Superefficient Refrigerators: Opportunities and Challenges for Efficiency Improvement Globally

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ABSTRACT

As an energy-intensive mainstream product, residential refrigerators present a significant opportunity to reduce electricity consumption through energy efficiency improvements. Refrigerators expend a considerable amount of electricity during normal use, typically consuming between 100 to 1,000 kWh of electricity per annum. This paper presents the results of a technical analysis done for refrigerators in support of the Super-efficient Equipment and Appliance Deployment (SEAD) initiative. Beginning from a "base case" representative of the average unit sold in India, we analyze efficiency improvement options and their corresponding costs to build a cost-versus-efficiency relationship. We then consider design improvement options that are known to be the most cost effective and that can improve efficiency given current design configurations. We also analyze and present additional "super-efficient" options, such as vacuum-insulated panels. We estimate the cost of conserved electricity for the various options, allowing flexible program design for market transformation programs toward higher efficiency. We estimate ~160TWh/year of energy savings are cost effective in 2030, indicating significant potential for efficiency improvement in refrigerators in SEAD economies and China.

Introduction

Global household refrigerator sales are estimated to be more than 100 million units per year (Heinzelmann 2007). Refrigerators are an energy-intensive mainstream product in many economies globally. Refrigerators are also often one of the first assets, after a television, that a typical low-income household acquires with increasing wealth. (Wolfram, 2012) Furthermore, refrigerators are a long-lived consumer good, with lifetimes on the order of 15 years in some instances, and they therefore have a substantial impact on both energy consumption and greenhouse gas emissions for many years.[1]Further, since base load power[2] is often provided by coal or nuclear power, reducing the need for such power plants through refrigerator efficiency improvement has implications both in terms of climate as well as nuclear safety.[3]
While there is a large body of technical and economic analysis on options to improve the

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[1] The United States Department of Energy (DOE) found a median lifetime of 16.2 years for standard-size refrigerator-freezers in the standards issued on September 15, 2011. (DOE, 2011)
[2] In households owning refrigerators these appliances likely constitute a "baseload" for the electricity grid. For example, a load survey in India, Garg et al. (2010), found that while load from other appliances varied throughout the day, load from refrigerators was constant and even over time.
[3] See http://www.eia.gov/todayinenergy/detail.cfm?id=1710 for an example of how coal-fired and nuclear-fired power plants are used to provide base load power.

efficiency of refrigerators, much of this detailed analysis has focused on developed economies such as the US, Europe, Japan and Australia. For example, recent analyses were conducted by the US Department of Energy (2011), European Ecodesign Initiative (2007-08), Australia's Department of Climate Change and Energy Efficiency (2007), and Japan's Top Runner program (2006). While these studies lay out possible energy efficiency improvement options and the corresponding savings potential in those economies, these are not applicable to other economies, particularly in the developing economies, due to differences in sizes, test procedures, electricity costs, and other local economic conditions.

In this paper, we present the results of a study of household refrigerator efficiency conducted in support of the Super-efficient Equipment and Appliance Deployment (SEAD) initiative and commissioned by the U.S. Department of Energy. [4]

We discuss energy efficiency improvement options that are possible given the most common refrigerator designs currently available in the various SEAD economies. [5] We then estimate the corresponding cost-effective and total energy savings potential in these economies. Finally, we provide insights and recommendations for policies and programs that can help to realize these energy savings, accelerate the penetration of efficient refrigerators, and reduce the electricity demand from these appliances.

Current Status of Global Refrigerator Efficiency Levels and Related Policies

In this section we discuss broad overarching trends in technology and energy consumption in the global refrigerator market and the current status of refrigerator efficiency programs in various countries.

Trends in Technology

The global household refrigerator market is dominated by refrigerator-freezer combinations with a bottom freezer (RF-BF) and refrigerator-freezer combinations with a top freezer (RF-TF). Based on an internet survey conducted by the authors, Table 1 below presents the percentage of dominant household refrigerators in each market. In Australia, Brazil, India, Indonesia, Mexico, and UAE, RF-TF is the dominant type and comprises a range of 40% to 55% of the market. In China, EU, Japan, and Russia, RF-BF is the dominant type and accounts for a range of 41%-76% of the market.

