Superefficient appliances and equipment: untapped energy savings for Chinese buildings

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Abstract

China is now one of the most active countries in adopting new and revised appliance and equipment efficiency standards, with 57 mandatory standards as of mid-2014. But because China typically sets its standards iteratively and aim to eliminate only the bottom 20 % efficiency models on the market, significant untapped efficiency gains beyond the mandatory efficiency level remain. As rising urbanization and incomes drive up Chinese residents' appliance ownership and equipment usage, further improving the efficiency of key residential appliances can result in enormous energy savings. In this study, we seek to quantify the gap between the minimum efficiency in mandatory standards and the maximum technically feasible and cost-effective levels in the market today.

This study evaluates the energy savings potential of adopting maximum feasible share of cost-effective and superefficient technologies for major residential appliances in China through 2050, taking into consideration efficiency standards that have already been adopted as well as expected autonomous technological improvements over time. For the major product types of refrigerators, televisions, room air conditioners, clothes washers, and natural gas and electric water heaters, we surveyed product-specific efficiency levels and costs of both the current market average and the most efficient models on the market. We then developed a bottom-up energy end-use model to evaluate the potential energy savings from full penetration of superefficient appliances by 2050. Our results show that cost-effective efficiency improvements in key appliances and building equipment hold the second biggest energy-savings opportunity – after passive design – in the building sector with the potential to reduce total building energy consumption by 8 % by 2050. These results have important policy implications, suggesting that more policies beyond standards may be needed to achieve the untapped energy savings that exist for major residential end-uses.

Introduction

China first introduced mandatory energy efficiency standards, commonly known as minimum energy performance standards (MEPS), in 1988 with the adoption of the Standardization Law of China. The first batch of minimum energy performance standards (MEPS) was adopted in 1989 for eight major products, including refrigerators, room air conditioners, clothes washers, rice cookers and televisions. In 1995, the China National Institute of Standardization (CNIS) was authorized to organize MEPS development and revision. In 1999, CNIS began the process of revising single-period mandatory energy efficiency standards and developing new standards based on review of similar international standards. After China announced its national energy consumption per unit of GDP and CO_2 emissions per unit of GDP targets for 2015 and 2020, greater emphasis has been placed on adopting new and revised MEPS, with a faster pace of new standards development and revisions over the last few years. Compared to an average of 3 to 4 new and revised MEPS developed per year in the early 2000s, China adopted 6 MEPS in 2012 and an unprecedented 12 MEPS in 2013. China also has a mandatory categorical energy information label known as the China Energy Label, which covers a smaller subset of products covered by MEPS. The label specifications of the minimum efficiency thresholds for each label efficiency grade are laid out in the national standards document, with the labeling thresholds adjusted simultaneously with each MEPS revision.

As of June 2014, China has adopted a total of 57 equipment-based MEPS[1], including 15 for household appliances, 13 for lighting products, 14 for industrial equipment, 5 for office equipment, and 10 for commercial equipment. In China, the principles for choosing target products for standard setting focus on the following characteristics (Zhou et al. 2013):

- High energy consumption and high energy savings potential.
- Widely used with mature industry and well-regulated market.
- Mature testing procedure and good testing infrastructure and ability nationwide.
- Stakeholder support.

In terms of guiding principles for standard-setting, China has generally aimed at eliminating the bottom 20 % efficiency of the market with each new standard and standard revision (Li 2012). Recently, after years of international collaboration and capacity building, CNIS began using economic and technical analysis including simplified engineering analysis, life-cycle cost analysis, and energy and environmental impact analysis to help determine the proposed MEPS level. Nevertheless, China lacks many of the key data inputs that are used internationally in evaluating possible MEPS levels and setting the final threshold, including most notably the absence of national residential and commercial end-use energy consumption surveys and detailed market data collected and reported by manufacturers and published by industry associations. Combined with inadequate financial and staff resources and more limited stakeholder participation, the minimum efficiency level mandated by many Chinese MEPS is often not stringent enough. As a result, significant untapped efficiency gains beyond the mandatory efficiency level remain in China. As rising urbanization and incomes drive up Chinese residents' appliance ownership and equipment usage, further improving the efficiency of key residential appliances can result in enormous energy savings. Letschert et al. 2012 had previously found that China and EU are the two countries with the most cost-effective savings possible from more stringent MEPS for 14 residential products and 2 industrial products evaluated in their study. In this study, we seek to quantify the gap between the minimum efficiency in mandatory standards and the maximum technically feasible and cost-effective levels in the market today.

