of a standards program, or a downstream incentive program.

[7] In converting from a per-blade to a total incremental cost we assume the fan has 3 blades.

Table 4. Cost of conserved electricity for various efficiency improvement options in India[8]

Efficiency Improvement Option[9]	Average Power Savings (W)	% Reduction from baseline power	Average incremental manufacturing cost($)	CCE_m ($/kWh)	CCE_c ($/kWh)
Improved AC Induction Motor (A)	25	36%	$1.5	$0.003	$0.005
BLDC Motor (B)	35	50%	$10.5	$0.014	$0.027
Efficient Blades (C)	10	15%	$3.5	$0.015	$0.031
A+C	32	45%	$5.0	$0.007	$0.014
B+C	40	57%	$14.0	$0.016	$0.032

Assumptions: Lifetime=10 years; hours of use per day = 8.7; discount rate = 7.6%; multiplier for markup and taxes = 2.0

Shown above, improved AC induction motors are the most cost effective single option, followed by BLDC motors. We also note that our cost and efficiency assumptions (and resulting CCE estimates) regarding efficiency improvement using more efficient blades are *conservative* and may very well be lower than those shown. This can be attributed to using cost and efficiency estimates for more efficient blades with a traditional appearance as discussed earlier rather than the most efficient blades [31]. Also, data on blades indicated *divergent* estimates of the costs of manufacturing depending on design, material, manufacturing, and treatment/finishing processes, which varied due to aesthetic considerations. Given the globally traded nature, maturity, and high contribution of material costs to the total costs of the efficiency technologies considered, we argue that cost estimates based on the data in India and US are likely to be a reasonable approximation of the costs in other regions.

Energy Savings Potential

We used the Bottom-Up Energy Analysis System[10] (BUENAS) to estimate the potential global energy and CO_2 emission savings from accelerated implementation of the engineering developments for ceiling fans described earlier. A detailed description of the methodology is available in [11] and [38]. This version of BUENAS covers thirteen major economies, representing 80% of the world's total energy consumption. Our objective is to provide an approximate estimate for the potential savings from accelerated adoption of efficient fans. Precise estimates of the saving potential in each of the economies covered will require significant further work in order to provide a more robust empirical basis for the assumptions used. Note that we have more robust data on India, China, and the US compared to other countries and hence the estimates of saving potential for these countries are likely to be more accurate than for the others.

Data and Methodology

BUENAS is an end-use energy forecasting model designed to provide a detailed assessment of the potential for energy savings and GHG emissions reductions from energy-efficiency standards and labeling programs worldwide (see [38] for a detailed description of the model). The model is "bottom-up" in that it calculates energy demand based on input data for individual appliance products. BUENAS is composed of three modules. The first calculates the number of appliances per household (diffusion) in a country at a given point in time, primarily based on an empirical relationship observed between appliance ownership and macroeconomic household variables such as household income. The second module

[8] We have assumed a 100% markup in estimating costs to the consumer in line with [25]. Lifetime and hours of use assumptions are in line with [37].

[9] Efficiency improvement options from single components (A, B, C) are presented first followed by efficiency improvement options from combining two options (A+C and B+C). The options are subsequently ordered by increasing cost of conserved energy. Also option C, efficient blades can be used with both BLDC and AC motors. While BLDC motors and AC motors are widely available, efficient blades may be proprietary designs, and also carry associated aesthetic tradeoffs.

[10] http://www.superefficient.org/en/Products/BUENAS.aspx

estimates energy consumption and efficiency improvements at the appliance level. The third module is a stock turnover module that calculates the sales of appliances every year based on retirement of old units and increased penetration of appliances in households. This module combines the sales in every year with unit energy consumption (UEC) to estimate the total stock energy consumption. The difference in stock energy consumption between a Business As Usual (BAU) and an efficiency case equals the savings. Energy savings are then converted into CO_2 equivalent emission mitigation according to the power generation mix from each country.

Results

This section presents the BUENAS results in terms of stock energy consumption and global potential energy savings. BUENAS also provides CO_2 emission mitigation potential calculated using country-specific carbon factors [11].

