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Perspective

Improving energy performance metrics to maximize the benefits of disruptive technologies

Won Young Park [a,*], Nihar Shah [a,*], Kenji Shiraishi [b], Edward Vine [a]

[a] *Lawrence Berkeley National Laboratory, United States of America*
[b] *University of California, Berkeley, United States of America*

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ABSTRACT

Advances in appliance and equipment systems' technologies also cause changes in their technical characteristics that can affect energy consumption and associated greenhouse gas emissions. Energy performance evaluation methods that use testing and metrics can evolve to account for energy consumption contributed from new technological characteristics. However, there is no systematic effort to enable the advancement of test procedures and performance metrics to maximize the energy, climate, and financial benefits of disruptive technologies. Therefore, it is important for countries to regularly update their energy-efficiency policy programs, such as standards and labels, by improving test procedures and metrics to reflect the innovation in emerging technologies as well as to mitigate the risk of deploying obsolete technology. This paper shows how energy performance metrics have been improving in selected appliances and equipment and provides insights to design a systematic effort to improve metrics and test procedures at the speed of ongoing changes in technologies and markets.

1. Introduction

The energy sector accounts for nearly three-quarters of the greenhouse gas (GHG) emissions estimated to have already contributed to the increase in global average temperatures by 1.1 °C since the pre-industrial age [1]. There is a general consensus that the current policy trajectory is inadequate to keep the global average temperature rise well below 2 °C [2,3]. Such a 1.5 °C- or 2 °C-compatible trajectory will require a much faster deployment of disruptive clean energy and energy-efficient technologies. Among various GHG mitigation measures, improving energy efficiency (EE) in electricity use is critical to lowering future energy demand and associated emissions. This is particularly true in the buildings sector, which has the largest savings potential and requires EE policies, such as minimum energy performance standards (MEPS), to be upgraded significantly faster than in the past to move toward the best available technologies (BATs) [1]. Such a transition to emerging technologies also requires a systematic effort to improve metrics and test procedures at the speed of ongoing changes in technologies and markets.

Many companies will consistently lead their industries in developing and commercializing new technologies, as long as those technologies meet the performance needs of their customers and comply with regulations [4]. In response to emerging or disruptive technologies, such companies undertake efforts to increase EE in appliances and equipment systems and approaches to measure their energy performance. For example, solid-state lighting (SSL) technology, such as light-emitting diodes (LEDs), is fundamentally different from conventional lighting technologies, such as incandescent and compact fluorescent light (CFL). Market penetration, measured in sales of LED lights globally, increased from about 2% in 2012 to 46.5% in 2019; penetration is expected to be about 90% by 2030 [5]. The SSL technology has challenged many traditional lighting performance metrics used for assessing color quality. In some cases, it has exposed the need for new metrics to effectively balance color quality and energy efficiency in a variety of lighting applications [6].

Another example is in the global television (TV) market transition.

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* Corresponding authors.
E-mail addresses: wypark@lbl.gov (W.Y. Park), nkshah@lbl.gov (N. Shah).

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Table 1
ISO test conditions for cooling efficiency in ACs.

ISO 5151: 1994/2010/2017			ISO 16358-1: 2013			16358-1: 2013/Amd 1:2019		
EER			CSPF (moderate climate)			CSPF (hot climate)		
Part load (%)	Outdoor DB/WB Temp. (°C)	Indoor DB/WB Temp. (°C)	Part load (%)	Outdoor DB/WB Temp. (°C)	Indoor DB/WB Temp. (°C)	Part load (%)	Outdoor DB/WB Temp. (°C)	Indoor DB/WB Temp. (°C)
Full (T1)	35/24 [RH 40%]	27/19 [RH 46%]	Full	35/24 [RH 40%]	27/19 [RH 46%]	Full	46/24 [RH 15%]	29/19 [RH 38%]
Full (T2)	27/19 [RH 46%]	21/15 [RH 52%]	Half			Half		
Full (T3)	46/24 [RH 15%]	29/19 [RH 38%]	Min[a]			Min[a]		
No outdoor temperature bin hours applied.			Full	29/19 [RH 39%]	27/19 [RH 46%]	Full	35/24 [RH 40%]	27/19 [RH 46%]
			Half			Half		
			Min[a]			Min[a]		
			ISO standard outdoor temperature bin hours are defined between 21 °C and 35 °C with total 1817 h.			Full	29/24 [RH 66%]	27/19 [RH 46%]
						Half		
						Min[a]		
						ISO standard outdoor temperature bin hours are defined between 21 °C and 46 °C with total 6493 h.		