[4] As an initiative of the Clean Energy Ministerial and a task within the International Partnership for Energy Efficiency Cooperation, the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative seeks to engage governments and the private sector to transform the global market for energy-efficient equipment and appliances. SEAD was first announced in December 2009 and launched as a $20 million Initiative in July 2010. SEAD aims to leverage high-level political dialogue to advance on-the-ground appliance and equipment efficiency efforts in targeted markets around the globe.

[5] As of March 2014, 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/

Table 1. Percentage share of dominant household refrigerators (2012)

Country	Most dominant type	Other dominant type
Australia	RF-TF (40%)	RF-SS (21%), RF-BF (17%)
Brazil	RF-TF (47%)	RF-BF (16%)
Canada	RF-FD (29%)	RF-BF (22%), RF-TF (22%)
China	RF-BF (76%)	RF-SS (10%)
EU	RF-BF (41%)	R-refrig (24%), RF-com (21%)
India	RF-TF (43%)	RF-com (29%)
Indonesia	RF-TF (55%)	RF-com (20%)
Japan	RF-BF (47%)	RF-FD (38%)
Korea	RF-SS (46%)	RF-TF (22%)
Mexico	RF-TF (51%)	RF-com (23%)
Russia	RF-BF (57%)	R-refrig (13%)
South Africa	RF-BF (32%)	RF-com (19%)
UAE	RF-TF (49%)	RF-BF (21%)
USA	RF-TF (32%)	RF-SS (28%), RF-FD (26%)

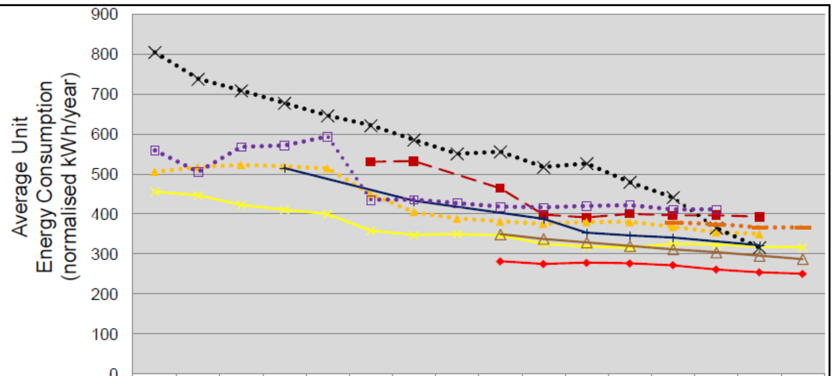
RF-BF Refrigerator-Freezer Combination – Bottom Freezer
RF-Com Refrigerator-Freezer Combination – Compact
RF-FD Refrigerator-Freezer Combination – French Door
RF-SS Refrigerator-Freezer Combination – Side by Side
RF-TF Refrigerator-Freezer Combination – Top Freezer
R-Refrig Refrigerator only

Source: Internet Sales Survey by authors, 2012

Trends in Energy Consumption

According to a benchmarking report recently updated by an IEA working group[6] (IEA 4E, 2014), an average annual improvement of 2.6% in unit energy consumption (UEC) was observed in all countries studied (see Figure 1). The report found that average UECs decreased from a range of 450-800 kWh/year in 1996 to a range of 250-400 kWh/year in 2011. EU countries appear to have lower normalized average UECs compared to North American countries and Australia. Meanwhile, Japan moved from an average UEC above 800 kWh/year in 1996, to an average UEC for new units only slightly above 300 kWh/year by 2010.[7] These trends indicate a significant potential for efficiency improvement exists in economies that have not yet reached similar levels (i.e 250-300 kWh/year) based on commercially available technology.

[6] The International Energy Agency Implementing Agreement on Efficient Electrical End-use Equipment
[7] Some of the difference in UECs between countries stems from the different average sizes in these markets or different configurations, with average sizes in North America being about 1.5-2 times average sizes in Asian countries and Europe. Since this paper presents analysis for different sizes (assumed to be typical) in each market, the results shown here only hold in the country for which the analysis is being presented and not for other countries with a different average size of refrigerator. Table 4 below shows the assumed typical sizes and UECs in the various countries studied.