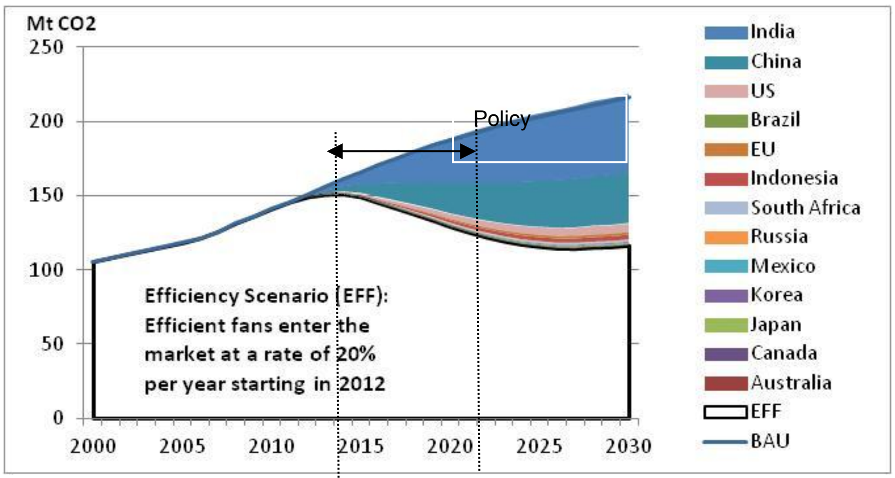

Figure 3. Potential CO_2 emissions reductions resulting from introduction of efficient fans, 2000-2030

Efficiency Scenario

In the efficiency scenario, efficient fans with BLDC motors gradually enter the market, gaining 20% of market share starting in 2012. The market reaches saturation in 2017 when 100% of fans sold are assumed to be efficient. The unit energy consumption (UEC) for efficient fans is assumed to be constant throughout the forecast period. We evaluate energy savings potentials in 2016, 2020, and 2030. Table 5 shows the results of the energy savings potential analysis, and Figure 3 shows the corresponding CO_2 emission results. India represents almost half of the potential electricity savings and CO_2 emission mitigation potential in the economies covered in this analysis.

Table 5. Annual and cumulative energy savings forecasts

	Annual Electricity Savings (TWh)			Cumulative Electricity Savings (TWh)		
Year	2016	2020	2030	2012-2016	2012-2020	2012-2030
Australia	0.05	0.12	0.21	0.12	0.50	2.31
Brazil	1.43	3.35	6.09	3.29	13.83	65.41
Canada	0.05	0.11	0.19	0.11	0.46	2.08
China	9.01	20.68	35.77	21.02	86.50	396.59
EU	0.48	1.08	1.76	1.14	4.59	20.22
India	14.17	33.54	62.38	32.52	137.91	660.60
Indonesia	1.12	2.63	4.81	2.59	10.88	51.51
Japan	0.24	0.54	0.84	0.56	2.27	9.90
Korea	0.11	0.26	0.44	0.26	1.07	4.91
Mexico	0.41	0.93	1.53	0.96	3.90	17.43
Russia	0.15	0.34	0.52	0.37	1.46	6.19
South Africa	0.17	0.40	0.65	0.40	1.67	7.46
U.S.	2.43	5.65	9.86	5.61	23.47	108.57
Total	**29.82**	**69.62**	**125.05**	**68.94**	**288.51**	**1353.19**

Realizing Cost-Effective Efficiency Improvements: Lessons for Market Transformation Programs

As discussed earlier in this report, there are several cost-effective options for improvement of ceiling-fan efficiency that would reduce fan energy consumption by more than 50%. Although highly efficient fans that incorporate most of the efficiency improvement options discussed in this paper are commercially available in certain countries (e.g., the U.S.), they constitute a very small percentage of sales. In some countries (e.g., India), fans with BLDC motors and efficient blades are not currently commercially available. Several barriers, including high purchase price and lack of information (e.g., lack of labels that recognize highly efficient performance), have been identified that contribute to the limited adoption of highly efficient fans [4]. In this section we discuss some broad insights for energy efficiency market transformation programs based on the earlier discussion.

General Insights

Some of the insights that can be drawn from the preceding discussion apply across various types of market transformation programs and policies. We discuss some such general insights with respect to key fan characteristics such as fan size and speed, and with respect to blade design.