This paper evaluates the energy savings potential of adopting maximum feasible share of cost-effective and superefficient technologies for major residential appliances in China through 2050, taking into consideration efficiency standards that have already been adopted as well as expected autonomous technological improvements over time. For the major appliance product types that have the highest ownership rates and high total energy consumption of refrigerators, room air conditioners, clothes washers, and televisions as well as the two dominating urban water heating technologies of natural gas and electric water heaters, we surveyed product-specific efficiency levels and costs of both the current market average model in the Chinese market and the most efficient models in the international market. We then developed a bottom-up energy end-use model to evaluate the potential energy savings from full penetration of superefficient appliances in China's residential sector by 2050, taking into consideration expected changes in size and usage as a result of rising income levels.

1. This number does not include the 7 additional mandatory energy efficiency standards that China has for transport vehicles, or what is commonly considered fuel economy standards.

Modeling methodology

BOTTOM-UP MODELING OF RESIDENTIAL EQUIPMENT

The bottom-up building energy end-use model used in this study is part of a larger national energy end-use model that includes residential and commercial building modules on the demand-side, and power generation and other energy transformation modules on the supply-side. This model provides an accounting framework of China's energy and economic structure using the LEAP (Long-Range Energy Alternatives Planning) software platform developed by Stockholm Environmental Institute. This model was developed as part of an ongoing collaborative project called "Reinventing Fire: China" between two U.S. research institutions, LBNL and the Rocky Mountain Institute, and the Chinese Energy Research Institute, the leading energy-related government think-tank that advises China's key policymaking body, the National Development and Reform Commission. This project adopts the "Reinventing Fire: U.S." methodology to develop a transformative pathway for China's building sector using updated and comprehensive baseline and transformative scenarios of Chinese building energy consumption to 2050.

China's residential buildings are modeled separately, with further distinctions by three major groupings of China's five climate zones, urban versus rural buildings, existing versus new buildings, and three retrofit versus two new building efficiency levels. As a bottom-up accounting model, our model calculates the future energy consumption of buildings, *ECB*, and the six individual types of end-uses in each residential type by using the following formula:

$$ECB = \sum_n \left\{ ACB_n \times \sum_q \left[P_{q,n} \times \left(\sum_k Intensity_{q,n} \times Share_{k,q,n} / Efficiency_{k,q,n} \right) \right] \right\} \quad (1)$$

Where:

k	Energy/technology type
q	End use
n	Building type
ACB_n	Floor space of building type n
$P_{q,n}$	Penetration of end use q of building type n
$Intensity_{q,n}$	Energy intensity of end use q of building type n
$Share_{k,q}$	The share of the k^{th} technology of end use q
$Efficiency_{k,q}$	Efficiency of the k^{th} technology of end use q

For all end-uses, including the appliances and water heating end-uses discussed in this paper, appropriate technology and fuel shares are assigned, with saturation (i.e., rates of penetration) and energy efficiencies based on historical statistical and survey data up to the base year (Tsinghua 2012) for urban and rural households. Future values are based on analysis of government plans, trends, and comparisons to other countries. In this study, both urban and rural households are included in the scope of the analysis, but electric water heaters and natural gas water heaters are not expected to be key water heating technologies in rural households. Instead, biomass and LPG stoves currently dominate and are expected to continue dominating water heating use in Chinese rural households. The distinctions for existing versus new buildings and for the different levels of retrofit versus new building design efficiency in our model are primarily intended to capture differences in heating, cooling and lighting usage and efficiency due to insulation and shell improvements and design changes (e.g., integrative or passive design) which do not directly impact residential appliances and water heating end-uses. Thus, the assumptions about appliance and water heating efficiency and technology shares are the same regardless of building vintage (existing vs. new) and retrofit/design levels. Similarly, because appliances[2] and water heating equipment usage do not vary significantly by climate zone, their energy use intensity per m^2 is also assumed to be the same across all climate zones. However, our energy use intensity assumptions do reflect expected changes in appliance ownership and usage trends including rising base energy intensity assumptions to reflect growing shares of larger refrigerators and TV screen sizes, more frequent operation of room air conditioner with lower temperature set-points and greater demand for heated water as household incomes rise.

KEY DATA INPUTS

For each of the six product types included in the scope of this study, we collected efficiency data and average cost data for two representative types of technologies:

1. Existing technology, representing our best estimate of the most common market-average efficiency model in the Chinese market, and
2. Superefficient technology, representing the most efficient technology model in the international market (including China) that is currently considered cost-effective.

Where possible, China-specific efficiency data and cost were obtained from online retail websites and other recent studies. If China-specific data were not found, U.S. efficiency and cost data for units with similar sizes and configurations were used as a proxy. The sections below review each product type and our assumptions for these two representative types of technologies.