DB = dry bulb, WB = wet bulb, RH = relative humidity.

[a] According to ISO 16358-1:2013 and ISO 16358-1:2013/Amd 1:2019, minimum-load operation is defined as the operation of the equipment and controls at minimum continuous capacity.

Source: Updated from [21].

The penetration of large size flat-panel-display (FPD) technologies, such as liquid crystal display (LCD), into the global TV market increased significantly in the late 2000s, replacing traditional cathode ray tube (CRT) TVs as analog broadcast phased out [7]. Also, in the early 2010s, the rapid improvement in LED technologies drove the adoption of LED backlights for LCD TV applications. Cold cathode fluorescent light (CCFL) backlit LCD TVs accounted for 62% of sales in 2010, but LED-backlit LCD TVs replaced them, representing about 75% of sales in 2014 [7]. Because the FPD technologies, such as LCDs and organic light-emitting diodes (OLEDs), are fundamentally different from the traditional CRT technology, performance metrics appropriate for large digital FPD technologies needed to be developed [8,9].

Global cooperation on the production and distribution of energy-efficient appliances and equipment systems can reduce costs to consumers by facilitating policy coordination, driving technological innovation, and increasing economies of scale [10–13]. However, a regional decision or international process for establishing EE evaluation methods, including test standards and performance metrics, still takes too long to keep up with the pace of technological change, losing the opportunity to effectively capture the savings potential in BAT or disruptive technologies. Moreover, energy performance metrics are as important as test procedures in EE policy programs but have received little international attention [12]. However, some researchers and companies may not be fully aware of the benefits of appropriate evaluation methods and may have concerns about too technically complicated or less practical ways of performance evaluation. Nonetheless, clear, consistent, and accurate test methods and energy performance metrics help policy makers understand what drives energy performance, formulate meaningful performance goals, and track progress toward those goals, and they encourage manufacturers to develop and deploy more efficient appliances and equipment systems [14].

It is an encouraging trend that a recent European Union (EU) strategy emphasizes in an urgent manner that its standardization must respond to an increasingly rapid innovation pace and needs to deliver standards in a timely manner [15]. Policy efforts must be changed to enable faster and better responses to such technological changes, while maintaining quality-assured policy outcomes rather than hampering such innovation trends. Advancement in energy performance testing and metrics for products and systems can be aligned with a broader range of evaluation, measurement, and verification (EM&V) activities. The remainder of this article discusses one example that shows current issues and ongoing actions to resolve them. It further identifies more opportunities for improving energy performance metrics as various technological fields evolve.

2. Advancement in energy performance metrics for new cooling technologies

An International Energy Agency (IEA) study estimates that space cooling applications were responsible for about 1 Gt of CO_2 emissions and nearly 8.5% of total final electricity consumption worldwide in 2019 [16]. Without major efficiency improvements to cooling equipment, the IEA estimates electricity demand for cooling in buildings could increase by up to 50% globally by 2030. In addition, worldwide energy demand and associated emissions from air conditioners (ACs) are expected to increase threefold by 2050 [17].