	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Australia (SWA)						530	532		465	398	391	401	396	397	392	
Austria (SWA)									281	274	277	276	272	261	254	250
Canada (SWA)	506	517	523	519	515	450	405	388	381	375	379	380	367	354	350	
Denmark (SWA)	456	447	423	411	400	358	347	350	347	325	318	315	325	324	317	317
Japan (SWA)	805	738	709	678	647	622	586	551	556	518	527	480	442	365	316	
UK (SWA)				515			433			388	353	346	341		321	
USA HEM (PWA)	559	506	568	572	594	436	436	428	418	417	420	423	412	412		
EU (SWA)									349	338	329	320	312	304	296	288
USA NPD (SWA)													378	374	367	366

Solid line = robust data Dashed line = indicative data Dotted line = illustrative data

Figure 1. Normalized[8] average unit energy consumption (UEC) of new refrigerator/freezer combination. *Source:* IEA 4E, 2014.

Trends in Energy Efficiency Regulation

Refrigerated appliances are typically among the first appliances to be regulated for energy efficiency due to the fact that they are among the first energy-intensive appliances bought as a household acquires increasing wealth. (Wolfram, 2012, CLASP) Mandatory requirements for labelling and/or minimum energy performance standards (MEPS) began to be introduced in some countries in the 1970s and 1980s. Table 2 summarizes MEPS programs for refrigerators and refrigerator-freezer combinations currently in place in major economies. In a recent report, an IEA working group found that major mandatory policy interventions continue, and actually appear to be accelerating (IEA 4E, 2014). This makes the information presented here useful and relevant for countries in setting stringent efficiency standards and labels.
Meanwhile, in Japan, the 'Top Runner' program was established in 1999 and has been revised several times since then.[9] In addition to this mandatory regulatory framework, many countries have voluntary labelling to identify premium products (e.g., ENERGY STAR in North America). Table 3 summarizes the various mandatory and voluntary as well as categorical or endorsement labelling[10] programs for refrigerators and refrigerator-freezers in the SEAD economies and China.

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[8] Declared UECs in various countries or regions can be misleading due to the differences in test methodologies. See the IEA 4E Benchmarking Document for Domestic Refrigerated Appliances (IEA 4E, 2014) for more details on the normalization methodology applied to the figure shown.
[9] The Japanese Top runner program, in place since 1999, sets mandatory energy efficiency standards. However, these are not "minimum energy performance standards" or MEPS unlike other economies, but standards where the "corporate average" is evaluated, allowing some flexibility, but also encouraging premium products onto the market.

Table 2. Minimum Energy Performance Standards (MEPS) for refrigerators and refrigerator-freezers in SEAD economies and China *Source:* CLASP Global S&L Database

Country	Type	Effective Date	Appliances Covered
Australia	M	2010	Refrigerators, refrigerator-freezers
Brazil	M	2011	Refrigerators, refrigerator freezers, and wine chillers
Canada	M	2001	Refrigerators, refrigerator freezers
China	M	2009	Refrigerators
European Union	M	2013	Refrigerators, refrigerator-freezers
Indonesia	M	2005	Refrigerators, refrigerator-freezers
Japan	Top Runner	2006	Refrigerators, refrigerator-freezers
Korea	M	2004	Refrigerators, refrigerator-freezers
Mexico	M	2013	Refrigerators, refrigerator-freezers and freezers
South Africa	M	TBD	Refrigerators, refrigerator-freezers
United States	M	2014	Refrigerators, refrigerator-freezers

M- Mandatory, V-Voluntary

Table 3. Labeling programs for refrigerators and refrigerator-freezers in the SEAD economies and China *Source:* CLASP Global S&L Database.