2. Room air conditioners are an exception because its energy use intensity does vary by climate zone, with higher assumed intensity (kWh/m^2) in the warmer climate zones.

Refrigerators

China introduced the first MEPS for refrigerators in 1989, and the refrigerator MEPS has subsequently been revised three times since in 1999, 2003 and 2008. Since 2008, the average efficiency of new refrigerators has risen quickly as a result of the time lag in standard revision and because it was included as a product in the national subsidy program for energy efficient products launched by the central government from 2012 to 2013. The subsidy program has also significantly increased refrigerator sales, with annual sales doubling from 30 million units in 2008 to 64 million units in 2012 (CNIS 2013).

We assumed the existing technology model corresponds to the China Energy Label Level 5 efficiency level with the most common size of 270 liters of capacity and consuming roughly 1.2 kWh per day based on survey of products for sale online. An average unit energy consumption of 445 kWh/unit/year is estimated for this model with an estimated cost of 320 USD per unit from Letschert et al. 2012.

For the superefficient technology model, we referenced an U.S. ENERGY STAR model with similar size of 252 liters of capacity with estimated annual energy consumption of 352 kWh/unit/year and cost of 1,300 USD per unit.

Room air conditioners

Individual room air conditioners are the most common type of residential cooling devices in China. Average household ownership of room air conditioners, particularly in urban areas, rose quickly from less than 10 % in 1995 to 31 % in 2000 to 81 % in 2005 and 100 % in 2008 (NBS 2013). By 2012, the average urban household owned more than one unit per household, illustrating that room air conditioner usage is increasing significantly with rising household incomes. MEPS have been implemented in China for fixed-speed room air conditioners since 1989 with subsequent revisions in 2000, 2004 and 2010, and for variable-speed room air conditioners since 2008 with a recent revision in 2013. The most common type sold today is the variable-speed air conditioner with cooling capacity of less than 4,500 watts, with sales drastically increasing from only 2 million units sold in 2008 to 24 million units sold in 2012 (CNIS 2013).

In the absence of consistent Chinese data, we referenced the California Energy Commission (CEC)'s Database for Energy Efficient Resources (DEER) database for new residential split and packaged air conditioning units for the efficiency and cost assumptions for both our existing and efficient technology models. Based on the DEER database data for representative units, the existing technology is assumed to have an efficiency of 257 % with a cost of 64 USD per kBtuh while the superefficient technology is assumed to have an efficiency of 364 % with a cost of 170 USD per kBtuh.

Clothes washers

China introduced its first MEPS for clothes washers in 1989, with subsequent revisions in 2003 and most recently in 2013. The annual sales of clothes washer has remained relatively consistent over the last five years, with annual sales ranging from 31 to 38 million units sold between 2008 and 2012 (CNIS 2013). The market share of front-load washers, which consumes more energy but uses less water, has increased in recent years in the Chinese market, making it the dominant technology with a 58 % share in 2010 (CNIS 2013).

Based on the reported 2010 sales-weighted average efficiency and a rough 40/60 market split between top-load, vertical impeller and front-load, horizontal drum clothes washers in CNIS 2013, we estimated that the average existing technology model is 143 kWh/unit/year with an associated cost of USD 220 per unit. For the superefficient technology model, we referenced a similar Top Ten USA clothes washer with an annual average energy consumption of 90 kWh/unit/year and cost of USD 779 per unit (Top Ten USA 2013).

Televisions

Unlike other appliances, efficiency improvements in televisions are expected as a result of both MEPS and technology shift towards more efficient TVs illuminated by Light-Emitting Diodes (LED) instead of Cold Cathode Fluorescent Lamps (CCFL) used in most LCD televisions and the rapid phase-out of plasma and CRT TVs from the Chinese market. China's first MEPS for televisions was introduced in 1989 with a revision in 2006. But in 2010, China introduced a significantly revised standard that is specifically for flat panel TVs and this MEPS had to be quickly updated with a revision in 2013 due to the rapid turnover in the TV market. Thus, for our analysis, we focused on the two leading existing TV technologies of LCD and LED TVs and the emerging technology of organic LED illuminated TV displays.

For the existing technology model, our assumptions for the two dominant TV technology types are:

- LCD TVs: average energy consumption of 76 kWh/unit/year, based on market survey data as published in Park et al. 2011.
- LED TVs: average energy consumption of 58 kWh/unit/year, estimated based on the ratio of Energy Efficiency Index for LED to LCD TVs published in Park et al. 2011.