The history of modern vapor compression cycle technology on which most modern ACs, heat pumps (HPs), and refrigeration equipment are based goes back to the early 1900s or even before.[1] Given the Kigali Amendment to the Montreal Protocol (2016), the global cooling equipment market is yet to transition toward energy-efficient and sustainable technologies, including low global warming potential (GWP) refrigerants. Their energy performances have been evaluated primarily in steady-state full-load operation. In the United States (US), seasonal energy-efficiency metrics that reflect the performance in part-load operations for HPs were developed in 1979 [20]. Since the mid-2000s, the penetration of inverter-driven variable-speed-drive (VSD) ACs and HPs have increased,[2] and region-specific seasonal energy-efficiency metrics in China, the European Union (EU), Japan, South Korea, etc., have been designed or adopted to estimate their energy performance under regional climatic conditions that affect the amount of time a system operates at part or full load. These metrics are increasingly used as an alternative to the traditional energy efficiency ratio (EER) or the coefficient of performance (COP) to set standards and labeling requirements

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[1] William Carrier invented the first modern electrical air conditioning unit in 1902 [18]. Jacob Perkins, an American inventor living in England, built the first vapor compression machine for producing ice in 1834 [19].

[2] The world's first split ACs with inverter-driven compressors for commercial and residential applications were introduced by Toshiba in Japan in 1980–1981.

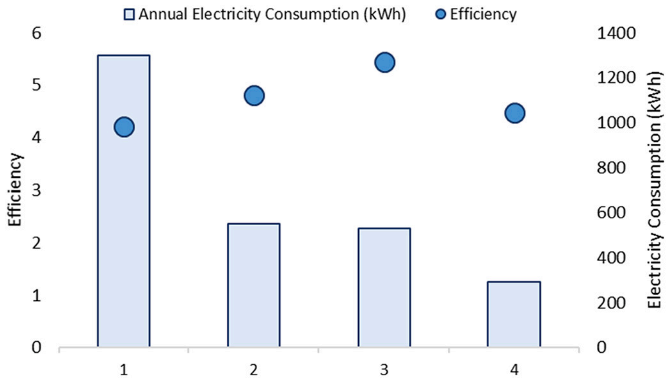

Fig. 1. Efficiency and annual electricity consumption estimated by ISO standards for one sample AC unit.

Efficiency measured in EER or CSPF and annual electricity consumption measured and calculated according to ISO standards with India outdoor temperature profile (total 1600 h), based on the analysis from [33].

1: EER 4.22; Annual energy consumption is calculated by rated power consumption times 1600 h without part-load performance considered.

2: CSPF 4.81 (equivalent to India SEER 4.81) in accordance with ISO 16358-1: 2013 without minimum load performance considered, consistent with the India AC standard (IS 1391) [34].

3: CSPF 5.44 in accordance with ISO 16358-1: 2013 including minimum load performance considered.

4: CSPF 4.47 in accordance with ISO 16358-1: 2013/Amd 1: 2019 including minimum load performance considered.

for ACs and HPs [21,22].[3] In particular, under the Japan Top Runner program,[4] which sets EE targets based on the most efficient performance within each product group on the market, efficiency performance metrics for ACs and HPs were improved by moving away from the EER (1st EE targets for 2004) to an annual performance factor (APF)[5] (2nd EE targets for 2010) [24]. The seasonal performance metrics— cooling seasonal performance factor (CSPF), heating seasonal performance factor (HSPF), and APF- contributed to the current International Organization for Standardization (ISO)'s seasonal efficiency metrics. ISO standards for testing and rating room ACs and HPs have been published and improved (ISO/R 859: 1968; ISO 5151: 1994/2010/2017) [25–28], and the seasonal energy efficiency metrics were published in 2013 (ISO 16358-1, -2, -3: 2013) [28–30]. ISO 16358-1 in the version of ISO 16358-1: 2013/Amd 1: 2019 [32] provides additional methods for CSPF for hot climates. Table 1 shows how the test conditions and energy performance metrics have evolved with ISO standards. Fig. 1 shows an example of efficiency and annual electricity consumption estimated by different versions of ISO standards for one VSD AC unit.