Country	Label	Effective Date	Appliances Covered
Australia	MC	2010	Refrigerators, freezers and refrigerator-freezers
Brazil	VE(2010), MC(2006)		Household refrigerators, freezers and combined refrigerator-freezer
Canada	VE(2010) MC(2001)		Refrigerators, refrigerator-freezers
China	VE(Ref and ref-freezers<500L) MC (refrigerators)	2010	Refrigerators, refrigerator-freezers
EU	MC	2012	Refrigerators, refrigerator-freezers
India	MC and VC	2014	Refrigerators, refrigerator-freezers
Indonesia	VC	2012	Refrigerators, refrigerator-freezers
Japan	MC	2006	Refrigerators, refrigerator-freezers
Korea	MC	2009	Refrigerators, refrigerator-freezers
Mexico	VE(2012), MC(2013)		Refrigerators, refrigerator-freezers
Russia	MC	2011	Refrigerators

[10] Categorical labels typically use a step ranking system to relative energy use of the model compared to other similar models(e.g. 1-star to 5-star, or A through F), while endorsement labels such as ENERGY STAR label indicate that the product is among the most energy efficient on the market without differentiating further. Endorsement labels may or may not be linked to categorical labels.

Country	Label	Effective Date	Appliances Covered
South Africa	MC	2005	Refrigerators, refrigerator-freezers
UAE	MC	2012	Refrigerators
US	MC, VE	2014	Refrigerators, refrigerator-freezers

M-Mandatory, V-Voluntary, C- Categorical Label, E- Endorsement Label.

Many standards and labelling programs that have been in place for a number of years are now due for revision, making the information presented here useful and relevant. In the next section, we discuss various energy efficiency improvement options for refrigerators.

Techno-economic Analysis of Efficiency Improvement Options for Refrigerators

We used two different and well-established software tools for refrigerator energy consumption to simulate the impacts of design changes. The US Environmental Protection Agency (EPA) Refrigerator Analysis (ERA) model is used for frost-free appliances, and the SIMARM tool is used for direct-cool appliances. ERA has previously been used to conduct all the refrigerator energy-engineering analyses in the US DOE's rulemaking analyses, whereas SIMARM is a proprietary refrigerator energy and thermal performance simulation tool that has been used to design refrigerators commercially and has been demonstrated to produce very reliable results for direct-cool appliances.

The base case is defined as a standard model, which is a typical RF-TF or RF-BF found in each country but is not the least efficient kind of product one can find on the market. Thus the analysis starts from a typical or mid-market point for much of the household refrigerator market.[11]

The base model specifications of refrigerators that form the majority of household refrigerators in every country varies from an electricity consumption of 273 kWh per year in China to 747 kWh per year in Russia and South Africa, as shown in Table 4 below. Even though the data presented in Table 4 are illustrative and cannot be compared directly *across countries* due to lack of availability of overlapping data sets, minor differences in test procedures and different average sizes, the data illustrate the large scope for energy efficiency improvement possible in many of the economies studied, particularly when compared with the levels identified in Figure 1 above.

[11] The approach taken is to analyze each market to determine the *most common type* of refrigerator sold on the market, where such data is available, identified during the internet survey referenced in Table 1. The characteristics of the predominant type are then analyzed to establish a base case model. The principle applied is to select a base case model that has the same (or as near as is possible from the models on the market) compartment volumes as the market average. The model is also selected to have an energy efficiency that is at, or somewhat lower than, the market average so that the impact of successive higher efficiency design changes described in the section titled "Design Options to Improve Energy Efficiency" pass through the spread of the efficiency of products found on the market.

Table 4 Annual unit energy consumptions of base model refrigerators in various economies in 2012
Source: Author's assumptions based on internet surveys in each economy.

Country	Type	Average Volume (Liters)	Unit Energy Consumption (KWh per year)
Australia	RF-TF	290	481.1
Brazil	RF-TF	288	611.4
Canada	RF-TF	382	513.6
China	RF-BF	111	273.4
EU	RF-BF	196	412.5
India	RF-TF	239	580.7
Indonesia	RF-TF	209	453.7
Japan	RF-BF	182	476.7
Korea	RF-TF	285	470.9
Mexico	RF-TF	227	503.7
Russia	RF-BF	225	746.8
South Africa	RF-BF	184	746.8
UAE	RF-TF	298	609.9
USA	RF-TF	382	513.6

Note: RF-TF (Refrigerator-Freezer Combination – Top Freezer), RF-BF (Refrigerator-Freezer Combination – Bottom Freezer)

To estimate costs of refrigerators with increasing efficiency above the base case models outlined in Table 4 above, local labor, supply chain markups, installation and maintenance costs, energy costs and capital costs are all adjusted for local economic conditions, based on a combination of sources such as literature, estimated factory gate costs, retail prices, expert contacts and official statistics.