It is important for market transformation programs to classify fans by size and take into account the effect of fan speed on efficacy. First-and-foremost, size categories are important in market transformation programs to preclude the possibility that simply increasing blade length, without necessarily delivering better service, could circumvent a policy based merely on efficacy. For instance, although airflow increases with larger blades the amount of cooling felt by the user may not. This is because the service delivered to the final user (in this case, cooling) depends not on the total volume of air moved, but also on the velocity of the air[11]. If market transformation policies classify fans by size, fan manufacturers will not be able to simply install longer blades to improve efficacy nominally without competing with other manufacturers in a separate size category or improving the service delivered to the final user. Second, operating speed is also an important criterion in designing market transformation programs because efficacy varies inversely with increasing fan speed [39]. This effect can be addressed either by using standard speed or minimum airflow in the test procedure for the program, such as in India's standard and labeling programs, or by changing the efficacy requirement at various speeds, such as in the ENERGY

[11] The coefficient of convective heat transfer off the human body depends on the velocity of the air [75].

STAR program. It should be noted that the testing burden would be lower in the first case, with a tradeoff on the accuracy of the test procedure at various speeds.

The literature discussed earlier indicates that there is remarkable potential for energy-efficiency improvements from changes in fan blade design. We also find that blade design improvements have greater efficacy/power consumption savings impact at higher speeds. This implies that market transformation programs in economies with hotter climates and higher average airflows (e.g. India) will benefit proportionally more from blade design improvements than economies where average airflows tend to be lower. (e.g. the US). For example, the most efficient blade designs discussed in the literature will improve efficacy by 86% at lower speeds (airflows), versus 111% at higher speeds (airflows) compared with conventional blade designs [30].

Standards and Labeling Programs

Efficiency levels specified by standards and labeling programs are far below what can be achieved by implementing cost-effective energy-efficiency options in ceiling fans (see Figure 4). For example, as seen from data on the efficacy of fans meeting the US ENERGY STAR requirements, fans using BLDC motors and efficient blades are significantly more efficient (with efficacy as high as 15 $\frac{m^3}{min}/W$) compared to efficiency requirement for qualifying for ENERGY STAR (efficacy of 2.1-4.2 $\frac{m^3}{min}/W$). Furthermore, the Indian Bureau of Energy Efficiency (BEE) voluntary star rating program for fans only covered 2% of the Indian market and only 18% of fans (without a light kit) on the US ceiling fan market were compliant with ENERGY STAR, indicating significant room for efficiency improvement [25], [3].

The standards and labels levels for BEE's star rating program in India are presented in Figure 13. These efficacy levels are tested under different conditions (notably airflow requirements/speeds) than standards and labels in the US, Europe and China so they cannot be directly compared against each other without accounting for this.[12] However, the improvements in efficacy discussed in this report are applicable across the range of commonly encountered airflows. This means that these improvements will offer significant energy savings of a similar order of magnitude regardless of airflow or test procedure alignment. For comparison, the US ENERGY STAR label has an efficacy requirement of 4.2 (m^3/min/W) at low speeds and 2.1 (m^3/min/W) at high speeds while the lowest standard for efficacy in China varies by fan size from 3.47 (m^3/min/W) for 1800 mm fans to 2.75 (m^3/min/W) for 900 mm fans [3], [5]. Figure 13 makes clear the significant potential for improvement in fan efficacy through increases in specified standards and labels.

The highest efficacy level recognized by labels in several countries is significantly lower than what can be achieved by adopting cost effective efficiency options. Hence current efficacy label levels need to be revised significantly to encourage deeper penetration of efficient ceiling fans at the top of the market with efficacies achievable using BLDC motors and efficient blades that are already on the market in the US, and that are cost-effective in other countries. The low penetration level of efficient ceiling fans in both India and the US seems to indicate the presence of barriers to efficiency other than information, such as first cost, that may not be able to be addressed within a standards and labeling framework.

[12] See [39] for a discussion of the effect of fan speed and motor speed on efficacy. Increasing airflow from 5000 CFM (the US high speed) to 7415 CFM (i.e.210 m^3/min, the minimum airflow for star rated fans in India), i.e. A 48% increase will yield a decrease in efficacy of at most 35%.

