International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2023, 13(5), 432-441.

Assessment of the Correlation between Energy Rating Labeling Regulations and Performance Metrics for Residential Air Conditioning Units: Case Study Variable Type Air Conditioners

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Received: 20 May 2023 **Accepted:** 20 August 2023 **DOI:** https://doi.org/10.32479/ijeep.14747

ABSTRACT

To comply with the Paris Agreement, many countries have implemented mandatory energy certification policies in the HVAC sector. These policies have encouraged the deployment of more energy efficient technologies such as variable or inverter driven technologies, which have been developed based on established seasonal performance metrics. Therefore, this paper presents an experimental evaluation of a variable-type air conditioner based on seasonal cooling metrics and performance ratings using various energy labeling programs from multiple regions around the world. The results of this work demonstrate that the energy efficiency rating of an air conditioner is significantly influenced by the distribution of the reference outdoor temperature in the labeling program issued by each region, and not just by the adoption of a technical standard. These results are crucial for the development of public policies aimed at designing better energy efficiency and labeling programs. In particular, the findings are especially relevant for decision making by governments, as the adoption of a technical standard can be simplified, and greater harmonization of performance metrics used globally can lead to greater energy savings and mitigate the effects of global warming.

Keywords: Energy Labelling, Energy Efficiency, Air Conditioning, Performance Metrics
JEL Classifications: L38, O57, C91

1. INTRODUCTION

Air conditioning systems (AC) are part of the appliances with the highest end-use energy consumption in most countries, being significantly used in factories, buildings, and houses (Anker-Nilssen, 2003). These devices, along with electric fans, account for nearly 20% of the total electricity used in buildings around the world (International Energy Agency, 2018). Nowadays, most of that electrical energy comes from fossil fuels, which are unsustainable and environmentally damaging. This is how high energy consumption directly contributes to global warming through greenhouse gases emission. For this reason, many countries around the world are implementing public policies to establish significant goals in energy savings. The potential high impact and relatively low cost of energy efficiency measure have led to the adoption of several plans to improve the performance of household appliances, buildings, and electricity distribution grids. The introduction of more energy efficient electrical appliances and labeling programs have contributed to crucial reductions in substantial energy use reductions in residential and commercial sectors. The three most used policy interventions in developing countries are information programs, labeling regulations, and financial incentives (Fatihah Salleh et al., 2019; Jain et al., 2018; Liang Wong and Krüger, 2017; Lim et al., 2018; World Energy Conuncil, 2020). Major elements of the recommended energy-efficiency policies include an internationally harmonized standard program, product certification and registration, infrastructure for testing performance, and an evaluation, measurement, and verification strategy (Abas and Mahlia, 2018; Inoue and Matsumoto, 2019; Park et al., 2021).

China is the largest market for air conditioning systems and produces about 70% of the world's room air conditioners (RACs) (Japan Refrigeration and Air Conditioning Industry Association, 2019; Karali et al., 2020; Wu et al., 2019). Therefore, any enhancement in the mandatory regulations established by the Chinese government will result in significant energy savings worldwide. In 2019, China updated and released the GB 21455 standard, which sets the minimum allowable values for energy efficiency and energy efficiency grades for RACs (Yuan et al., 2011; Zeng et al., 2014; Zhang et al., 2018). Since 2015, China has been implementing the Top Runner Program for End-Use Energy Consuming Appliances and Products, a voluntary initiative that identifies the most energy-efficient models. It is crucial to determine the actual energy consumption and usage patterns of RACs for both their design and evaluation of energy efficiency (Phadke et al., 2020; Wu et al., 2017; Zhou and Bukenya, 2016).

In Australia and New Zealand, the Equipment Energy Efficiency (E3) program mandates the Minimum Energy Performance Standards (MEPS) for air conditioning systems sold in the region. The performance metrics of this program are based on the AS/NZS 3823.1.1:2012 standard, which is an identical adoption of the ISO 5151 (2010) and the AS/NZS 3823.4.1 (2014) standards, both based on the ISO 16358-1 (2013) standard (Department of the Environment and Energy of Australia, 2018).