The approach outlined above generates cost versus efficiency curves for each economy, including manufacturer (or factory gate) costs and costs to the end user at each level of efficiency corresponding to a design change. The efficiency levels are calculated using climate specific and local hours of use data, generating different efficiency levels for the same model in different economies.

Note that the analysis presented in this paper provides initial estimates of costs for various levels of efficiency improvements and is likely to need further refinement and validation in order to be used for program design purposes.

Design Options to Improve Energy Efficiency

Various options to improve refrigerator efficiency exist, including the following:

- optimization of capillary tube characteristics
- optimization of thermostatic control including use of electronic control
- optimization of evaporator characteristics
- optimization of condenser characteristics
- use of a higher efficiency compressor
- increasing insulation thickness and
- using vacuum insulation panels (VIPs)

In Table 5 below, we show an example of region-specific options for India, the corresponding energy consumption, savings (%) compared to the base case, and costs. A fuller presentation of the complete results of this analysis will be shown in a forthcoming report. (Shah et al). If the efficiency improvement options shown in Table 5 are employed, then the higher efficiency refrigerator could save between 9-85% of energy compared to the base case model in India.

Table 5 Efficiency improvement options and corresponding energy savings for India *Source:* Shah et al.

Option #	**Change from previous option**	**Energy Consumption kWh/year**	**% Energy Savings from Base Case**	**Incremental Cost from Base Case (Rs)**
Base case	Samsung RT35BD (fresh-food compartment= 239 litres, frozen food compartment= 80 litres, energy consumption 399kWh/yr.)	580.7	0%	0
1	Insulation in freezer walls/door = 60mm.	529.6	9%	46
2	Insulation in freezer walls/door = 80mm and in fresh-food compartment doors/walls to 60mm.	405.9	30%	101
3	Replacement of EER = 4.4 compressor with EER=6.0 compressor	202.2	65%	3410
Design options with less certain impacts				
4b	As Option 3 with 90mm in freezer compartment and 65mm in fresh-food compartment and with optimised gaskets	138.3	76%	3807
5b	As Option 4b with maximum VIPs	95.6	84%	4677
6b	As Option 5b with ER=6.57 compressor	86.1	85%	16095

Note: Efficiency improvement options used in the study for other SEAD countries vary from those shown above.

Efficiency improvement design options employed in other countries also showed similarly that energy consumption could be reduced from the base case model considered in the economy by between 50-90% if the best available technology options are used. In the next section we present cost-effectiveness calculations for the various energy efficiency design options considered in these economies.

Cost-Effectiveness of Efficiency Improvement

In this section, we discuss the calculation method and the results of the analysis of cost effectiveness of the options.

The cost-effectiveness metric used in the analysis presented here is the cost of conserved electricity (CCE), which is calculated by dividing the incremental cost of a design change by the incremental energy saved by the design change. The design change is considered with respect to a design corresponding to the market average efficiency level in each economy. The cost of conserved electricity is calculated as the cost to the end user or consumer of conserved electricity, which considers the incremental cost of the higher efficiency model to the consumer or end user, i.e. considering the difference in retail prices between the baseline and the more efficient model.

The CCE is then calculated for each economy at various efficiency levels as follows:

CCE = (Annualized incremental cost to consumer of efficient refrigerator ($))/(Annual electricity consumed by average refrigerator-Annual electricity consumed by efficient refrigerator (kWh))[12]

The energy efficiency metric used in the analysis presented here is the Energy Efficiency Index (EEI). The Energy Efficiency Index (EEI) is a dimensionless metric of the efficiency of the refrigerator which accounts for differences in capacity or other factors by comparing the annual energy consumption of the refrigerator to a reference consumption that is based on the refrigerator and freezer storage volume.[13] Lower EEI implies higher efficiency.