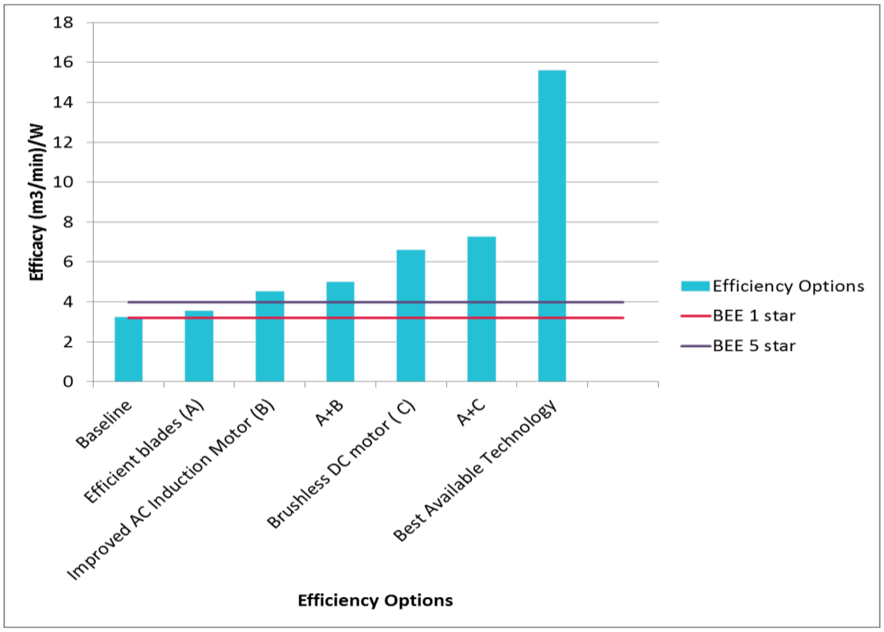

Figure 4. BEE (India) star labels compared to estimates of potential ceiling fan efficacy[13]

Incentive Programs

Incentive programs for efficient fans could accelerate the penetration of superefficient fans for the following reasons. First, adoption of cost-effective efficient appliances is often hindered by high first cost, e.g. as discussed in [6]. In emerging economies, consumers are highly sensitive to high first costs [4]. Second, due to the importance of aesthetics discussed earlier, it is not practical or desirable to mandate efficiency improvement from blade design through MEPS. However, the full existing potential from more efficient blades, as well as from BLDC motors, could be exploited through incentive programs for superefficient fans. Such programs could cost effectively target efficacies of up to 15 $\frac{m^3}{min}/W$, as discussed earlier. There are several examples of financial incentive programs that lower the first cost of cost-effective energy efficient appliances and equipment to accelerate their adoption. However, despite the large saving potential, financial incentive programs to promote the adoption of highly efficient fans are not common.

Conclusions

This paper presents an analysis of the potential for improvement of ceiling fan components to reduce global energy consumption and GHG emissions. Improved blade design and AC induction motor materials, and the increased use of BLDC motors, are identified as cost effective options to improve the efficiency of ceiling fans. Adaptation of these technologies could provide ceiling fan power consumption savings of more than 50%. Out of the several types of policies typically used to accelerate adoption of efficient products (e.g., awards, incentives, and standards and labeling programs), standards and labeling programs are most commonly used to accelerate the market penetration of efficient fans.

Efficacy levels are tested under different conditions (notably airflow requirements/speeds) in various countries so they cannot be directly compared against each other without accounting for this fact. Nevertheless, the improvements in efficacy discussed in this report are applicable across the range of commonly encountered airflows. Meaning these improvements will offer significant energy savings of a similar order of magnitude regardless of airflow or test procedure alignment.

[13] Note: The baseline efficacy value is based on the average values reported as 'National Player's Models' presented in (Garg & Jose 2009). Incremental improvements correspond to those presented earlier. The efficacy level of the best available fan corresponds to the fan with the highest efficacy in Figure 8.

The highest efficacy level required by standards and labeling programs in several countries is significantly lower than what can be achieved by adopting the cost effective efficiency improvement options discussed here. Hence current efficacy label levels need to be revised significantly to encourage deeper penetration of efficient ceiling fans at the top of the market.

The low penetration level of efficient ceiling fans in both India and the US, even with labeling programs in place,[14] seem to indicate the presence of barriers. These barriers to efficiency, in addition to information, such as first cost, may not be able to be addressed fully within a standards and labeling framework, particularly in emerging economies with price sensitive consumers. However, despite the large saving potential, financial incentive programs that promote the adoption of highly efficient fans by removing the first cost barrier are not common.