China provides one recent example of aligning a market transition with performance metric development and adoption. China had the MEPS for ACs and HPs in EER until the seasonal efficiency metrics, SEER for cooling types (ACs) and APF for reversible types (HPs), were adopted in 2013. Between 2010 and 2013, the share of VSD units increased from 18% to 45%. Between 2018 and 2019, China revised the MEPS by combining the performance metrics into SEER and APF and improving the requirements. In 2020, when the new MEPS went into effect, the share of VSD units increased to 98% (see Fig. 2).

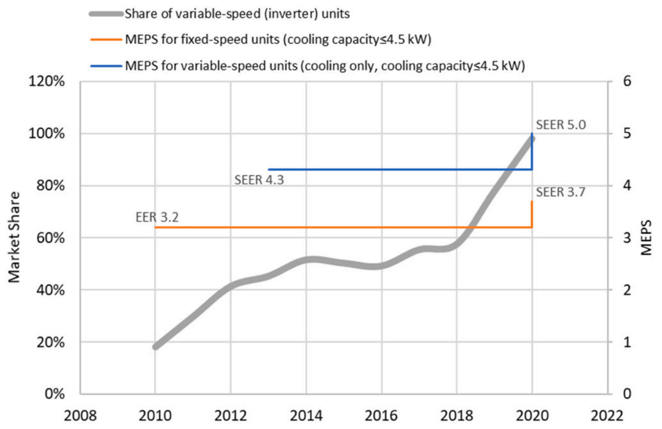

Fig. 2. Market improvement with performance metric and MEPS improvement in China.

Source: Authors' work based on [35,36].

However, the existing seasonal EE metrics for ACs and HPs still have room for further improvement. First, many alternative technologies have shown promising results in laboratory settings or pilots, but most have yet to be tested at scale in the field and commercialized [37]. Some alternative technologies, especially hybrid types, need appropriate test methods and metrics for performance evaluation.

For example, the final winning products of the Global Cooling Prize[6] used smart hybrid designs: specifically, optimized indoor cooling using smart operation in multiple modes of vapor-compression refrigeration, direct evaporative cooling, and ventilation depending on outside weather conditions.[7] Hybrid designs included features compatible with renewable energy systems, such as integrating a solar photovoltaic panel into the outdoor unit or employing direct-current (DC) electrical components [38]. The testing of winning prototypes under simulated real-world conditions, as per the Prize's testing protocol, identified gaps in the testing standards adopted for assessing the performance of room ACs today. These results indicate that the current test standards recognize only 69% or just over two-thirds of the weighted energy reduction achieved by the winning technologies compared with the baseline unit when operating under simulated real-world conditions [39]. The India room AC test standard, which is consistent with ISO 16358-1: 2013, assesses the performance of ACs at standard outdoor and indoor temperatures without much consideration for humidity conditions (see Table 1). However, in a real-world scenario, humidity is an important factor, and efficient removal of moisture from the air has a major effect on occupant comfort. The Prize also found that in the Indian climate, ACs with fully VSD compressors delivered higher savings than recognized by current test standards due to the ACs operating at much lower levels of rated capacity [39]. This result leads to recommending that the

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[3] ISO standard 5151 defines EER as the ratio of the total cooling capacity to the effective power input to the device at any given set of rating conditions, and it defines COP as the ratio of the heating capacity to the effective power input to the device at any given set of rating conditions. We note that EER and COP have alternative definitions in certain regions [28].

[4] The Top Runner Program was introduced in 1999 to establish energy consumption efficiency standards for appliances, equipment, vehicles, and other items in these sectors [23].

[5] ISO standard 16358 defines APF as the ratio of the total amount of heat that the equipment can remove from and add to the indoor air during the cooling and heating seasons, respectively, to the total amount of energy consumed by the equipment for both seasons [31].

[6] In 2018, the Government of India and Rocky Mountain Institute launched the Global Cooling Prize [38], an international innovation competition to develop super-efficient and climate-friendly residential cooling solutions for homes. The Global Cooling Prize target was set at a climate impact (including indirect emissions from energy consumption) of five times lower than the market average. This efficiency improvement will be particularly important for emerging economies with hot climates where air conditioning use is expected to increase dramatically.