Similarly, in 2019, the Indian government launched the India Cooling Action Plan (ICAP) with the goal of providing cooling comfort throughout the country while also addressing economic and social development issues in a sustainable manner. India's government mandates that every room AC be tested in accordance with the IS 1391 standard, and the methodology for calculating the cooling seasonal total load, the cooling seasonal energy consumption, and the Indian seasonal energy efficiency ratio must comply with the ISO 16358-1 standard (Bhattacharya et al., 2020).

There are multiple energy efficiency metrics available, and different countries use different testing procedures and metrics to represent seasonal energy efficiency. For instance, in the United States, the ANSI/AHRI 210.240 - Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment standard was updated in 2017, and a new test procedure will come into effect in 2023. This standard outlines the testing procedures, standard method, and ambient conditions to test ACs based on the Seasonal Energy Efficiency Ratio (SEER) metric for cooling mode and the Heating Seasonal Performance Factor (HSPF) function for heating mode (Cadeo Group, 2020).

For cooling systems, most countries use the Cooling Seasonal Performance Factor (CSPF) metric based on ISO 16358-1. Australia, China, the European Union, and India follow the CSPF performance metric based on ISO 16358 procedures. However, this may cause confusion since the efficiency metric for product classification purposes is called SEER, but it is not determined following the ANSI/AHRI requirements.

Due to the increasing use of variable-speed ACs, commonly known as inverter-driven ACs, the Energy Efficiency Ratio (EER) metric has been replaced by various part-load and seasonal performance metrics specific to each region. As a result, policymakers lack comparative data to create more effective AC efficiency market-transformation programs (Chen et al., 2018). A comparative analysis of fixed and variable RAC systems using EER and CSPF metrics was conducted, demonstrating that the CSPF is more accurate when compared to the EER under real operating conditions, since it considers how the system behaves as the outdoor temperature changes (Andrade et al., 2019; Andrade et al., 2021; Serrato et al., 2019). Variable-speed ACs are more effective than constant-speed units during months and in locations with part-load operation, even in hot climates where building load and outdoor temperatures change over time. Seasonal efficiency metrics aim to provide a more representative calculation of seasonal performance by taking efficiency at several part-load conditions into account. These calculations differ by both country and compressor type but all account for performance at multiple non-peak cooling load points. Improving the performance metrics of RACs could provide significant energy and associated emissions savings, particularly in emerging economies with hot climates where cooling demand is expected to increase dramatically (Lim et al., 2019; Shah et al., 2021; Yoon et al., 2018).

The ASEAN Standards Harmonization Initiative for Energy Efficiency (SHINE) program supports efforts to improve AC energy-efficiency standards by recommending the adoption of the CSPF metric in accordance with ISO 16358. The SHINE program has set a minimum Weighted Energy Efficiency Ratio (WEER) of 2.9 or a minimum CSPF of 3.08 since 2020 as a mandatory MEPS for all fixed- and variable-speed ACs below 3.52 kW in cooling capacity, using the standard methods based on ISO 5151 and CSPF defined in ISO 16358. The program aims to phase out inefficient ACs and increase the share of high-efficiency ACs by harmonizing test methods and energy-efficiency standards, including adopting common MEPS requirements, and influencing consumer purchasing decisions. In the East African Community (EAC) and Southern African Development Community (SADC), only six countries have MEPS, of which three have mandatory regulations, and the others are voluntary programs when cooling energy consumption is expected to increase in the coming years. For these regions, the energy labeling programs are not directly comparable and thus confuse consumers (Khanna et al., 2020; Park et al., 2021; Park et al., 2021).

The review of literature shows that most countries in the world are adopting regulations based primarily on ISO or ANSI/AHRI technical standards for energy efficiency labeling and certification purposes. This research paper presents an experimental assessment of a variable-type air conditioning system, utilizing CSPF and SEER performance metrics, and classifying it using energy labeling programs from various regions. The key contribution of this study is to demonstrate that the energy efficiency rating of a variable-type air conditioning system is significantly influenced by the distribution of reference outdoor temperature bins, typically included in the labeling program issued by each region, and not solely by the adoption of a technical standard. These findings hold great significance since air conditioning systems are typically programmed by manufacturers to comply with standard regulations defined by each region's labeling program. However, for this study, the air conditioning system was programmed directly from the motherboard using software codes provided exclusively by the manufacturer. This approach enabled testing of the equipment in accordance with both technical standards. The results obtained from this research provide valuable insights for the development of public policies aimed at designing improved energy efficiency and labeling programs. Moreover, these conclusions are particularly relevant for government decision-making, as the implementation of user-friendly technical standards can lead to higher energy savings and reductions in carbon dioxide emissions, thereby mitigating the effects of global warming.