One notable example under development is the Super-Efficient Equipment Program (SEEP) in India where financial incentives will be provided to fan manufacturers to produce and sell highly efficient fans; fans that consume less than half of the energy consumed by fans typically sold on the Indian market [4]. Even if the entire incremental cost of the highly efficient fans is covered by the financial incentives, the cost of the conserved electricity for efficiency improvements over 50% is just 0.7 rupees per kWh (US$0.014/kWh) which is about one sixth of the cost of supplying electricity in India [6]. SEEP or a similar upstream incentive program for ceiling fans would be cost-effective even assuming higher costs and lower hours of use as discussed earlier. Therefore there remains significant scope for improved policy design and implementation for aggressive and cost effective ceiling fan efficiency improvements.

References

[1] de la Rue du Can S., et al. *Residential and Transport Energy Use in India: Past Trend and Future Outlook*. Berkeley CA: Lawrence Berkeley National Laboratory report LBNL-1753E, 2009

[2] Garg S. and Jose A. *Energy-Efficiency Labelling of Ceiling Fans in India: Challenges and the way forward.* Proceedings of the 5th International Conference on Energy Efficiency in Domestic Appliances and Lighting, 2009 http://www.enbook.pl/sites/default/files/publikacje/150/20120130/energy_efficinency_in_domestic_vol_3_p2.pdf

[3] U.S. DOE and U.S. EPA. ENERGY STAR. Available at: http://www.energystar.gov/. Accessed July 26, 2011.

[4] Singh D., Barve A. and Sant G. *Ceiling Fan The Overlooked Appliance in Energy Efficiency Discussions*, Pune, India: Prayas Energy Group, 2010.

[5] General Administration of Quality Supervision Inspection and Quarantine of the People's Republic of China,(AQSIQ). *Minimum allowable values of energy efficiency and energy efficiency grades of AC electric fans GB 12021.9-2008*. Standardization Administration of the People's Republic of China, 2010.

[6] Sathaye J. and Gupta A. *Eliminating Electricity Deficit through Energy Efficiency in India: An Evaluation of Aggregate Economic and Carbon Benefits*. Berkeley CA: Lawrence Berkeley National Laboratory report LBNL-3381E, 2010.

[7] Letschert V. and McNeil M. *The Boom of Electricity Demand in the Residential Sector in the Developing World and the Potential for Energy Efficiency*. Berkeley, CA: Lawrence Berkeley National Laboratory report LBNL-2329E, 2008.

[14] BEE's voluntary star rating program for fans only covered 2% of the Indian market, while only 18% of the fans(without a light kit) on the US ceiling fan market were compliant with ENERGY STAR (PWC, 2012, and EPA 2011) indicating significant room for efficiency improvement.

[8] Waide P., et al. Opportunities for Success and CO2 Savings from Appliance Energy Efficiency Harmonisation. Navigant Consulting in Partnership with CLASP. Available at: http://www.clasponline.org/clasp.online.resource.php?disdoc=781#opportunities. Accessed July 26, 2011.

[9] Emerson Climate Technologies. Midway Eco. http://www.emersonfans.com/Pages/Fan.aspx?Fan=Midway%20Eco. Accessed 12/15/2010.

[10] Bureau of Indian Standards, 2007. Indian Standard - Specification for Electric Ceiling Type Fans and Regulators (3rd Revision), Edition 4.6, (Incorporating Amendment Nos 1-6).

[11] Koomey J., et al. *Defining a standard metric for electricity savings*. Environmental Research Letters 5. 2010.

[12] Calwell C. and Horowitz N. *Ceiling Fans: Fulfilling the Energy Efficiency Promise*. Home Energy, 18(1) 2001, pp.24-30.

[13] Hwang R.-L., et al. *Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot-humid regions*. Building and Environment 44(6) 2009, pp.1128-1134.

[14] Arens E., et al. 2009. *Moving Air for Comfort*. ASHRAE Journal 51(5) 2009, pp.18-28.

[15] Ho S., Rosario L. and Rahman M. *Thermal comfort enhancement by using a ceiling fan*. Applied Thermal Engineering 29(8-9) 2009, pp.1648-1656.

[16] Santamouris M., et al. *Recent progress on passive cooling techniques: Advanced technological developlments to improve survivability levels in low-income households*. Energy and Buildings 39(7) 2007, pp.859-866.