[7] In November 2019, the Global Cooling Prize narrowed the 139 applicant teams, representing 31 countries, to eight finalists composed of established global AC manufacturers, technology startups, and other organizations [38,39]. The technologies employed across these teams indicate several emerging trends in room AC design.

current AC test standards and metrics accommodate the features in emerging BATs.

Second, the existing performance evaluation methods are based on the performance measurement under manufacturer-controlled compressor settings at given rating conditions. In other words, to date, testing VSD or inverter-driven products could not be conducted independently from manufacturers [22,40]. As an alternative, dynamic load-based testing, which allows the ACs to operate in an environment closer to actual use conditions, is being explored and requires further research.[8] Fig. 3 shows the trends in cooling efficiency performance evaluation.

3. Opportunities for development and improvement in energy performance evaluation of technologies

There are opportunities in energy performance evaluation of appliances and equipment systems that can help keep the world on a trajectory to comply with the 1.5 °C or 2 °C goals of the Paris Agreement. This section identifies three such opportunities and provides examples of each.

3.1. *Taking a systemic approach*

A systemic approach to designing new test procedures and performance metrics, or improving existing ones, can mitigate the risk of obsolete technologies being deployed in markets, and reflect the benefits of using the best available and emerging technologies.

3.1.1. *Space and water heating*

Globally, fossil fuel-based heating equipment and inefficient conventional electric heating technologies account for ~80% of heating equipment sales [42]. While the annual fuel utilization efficiency (AFUE) defines the efficiency of gas furnaces and gas HPs, the heating seasonal performance factor (HSPF) applies to electric HPs. Similarly, while the energy factor (EF) is defined for gas water heaters, the COP, HSPF, and EF represent the performance of heat pump water heaters (HPWH). Therefore, it is important to understand the different metrics used for different technologies within the same product category. Furthermore, for hybrid (dual fuel) HPs, which use both an electric HP and a gas furnace, the test procedures and energy performance metrics need to improve to account for such new or hybrid characteristics.

3.2. *Applying advanced test procedures more broadly*

Advanced test procedures and performance metrics for one single equipment type or system can apply to a broader emerging technological context that affects many different appliances and equipment groups within it.

3.2.1. *Connectivity*

Various electronic equipment and appliances have connected features, such as network standby modes under which the products perform a subset of what a personal computer does when in sleep mode (which is different from traditional passive standby mode). As connectivity is more widely available at an equipment level, grid-interactive or demand response functionality becomes more critical as cost-effective opportunities in electricity service require appropriate evaluation metrics and methodologies (including advanced metering). Further, such connectivity will be crucial in designing the grid of the future where flexible and intelligent loads can support higher penetration of intermittent renewable generation.

3.2.2. *Renewable energy, DC applications, and battery charging*

While appliances and equipment typically operate over alternating current (AC) power, many electronics and some appliances work inherently on direct current (DC) power. Those DC appliances are energy efficient and can potentially increase the affordability of off-grid solar power systems. The Global Lighting and Energy Access Partnership (Global LEAP) Awards has helped develop test methods for off-grid products to identify best-performing technologies. A continued effort will be needed as the off-grid market grows. Along with the increased adoption of renewable energy and DC applications, sales of battery-powered products and systems—including electric vehicles— are growing. The emerging market of battery and chargers will require quality-assured and energy-efficient infrastructure.

3.2.3. *User behavior*

It has been challenging to analyze consumer behavior using various appliances and equipment. However, deploying smart meters enable researchers and policy makers to better understand consumer usage patterns, which helps improve the energy performance metric to better reflect real-world energy consumption.

3.3. *Improving energy performance calculation*

Improvements in energy performance calculation can better reflect real-world energy consumption of the products and systems. If actual usage in the field is significantly different from usage predicted by measurement (as discussed for ACs in Section 2), test procedures, performance metrics, and calculation methods would need to be modified. This will impact national, regional, and global analyses of consumption estimates and savings potential.