For the superefficient technology model, which is not expected to have notable market shares prior to 2015 because the technology is currently still undergoing commercial deployment in the global market, our assumption is that OLED TVs will be 40 % more efficient than the LCD TVs on the market based on their reported 40 % lower average power consumption compared to LCD displays (Wee et al. 2013).

For the base year of 2010, we used the published market shares by technology in Park et al. 2012 to calculate a sales-weighted average unit energy consumption.

We also make the additional assumption that TV screen size will grow bigger from its current average size of 33 inches as household income sizes. However, we assume the new average screen size of 40 inches by 2050 will be smaller than that of the average screen sizes internationally because of the much smaller average floorspace of the high-rise multi-story apartments that dominate Chinese residences.

Natural Gas Water Heaters

Instantaneous natural gas water heaters are a relatively new product to be covered by MEPS, with its first MEPS released in 2007. Its usage has risen quickly, particularly amongst large and medium cities, and is expected to continue rising given the government's recent efforts to promote the residential fuel switch to cleaner natural gas with targeted natural gas penetration rates of 94 % in the largest cities and 65 % in smaller cities by 2015 (CNIS 2013). Annual sales of natural gas water heaters have increased from 8 million units in 2008 to nearly 10 million units in 2012 (CNIS 2013). In the absence of available Chinese data, our assumptions for the existing and superefficient technology model efficiency and costs are taken from the CEC DEER database. Based on the DEER database for common units in new residential buildings, we assumed 60 % average efficiency with associated cost of USD 274 per unit for the existing technology model and 80 % average efficiency with cost of USD 707 per unit for the superefficient technology model (DEER 2013).

Electric Water Heaters

China introduced the electric water heater MEPS in 2008, and domestic sales of electric water heaters have grown rapidly since then. Annual electric water heater sales in China increased by 45 % between 2008 and 2012, growing from 13.1 million units sold in 2008 to 19 million units sold in 2012 (CNIS 2013). Part of this recent growth, particularly from 2011 to 2012, was driven by the national subsidy program for efficient products. Similar to natural gas water heater, we also based our assumptions for electric water heaters on common units in the DEER database for new residential buildings. The existing technology model is assumed to have average efficiency of 89 % and cost of USD 316 per unit, while the superefficient technology model is assumed to have average efficiency of 93 % and cost of USD 365 per unit (DEER 2013).

SCENARIO ANALYSIS

In order to evaluate the gap between the current efficiency levels with business-as-usual rates of improvement in the future and potential energy savings from full penetration of superefficient appliances by 2050, we developed a baseline and transformative scenario. The baseline scenario represents a business-as-usual pathway of development in which policies including MEPS in place by 2010 will continue to have an impact and autonomous technological improvements will occur, resulting in some adoption of the superefficient technology by 2050. In contrast, the transformative scenario assumes full adoption of the maximum technically feasible and cost-effective technologies by 2050. For all appliances and water heating end-uses, this means that under the transformative scenario, the current 100 % share of existing technologies in 2010 will shift to 100 % share of superefficient technology by 2050. TVs are modeled slightly differently because it is represented by three different technologies, so we assume changing market shares with accelerated shift towards 50 % OLED TVs by 2030 and 100 % by 2050 with complete phase-out of LCD by 2030 under the transformative scenario. Table 1 shows the average final energy intensity for each end-use technology (and weighted-average intensity for TVs) for the 2010 base value as well as the 2050 values under the two different scenarios, taking into consideration different shares of existing versus superefficient technologies and their respective different efficiencies.

More details on the overall modelling methodology for residential buildings, including the underlying assumptions for other end-uses, can be found in another eceee Summer Study paper (Zhou et al. 2015).

Table 1. Comparison of Final Energy Intensities by End-Use and Scenario.

	Energy Consumption Metric	2010 Base Value	2050 Reference Scenario	2050 Transformative Scenario
Refrigerators	kWh/unit/year	445	325.3	283.8
Room air conditioners	kWh/m²/year	5.9	16.1	13.3
Clothes washers	kWh/unit/year	143	140.8	109.1
Television	kWh/unit/year	77	100	88
Natural gas water heater	MJ/m²/year	9.4	41.9	35.6
Electric water heater	MJ/m²/year	9.4	46.7	45.5