[17] Chakraborty A., et al. *Energy Conservation in Ceiling Fans*. Proceedings of the 13th National Power Systems Conference. Chennai, India, 2004, pp. 835-838.

[18] Riviere P. *Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation)*. Study on comfort fans - final report, 2008. Available at: http://www.ebpg.bam.de/de/ebpg_medien/010_studyf_08-11_comfortfans_parts1-8.pdf [Accessed July 26, 2011].

[19] European Commission. Commission Working Document on possible Ecodesign Requirements for air-conditioning appliances and comfort fans, 2010. Available at: http://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Lots/Working_Documents/Lot_10_Air-Con_April_2010/WD_Airco_Ecodesign_Regulation_for_CF.pdf. Accessed July 26, 2011.

[20] Pednekar A. Personal Communication, 2010.

[21] Desroches L.-B. and Garbesi K. Max Tech and Beyond: Maximizing Appliance and Equipment Efficiency by Design. Berkeley CA: Lawrence Berkeley National Laboratory Report LBNL-4998E, 2011.

[22] Liu C.-S., et al. *Development of New Structure of BLDC Servo Motor for Ceiling Fan*. In Proceedings of the 4th IEEE Conference on Industrial Electronics and Appliances, 2009, pp. 2640-2643.

[23] Schmidt K. and Patterson D. *Performance results for a high efficiency tropical ceiling fan and comparisons with conventional fans: Demand side management via small appliance efficiency*. Renewable Energy 22(1-3) 2001, pp.169-176.

[24] Parker D. Personal Communication at Florida Solar Energy Center, 2010.

[25] PWC (Price Waterhouse Coopers). *Design of Monitoring and Verification Systems for SEEP for Fans- Inception Report*. unpublished draft, 2012.

[26] Volk S. Propeller Breeze Enhancing Blades for Conventional Ceiling Fans. United States Patent Number 4892460,1990.

[27] Bird G. High Efficiency Ceiling Fan. United States Patent Number 6733241, 2004.

[28] Sonne J. and Parker D. *Measured Ceiling Fan Performance and Usage Patterns: Implications for Efficiency and Comfort Improvement*. In Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings: Energy Efficiency in a Competitive Environment (Pacific Grove CA, 1998), pp. 335-341.\

[29] Gossamer Wind. *What is So Special About These Fans*. http://www.gossamerwind.com/content/what-so-special-about-these-fans-0. Accessed 4/20/2011.

[30] Parker D., Hua G. and Hibbs B. High Efficiency Ceiling Fan. United States Patent Number 6039541, 2000.

[31] Parker D. & Hibbs B. Efficient Traditionally Appearing Ceiling Fan Blades with Aerodynamical Upper Surfaces. United States Patent Number 7665967, 2010.

[32] Sathaye N. 2011. Personal Communication.

[33] ENERGY STAR. ENERGY STAR Ceiling Fan Product List posted on November 14, 2012. http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CF

[34] ENERGY STAR. ENERGY STAR Unit Shipment and Market Penetration Report Calendar Year 2010 Summary, 2011. http://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2010_USD_Summary_Report.pdf

[35] ENERGY STAR. ENERGY STAR Unit Shipment and Market Penetration Report Calendar Year 2011 Summary, 2012. http://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2011_USD_Summary_Report.pdf

[36] Chiang J., Fairchild Semiconductor. Power Point presentation, September 16, 2010. Available at: http://edg1.vcall.com/irwebsites/fairchildsemi/Final%20-%20PCIA.pdf

[37] Boegle A., Singh, D. and Sant, G. *Estimating Technical Energy Saving Potential from Improving Appliance Efficiency in Indian Households*. In ACEEE Summer Study on Energy Efficiency in Buildings: The Climate for Efficiency is Now (Pacific Grove CA, 2010).

[38] McNeil M., Letschert V.E., de la Rue du Can S., and Ke J. Bottom-Up Energy Analysis System – Methodology and Results. Berkeley CA: Lawrence Berkeley National Laboratory report LBNL 5722E, 2012.

[39] Davis Energy Group Energy Solutions. *Codes and Standards Enhancement Initiative For PY2004: Title 20 Standards Development: Analysis of Standards Options for Ceiling Fans*, 2004

[40] Parker D., Su G. and Hibbs B. High Efficiency Ceiling Fan Blades. United States Patent Number 6659721, 2003