2. MATERIALS AND METHODS

In this section, the paper presents a description of the sample equipment tested, the test method used, the established environmental conditions, and the testing scheme performed. The purpose of this section is to thoroughly describe the conditions in which the results were obtained and to establish how to reproduce the results. All tests were conducted at the Laboratorio de Ensayos para Equipos Acondicionadores de Aire (LPEA) at the Universidad Tecnológica de Pereira. The LPEA is accredited according to the International Standard ISO/IEC 17025 (2017). The standard method used was the balanced ambient room-type calorimeter. A non-ducted AC mini split variable type only for cooling was evaluated. Table 1 shows the technical specifications of the test sample[1].

Table 2 shows the standard rating ambient conditions. The test condition tolerances were defined within ISO 5151 and ASHRAE Standard 37, ASHRAE Standard 116. The standard rating tests were performed at 230 V ± 1% and 60 Hz. The variation of arithmetical mean values from specified test conditions was ±0.3 K for dry bulb and ±0.2 K for wet bulb temperatures.

The first column of Table 2 shows the denomination of the performance metrics according to the international standard. According to the ISO standard, two mandatory tests are required named as the full and the half load capacity. The half load capacity fixes the compressor speed at 50% of capacity factor and aims at obtaining the half cooling capacity for the second test. According to the ANSI/AHRI 210.240 standard, five mandatory tests are required, named as A_2, B_2, E_v, B_1 and F_1.

The reference outdoor temperature bin distribution was selected according to the interval proposed in both standard and is presented in Figure 1.

The reference outdoor bin distribution simulates the outdoor or ambient temperature in which the equipment under test is operating at different thermal load conditions during a reference bin hour. Note that for 35°C the equipment will be functioning a short time, between 23°C and 29°C the equipment will be functioning most of the time. This temperature distribution is closely related to the cooling load (or building load), which may widely vary from region to region depending on climate conditions, building structures, and the use of the ACs. To certificate and rate the performance, each region must establish the cooling load.

Table 1: Technical specification of the test sample

Nameplate information	AC-mini split type
Rated cooling capacity	7034 W (24000 Btu/h)
Technology type	Variable capacity
Climate class	T1
Voltage	220-240 V monophasic
Refrigerant	R-410A (1600 g)

The statistical validity of the information was determined by evaluating 7200 data points collected from each variable at an equal interval of 5 seconds for each performance test, for a total of 50,400 data points collected and evaluated. For this, a total of 7 tests were carried out and, in all cases, the minimum variation allowed for steady-state conditions was 2% of the total cooling capacity estimated according to the ISO TS 16491 guide. The ANOVA showed that the test results are within the control limits defined as 3 times the standard deviation, which guarantees repeatability and reproducibility of the information. The expanded uncertainty was 3% of total cooling capacity with $k = 2$ expressed with a level of confidence of 95%. The recording data interval was 120 min for all tests.

3. THERMODYNAMICS APPROACH

3.1. CSPF Thermodynamics Model

The standard ISO 16358-1 is used to calculate the *CSPF*. The scope of this standard specifies the testing and calculating methods for seasonal performance factor of an equipment covered by ISO 5151, ISO 13253 and ISO 15042 standards. In accordance with ISO 16358-1, the *CPSF* was calculated using equation (1).

$$CSPF = \frac{L_{CST}}{C_{CSE}} \quad (1)$$

where L_{CST} represents the cooling seasonal total load and C_{CSE} is the cooling seasonal consumption. The L_{CST} was calculated using the outdoor temperature bin distribution climate reference by means of equation (2).

$$L_{CST} = \sum_{j=1}^{m} L_c\left(t_j\right)\bullet n_j + \sum_{j=m+1}^{n} \varnothing_{ful}\left(t_j\right)\bullet n_j \quad (2)$$

where n_j represents the bin hours[2], and t_j is the outdoor temperature corresponding to each temperature bin n_j.