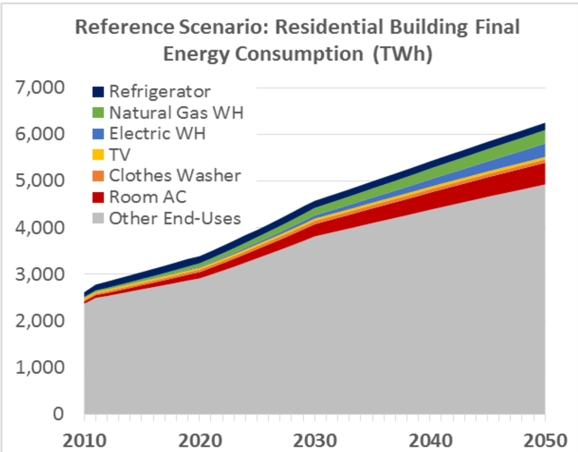

Figure 1. Reference Scenario Residential Energy Consumption, 2010–2050. Note: Other end-uses include all heating, cooking, and lighting end-uses as well as other minor cooling and water heating end-uses.

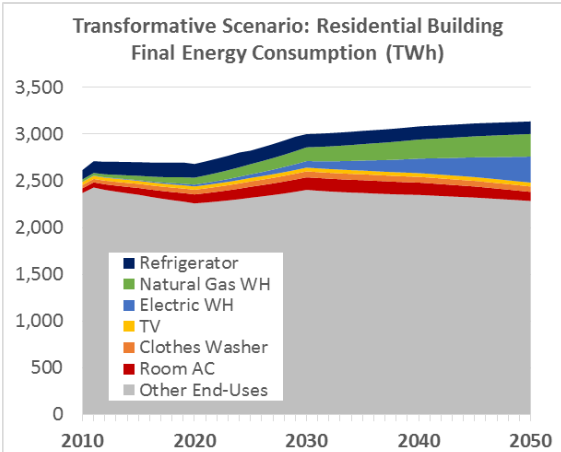

Figure 2. Transformative Scenario Residential Energy Consumption, 2010–2050. Note: Other end-uses include all heating, cooking, and lighting end-uses as well as other minor cooling and water heating end-uses.

Modeling Results and Discussion

TOTAL RESIDENTIAL ENERGY CONSUMPTION RESULTS

Under the Reference scenario, total residential building energy consumption will continue to grow from 2,617 TWh in 2010 to 6,256 TWh in 2050 as seen in Figure 1. The four major appliances and two major water-heating technologies modeled in this study contributes to a growing share of residential energy consumption, from 8 % and 1 %, respectively, in 2010 to 12 % and 9 %, respectively in 2050. The other end-uses include residential heating, which accounts for the largest share of residential energy consumption but is mostly provided by district heating boilers that are not regulated by MEPS, as well as cooking and lighting. The notable increase in water heating share of total residential energy consumption is due in part to the expected significant increase in demand for heated water as household incomes increase over time. Together, the annual final energy consumption of these four key appliances and two water heating technologies increases five-fold by 2050, rising from 246 TWh in 2010 to 1,324 TWh in 2050.

Under the transformative scenario where 100 % of the technologies in 2050 have reached the current superefficient level, the growth in residential energy consumption is much slower with the 2050 annual final energy consumption only slightly higher than the 2010 level. Total final energy consumption grows from 2,617 TWh in 2010 to only 3,137 TWh in 2050. This is due in part to significant efficiency improvements in the six selected products with 100 % adoption of superefficient technologies, but also due to reductions in heating, cooling and lighting loads and significant efficiency improvements in all other residential end-uses as discussed in greater detail in Zhou et al. 2015. The four major appliances and two major water-heating technologies modeled in this study contributes to higher share of residential energy consumption under this scenario by 2050, with shares of 11 % and 17 %, respectively. In absolute terms, the annual final energy consumption of these six selected products increases from 246 TWh in 2010 to 851 TWh in 2050. Compared to the 1,324 TWh consumed by these six end-uses in 2050 under the reference scenario, this represents a 36 % reduction in the final energy consumption of the six residential end-uses.

ENERGY SAVINGS POTENTIAL OF SIX KEY END-USES

Figure 3 shows the annual energy savings potential for each of the six major end-uses of adopting 100 % superefficient technologies by 2050, compared to the reference scenario of autonomous improvement. The energy savings potential steadily rises, from 54 TWh in 2020 to 165 TWh in 2030 to 307 TWh in 2050 and 473 TWh by 2050. Compared to the 2050 annual total building energy consumption of 6,256 TWh, the 2050 annual savings energy potential of these six key end-uses represent an 8 % reduction in final energy.