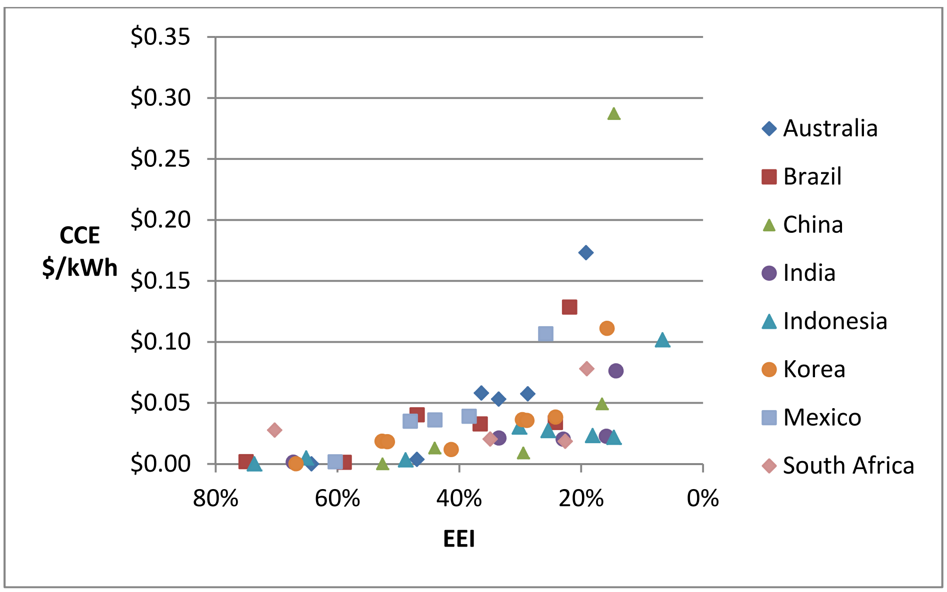

Figure 2. Cost of Conserved Electricity (CCE) versus efficiency for refrigerators in various economies
Source: Authors' calculations.

[12] A lifetime of 10 years is assumed, while an economy specific discount rate is used for these calculations. For example, the discount rate used for India is 8%.

[13] EEI = Annual Energy Consumption/Standard Annual Energy Consumption, where the Standard Annual Energy Consumption is defined based on various factors including the type of the appliance, the volumes of the various compartments and the design temperatures of the compartments. See http://www.legislation.gov.uk/uksi/2004/1468/schedule/5/made for an example of the equations used for defining Standard Annual Energy Consumption in the UK.

Figure 2 above shows the CCE versus the energy efficiency index for the different efficiency improvement options discussed in the earlier section for selected SEAD economies.

As shown in Figure 2, it appears that EEI levels of between 20-30% are cost-effective for many economies. The cost effective level is identified by comparing the electricity tariffs in these economies to the corresponding cost of conserved energy. For example in India, the electricity tariff of about $0.04/kwh would lead to an EEI of ~20% being cost-effective. In fact, our results indicate that the efficiency level of the best available technology on the market (typically vacuum insulation panels) and the cost effective efficiency level are only about 10-15% apart in terms of EEI (not in terms of cost!) for most economies. In other words one can go a long way toward the best available technology, cost-effectively. However, deploying the best available technology itself is still cost-prohibitive. In the next section we discuss the energy savings potential available from cost-effective efficiency improvement as well as the savings potential if the best available technology is adopted.

Energy Savings Potential from Efficiency Improvement

We estimate energy savings potential based on the best available technology for efficiency improvement and the cost-effective energy efficiency improvement options discussed above. The savings potential is calculated using the Bottom-Up Energy Analysis System (BUENAS) developed by Lawrence Berkeley National Laboratory (McNeil et al. 2013). In order to forecast the number of refrigerators being used, sales and stock from the BUENAS model were used, but were scaled down to the segment of the market which the baseline model represents. For example, the product class of the baseline model in India is a frost-free refrigerator with a top-mounted freezer, with a volume and annual energy consumption typical of the product class. BUENAS's dataset already contained frost-free sales, so we needed to scale down the numbers to only represent the top-mount market. Each country's refrigerator sales were scaled to account for the type of freezer-mount, the model's volume, and energy consumption.