In the range $L_c\,(t_j) \leq \varnothing_{ful}\,(t_j)$ for $j = 1$ to m the defined cooling load at outdoor temperature $L_c\,(t_j)$ was calculated using equation (3). The L_c was determined at intervals between $t_0 = 20°C$ for a 0% load and $t_{100} = 35°C$ for a 100% cooling load.

1 Due to the confidentiality of the information, this paper does not present any information about the manufacturer or any trademark.

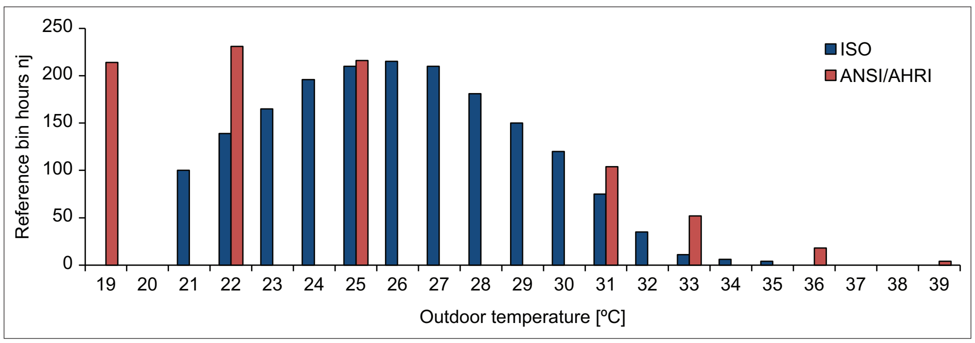
2 Outdoor temperature bin hours used for calculating seasonal efficiency of an AC system are defined as a set of hours at each outdoor temperature that requires cooling and heating.

Table 2: The experimental setup and ambient conditions

Performance metric	Description	Ambient conditions	
		Indoor room	Outdoor room
CSPF according to ISO 16358-1 (2 required tests)*	$Ø_{ful}$ (35)– Standard cooling capacity Full capacity (Capacity factor 100%)	*Tdb*=27.0°C *Twb*=19.0°C	*Tdb*=35.0°C *Twb*=24.0°C
	$Ø_{haf}$ (35)– Standard cooling capacity Half capacity (Capacity factor 50%)		
	ISO references outdoor temperature bin distribution – cooling only		
SEER according to ANSI/AHRI 210.240 (5 Required Tests)	A_2 - Full capacity (Capacity factor 100%)	*Tdb*=26.7°C *Twb*=19.4°C	*Tdb*=35.0°C *Twb*=23.9°C
	B_2 - Full capacity (Capacity factor 100%) B_1 - Minimum capacity (Capacity factor 21–24%)		*Tdb*=27.8°C *Twb*=18.3°C.
	Ev – Intermediate (half) capacity (Capacity factor 50%)		*Tdb*=30.6°C *Twb*=20.6°C
	F_1 - Minimum capacity (Capacity factor 21–24%)		*Tdb*=19.4°C *Twb*=11.9°C
	ANSI/AHRI references outdoor temperature bin distribution – cooling only		

*The low temperature cooling capacity was calculated following the default equations proposed in the ISO 16358-1

Figure 1: Reference temperature bin hours distribution. Adapted from ISO 16358-1 and ANSI/AHRI 210.240



$$L_c\left(t_j\right) = \varnothing_{ful}\left(t_{100}\right)\bullet\frac{t_j - t_0}{t_{100} - t_0} \quad (3)$$

The cooling seasonal consumption C_{CSE}, was obtained using equation (4).

$$C_{CSE} = \sum_{j=1}^{p}\frac{X\left(t_j\right)\bullet P_{haf}\left(t_j\right)\bullet n_j}{PL\left(t\ \right)} + \sum_{j=p+1}^{m} P_{hf}\left(t_j\right)\, n_j + \sum_{j=m+} P_{ful}\left(t_j\right)\, n_j \quad (4)$$

The *CSPF* performance metric is presented as a linear model, so at least two additional points are required to make the projection. The standard cooling capacity was obtained while the outdoor temperature was $t_j = 35°C$. According to ISO 16358-1, the low temperature cooling capacity was calculated following the default correlations proposed in the standard[3] evaluated at $t_j = 35°C$.