As shown in Figure 3, room air conditioners alone account for the majority of the total energy savings potential for these six products with a 78 % share in 2050. Although the incremental improvement in room air conditioner final energy intensity between the two scenarios appear relatively small with 3.2 kWh/m², it is actually very significant given the scale of China's total residential building floorspace area. By 2050, China is expected to have 49 billion m² of urban residential floorspace and 14 billion m² of rural residential floorspace (Zhou et al. 2015). The second end-use with significant energy savings potential is natural gas water heater, which contributes 10 % of the total energy savings potential by 2050. This is also because of the large scale of China's total residential floorspace, with natural gas water heaters providing heated water to 30 % of all urban residential floorspace by 2050, and because the incremental efficiency improvement from existing to superefficient technology is relatively large. Part of this energy savings potential, however, may be overestimated since the current analysis is based on the U.S. DEER database and may not necessarily representative of the Chinese market situation. Interestingly, electric water heaters – which account for 20 % of all urban residential floorspace by 2050 – has the smallest energy savings potential of the six selected products because the incremental improvement between the existing and superefficient technology is so small. Intuitively, this make sense because electric water heaters are already very efficient with an existing average efficiency of 89 %, and superefficient electric water heaters only reach a slightly higher efficiency level of 93 %. The other three end-uses, TVs, clothes washers and refrigerators also have relatively modest savings potential that are similar in magnitude. One reason is that the total expected stock of these devices by 2050 (i.e., scale of savings) is not as large as air conditioners and natural gas water heaters. Specifically, there is only a total expected stock of 603 million TVs, 402 million clothes washers and 400 million refrigerators across all residential households in 2050. Combined with their relatively low incremental improvement in final energy intensity, where some of the efficiency gains are offset by increased usage, refrigerators, TVs and clothes washers only account for 5 %, 3 % and 3 %, respectively, of the total residential energy savings potential in 2050.

In understanding the scale and magnitude of these potential savings, it is helpful to contextualize the electricity savings (excluding natural gas water heater savings) in terms of the avoided new electricity supply by comparing the electricity savings to the annual average electricity output of the Three Gorges Dam, the world's largest hydroelectric dam, and a typical 1,000 MW coal-fired power plant in China. Assuming an average capacity factor of 50 % and the total installed capacity of 22.5 GW, the Three Gorges Dam produces an average of 100 TWh of electricity annually. A typical 1,000 MW Chinese coal-fired power plant, assuming the 2010 average coal-fired power generation efficiency of 38 % and average capacity factor of 55 %, produces an average of 4.8 TWh annually.

Figure 4 compares the scale of the 2030 and 2050 annual electricity savings from full adoption of superefficient technologies for the five electric end-uses by 2050 with the two typical sources of electricity generation in China. By 2030, the annual electricity savings from these five superefficient technologies alone is equal to 1.5 times the output of the Three Gorges Dam, and 32 times the output of a typical 1,000 MW Chinese

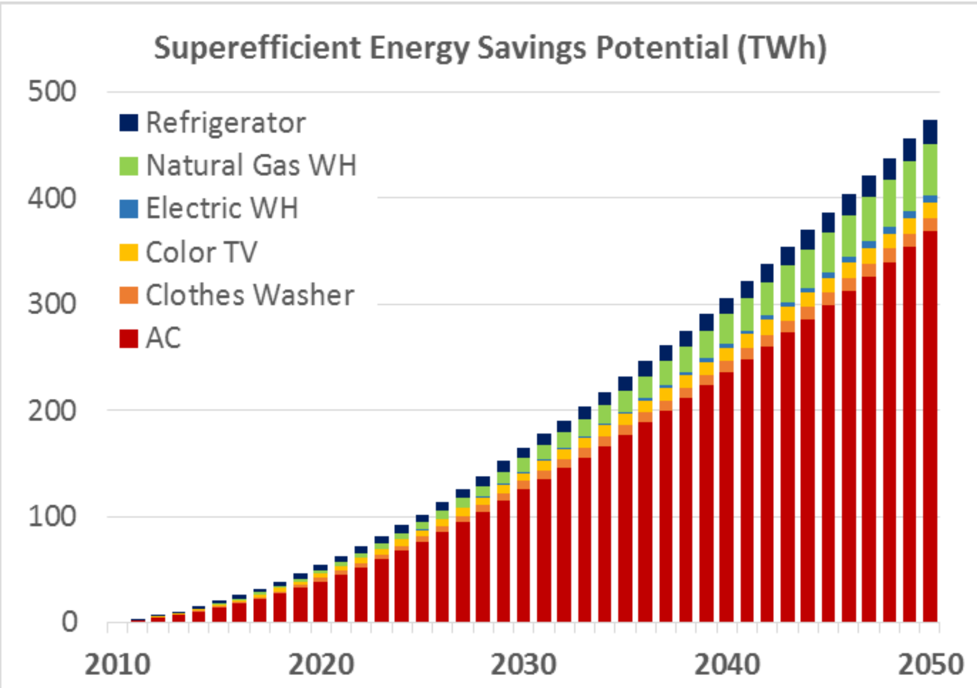

Figure 3. Annual Energy Savings Potential by Product under Transformative Scenario with Full Adoption of Superefficient Technologies, 2010–2050.