3.3.1. *Large commercial refrigeration systems*

Most refrigerated display cabinets with remote condensing units are installed as a large system. The systems are usually supplied by a compressor rack system with one or more large outdoor condensers that are manufactured by a different company than the one that makes the display case. As a result, the compressor rack and condensing system can be very different from installation to installation. The large size of the rack and condensing system and the fact that they are rarely directly paired with the refrigerated case make it challenging to test the complete system and get a representative value in a laboratory setting. As a result, to make the performance test manageable, current standards use standard efficiency values for the compressor-condenser system and only keep the physical remote unit test to test how much refrigerant enthalpy is needed to maintain the required temperature conditions. However, ISO 23953-2: 2015[9] [43] and AHRI 1200: 2013 [44] energy consumption calculation methods for remote condensing units are very different, resulting in a 50% difference in energy consumption estimates of the same model, which indicates a need to improve the methodology [11,45].

4. Concluding remarks

Ongoing technological developments need continuous improvements in evaluation methods. It is especially important to emphasize international harmonization in moving the global market toward an energy-efficient and sustainable economy. The primary goal of performance metrics and test methods is to reduce GHG emissions and increase energy efficiency by enabling the appropriate deployment of emerging technologies and effective applications of products and systems.

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[8] For example, Canada adopted CSA EXP07, which includes dynamic load testing for inverter-driven ACs and HPs. There is also a current proposal to include dynamic testing in EN 14825, the EU standard [22]. IEA Energy Efficient End-use Equipment (4E), an international collaboration platform, is conducting research on developing dynamic testing in 2021 and 2022 [41].

[9] The standard is under revision at the time of this study.

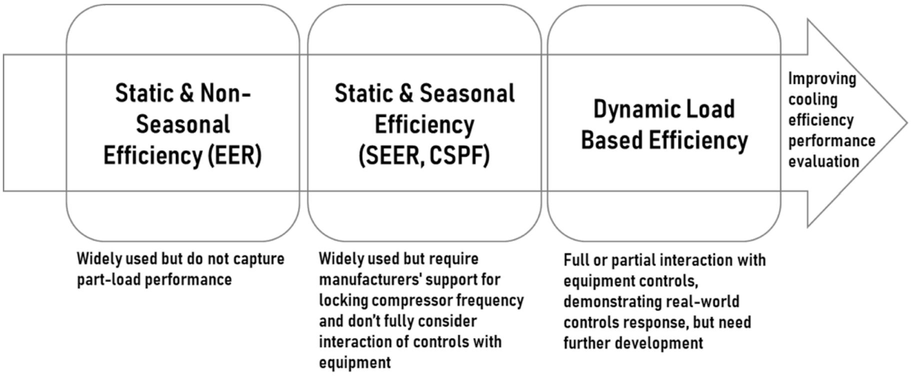

Fig. 3. Improving cooling efficiency performance evaluation methods.

Advanced test procedures and performance metrics can mitigate the risk of deploying obsolete technologies and promote the benefits of the best available and emerging technologies by applying them to a wider context, resulting in energy consumption that reflects actual operations.

One of the challenges to achieving widespread adoption of BATs is determining which performance metrics are of greatest value to the stakeholders affected by EE standards programs, including regulators, industries, utilities, and consumers, and then discovering the most reliable ways to measure them. Consequently, there is a need to accelerate performance metrics and test development to keep pace with evolving technologies.

Advancement in energy performance testing and metrics for products and systems can align with a broader range of EM&V activities. For example, recent EM&V schemes apply automated data collection and processing, and machine learning to estimate resource consumption and savings at a site or program level.

Finally, a systematic approach to designing energy efficiency performance metrics and test procedures that supports faster deployment of disruptive technology compatible with a 1.5 °C or 2 °C trajectory is sorely needed.

Declaration of competing interest

This study was supported by the National Philanthropic Trust, United States. The authors declare that they have no known competing financial interests or personal relationship that could cause a conflict of interest regarding this article.

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