Our final energy demand is modeled from 2010 to 2030. The efficiency scenarios assume that the baseline refrigerator technology is sold until 2015, when all refrigerator sales become the target efficiency design.

As shown above in Figure 3 below, we estimate that if cost effective energy efficiency improvement options are adopted in the SEAD economies and China, annual energy savings of about 160 TWh would be achieved in 2030. For best available technology improvement options, a savings of about 174 TWh is possible in 2030. Also, as discussed earlier, our results indicate that the efficiency level of the best available technology on the market (typically vacuum insulation panels) and the cost effective efficiency level are only about 10-15% apart in terms of EEI for most economies.

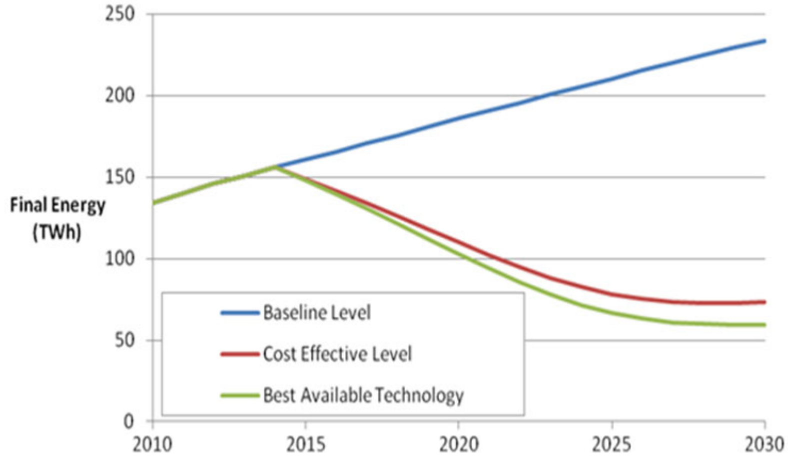

Figure 3. Energy consumption by refrigerators from sales in 2010-2030 in the SEAD economies and China.
Source: Authors' calculations.

Conclusions and Implications for Market Transformation Programs

Residential refrigerators are often one of the first appliances to be regulated in terms of energy performance and energy efficiency standards and labelling programs targeting residential refrigerators and refrigerator-freezers are in place in nearly every economy studied. The research presented here aims to answer whether there are uncaptured opportunities for energy savings from efficiency improvement of residential refrigerators and to quantify these opportunities.

We draw the following conclusions based on the analysis presented here:

First, MEPS and labelling programs in some economies (notably, Japan) have achieved significant energy efficiency improvements to reduce annual energy consumption in standard refrigerator-freezers to a unit energy consumption of ~250-300kWh/year. This indicates there may be significant potential to capture spill-over energy savings benefits from such commercially available technology.

Second, using the best available technologies e.g. vacuum insulation panels could achieve energy consumption levels ~90% below the baseline levels in many economies, incidating large technically feasible energy savings potential remains uncaptured.

Third, the levels of cost-effective efficiency improvement in most economies are only about 10-15% away (in terms of EEI) from the best available efficiency possible using commercially available technology. However, these best available efficiency levels are still much further away in cost terms, indicating that while much of the technically feasible potential can be captured cost-effectively, the figurative "last mile" is much more cost-prohibitive. This also seems to indicate diminishing returns in terms of energy efficiency policymaking after the cost-effective potential has been captured.

Fourth, if cost-effective energy efficiency levels are adopted in the SEAD economies and China, energy savings of ~160 TWh/year would be achieved in 2030, indicating significant potential for energy efficiency improvement. As discussed earlier, refrigerator efficiency improvement programs are particularly important for base-load energy consumption reduction, and will thus have a disproportionate impact in terms of climate as well as nuclear safety.

Finally, many standards and labelling programs have been in place for a number of years, and need to be revised in order to capture the benefits outlined above from commercially available technologies.

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