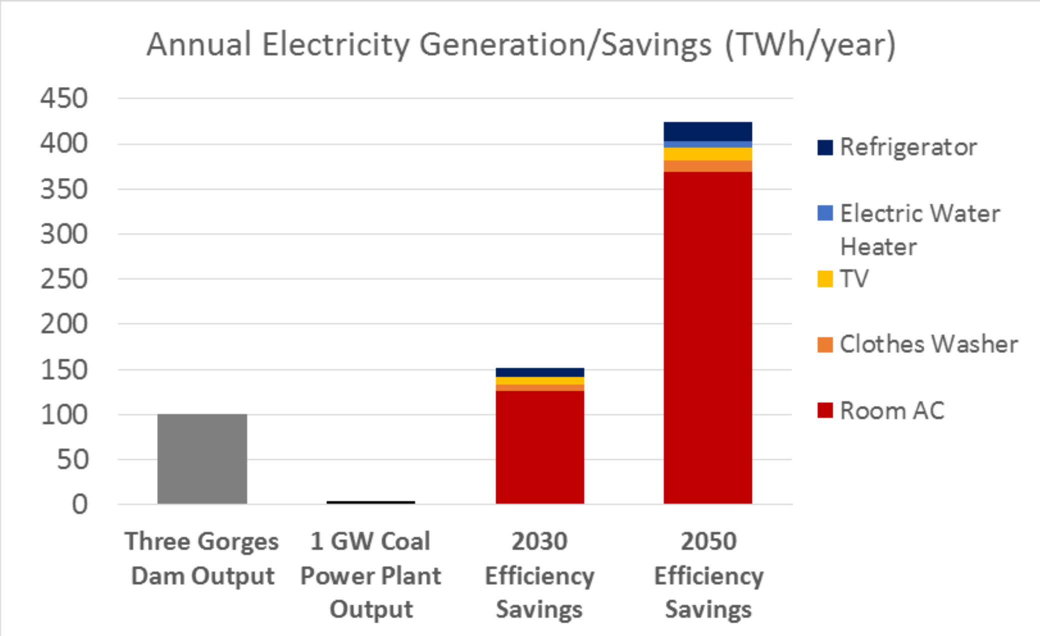

Figure 4. Comparison of 2030 and 2050 Electricity Savings for Selected Superefficient Electric End-uses under Transformative Scenario with Electricity Generation.

coal-fired power plant. By 2050, the annual electricity savings would offset the electricity output of four Three Gorges Dam equivalents, and 88 typical 1,000 MW Chinese coal-fired power plants. The large scale of these savings and avoided electricity generation for only five major residential end-uses show that adopting higher levels of efficiency that are still cost-effective for its MEPS revisions can result in significant energy impacts.

Conclusions and Next Steps

Although China has ramped up its MEPS program in the last few years, resulting in a notable total of 57 MEPS covering all major residential end-uses and lighting products as well as office, commercial and industrial equipment, funding and data limitations have resulted in significant untapped efficiency gains with each new MEPS revision. Because China sets its standards iteratively and typically eliminate only the bottom 20 % efficiency models on the market with each new or revised standard, there are still significant cost-effective efficiency improvement potential not captured by the current standards. Using a bottom-up energy end-use model, we developed two scenarios to represent a business-as-usual pace of autonomous technological improvement and a transformative pathway with 100 % adoption of current cost-effective superefficient technologies for six major end-uses by 2050. The full adoption of superefficient technologies by 2050 could be achieved with more aggressive and regular MEPS revisions that capture more of the cost-effective efficiency gains, which would require greater financial and technical capacities to support more detailed techno-economic analyses in the standard-setting process. The untapped efficiency gains could also be captured through more market-based mechanisms, such as the recent national subsidy program for the purchase of key energy efficient appliances. Likewise, the recent December 2014 announcement by the Chinese government of plans to implement a voluntary "Energy Efficiency Leaders" program that would help distinguish superefficient models on the China Energy Label with possible subsidies for superefficient products can further support market demand for more efficient products and strengthen the basis for more stringent MEPS.

We found that the four major residential appliances of room AC, TVs, refrigerator and clothes washer and the two major water-heating technologies of electric and natural gas water heaters account for 12 % and 9 %, respectively, of total annual residential final energy consumption by 2050. If 100 % adoption of superefficient technologies were achieved by 2050, the annual final energy consumption of these six major end-uses could be reduced by 36 %, or 473 TWh by 2050. The annual energy savings potential represents an 8 % reduction in total residential final energy consumption by 2050, representing the second biggest energy-savings opportunity in the residential building sector after passive design. Of the six end-uses, room air conditioners account for the majority of energy savings potential given its expected increase in ownership and usage across growing residential building stock that totals 63 billion square meters by 2050. Natural gas water heaters are also expected to result in the second largest savings potential due to its prevalence and relatively large uncaptured efficiency improvement potential. The other four end-uses have smaller energy savings potential, but total savings from the five electric end-uses (excluding natural gas water heaters) could offset the electricity output of four Three Gorges Dam equivalents or 88 GW of coal-fired power plants annually by 2050.

This current study faces a limitation in its economic analysis of the full adoption of superefficient equipment under the transformative scenario due to Chinese data availability that could be improved with more detailed analysis in the future. The cost and efficiency data for some (but not all) of the current cost-effective superefficient technologies were taken from the U.S. market due to a lack of available Chinese data. Although we only used data from U.S. technologies that are comparable to popular Chinese models in size, the cost data are nevertheless for U.S. products with the technology's cost-effectiveness defined by U.S. retail and electricity prices. If these technologies were produced and sold in the Chinese domestic market, the technology capital cost and energy prices would likely be different and could change the cost-effectiveness of specific technologies. However, we believe that these superefficient technologies would likely still be cost-effective, particularly in the future. On one hand, the capital costs and thus retail prices of the superefficient technologies are likely to be lower if they are produced in China due to lower labor costs. On the other hand, although Chinese residential electricity prices are currently relatively low, ranging from 0.06 USD/kWh to 0.10 USD/kWh in different provinces in 2011, because of government-set prices that subsidize residential electricity use, greater market reform in the power sector could result in gradually increasing residential electricity prices that are more on par with current U.S. levels. Actual Chinese data, which requires more time and budget to collect that is outside the scope of this study, would be needed to prove these two hypotheses. Having detailed Chinese cost data for all of the superefficient technologies would enable detailed cost-effectiveness analysis of the energy savings potential by technology, and can result in a cost-curve comparing the cost of conserved energy for the six products or net present value calculations of the energy saved by full adoption of the six superefficient technologies.

References

California Energy Commission. 2013. "DEER – Database for Energy Efficient Resources." Available from: http://www.energy.ca.gov/deer/.

China National Institute of Standardization. 2013. "White Paper for the energy efficiency status of China energy-used products 2013." Beijing: China Standards Press.

Li Pengcheng. 2012. Personal Communication, researcher at China National Institute of Standardization. 11 December 2012.

Letschert V, N Bojda, J Ke, M McNeil. 2012. "Estimate of Cost-effective Potential for Minimum Energy Efficiency Performance Standards in 13 Major World Economies – Energy Savings, Environmental and Financial Impacts." LBNL-5723E. Berkeley: Lawrence Berkeley National Laboratory. Available from: http://www.superefficient.org/Resources/~/media/Files/BUENAS%20CEP%20Scenario-%20LBNL-5723E.pdf.

National Bureau of Statistics of China (NBS). 2012. "China Statistical Yearbook 2012." Beijing: China Statistics Press.

Top Ten USA. 2013. "Top Ten USA Products." Available from: http://www.toptenusa.org.

Tsinghua University Building Energy Research Center. 2012. "China Building Energy Efficiency Development and Research Annual Report 2012." Beijing: China Construction Industry Press.

Wee T, T Okoshi, A Misra, R Balan. 2013. "Focus: A Usable & Effective Approach to OLED Display Power Management." Presented at the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing. Zurich: 8–12 September 2013. Available from: http://conferences.sigcomm.org/sigcomm/2012/paper/mobigames/p25.pdf

Zhou N, N Khanna, D Fridley, J. Romankiewicz. 2013. "Development and implementation of energy efficiency standards and labeling programs in China: Progress and challenges." LBNL-6141E. Berkeley: Lawrence Berkeley National Laboratory. Available from: china.lbl.gov/sites/all/files/china_sl_info.pdf

Zhou N, W Feng W, N Khanna, L Hong, D Fridley, E Franconi. 2015. "Transformative Pathways for Chinese Buildings by 2050." Paper accepted for the 2015 eceee Summer Study on Energy Efficiency.

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