3.2. SEER Thermodynamics Model

The standard ANSI/AHRI 210.240 was used to calculate the *SEER*. This performance metric estimates the functioning of the AC in different operating modes in which the capacity factor varies in a minimum, intermediate, and full capacity, but also the building load varies in an outdoor temperature range. For variable speed capacity systems was calculated using the equation (5).

$$SEER = \frac{\sum_{j=1}^{8} q(t_j)}{\sum_{j=1}^{8} E(t_j)} \quad (5)$$

where the quantities $q\ (t_j)$ represent the total cooling capacity, and $E\ (t_j)$ indicates the total power input during each test condition (nominal, intermediate and minimum) evaluated at each temperature range t_j. The performance metric *SEER* shall be estimated in function of the building load *BL*, which indicates the thermal load of the room to be conditioned, and it shall be calculated using the equation (6).

$$BL\left(t_j\right) = \left(\frac{t_j - 65}{95 - 65}\right)\bullet\left(\frac{\dot{q}_{A,full}}{SF}\right) \quad (6)$$

The rated full load net capacity $q_{A,full}$ represents the cooling capacity evaluated at 100% of capacity factor and is taken from the test result defined as A_2. The sizing factor SF is defined as the ratio of the cooling capacity to the maximum cooling demand. The standard proposed $SF = 1.1$ as a value by default.

3 *Default co*rrelations: Øful29=1.077·Øful35; Pful29=0.914·Pful35 Øhaf29=1.077·Øhaf35 ;Phaf29=0.914·Phaf35

Three cases shall be considered:

Case I: cycling at low speed.

This case occurs if $BL(t_j) \leq q_{low}(t_j)$, where $t_j \leq t_I$, for this case $q(t_j)$ was calculated by equation (7). The total bin energy estimated at outdoor temperature $E(t_j)$ represents the total power input demand of the AC and it is evaluated in a temperature range. For Case I, the $E(t_j)$ was calculated using the equation (8).

$$q\left(t_j\right) = CLF^{low} \bullet \dot{q}_{low}\left(t_j\right) \bullet n_j \tag{7}$$

$$E\left(t_j\right) = \frac{CLF^{low} \bullet P_{low}\left(t_j\right) \bullet n_j}{PLF^{low}} \tag{8}$$

Case II: continuous operation at intermediate speed.

This is when the $q_{low}(t_j) \leq BL(t_j) \leq q_{full}(t_j)$, where $t_I \leq t_j \leq t_{II} \leq$, in this case $q(t_j)$ was calculated according to equation (9) and the $E(t_j)$ using the equation (10).

$$q\left(t_j\right) = BL\left(t_j\right) \bullet n_j \tag{9}$$

$$E\left(t_j\right) = \frac{\dot{q}_{int-Bin}(t_j)}{EER_{int-Bin}(t_j)} \tag{10}$$

Case III: continuous operation at full speed.

For this case, $BL(t_j) > q_{full}(t_j)$, and $t_j > t_{II}$.

In this operating stage, the cooling capacity $q(t_j)$ and total bin energy $E(t_j)$ which are evaluated at outdoor temperature shall be calculated according to equations (11) and (12).

$$q\left(t_j\right) = \dot{q}_{full}(t_j) \bullet n_j \tag{11}$$

$$E\left(t_j\right) = P_{full}(t_j) \bullet n_j \tag{12}$$

The seasonal efficiency calculations differ both by country and by compressor type, but all account for performance at multiple non-peak cooling load points. This differentiation in temperatures and hours is important for countries and regions to be able to establish seasonal efficiency values that are representative of the performance of equipment in their climate and geography.

4. RESULTS AND DISCUSSION

The overall test results are presented in Table 3. The Appendix A.1-A.3 showed the detail calculations of both performance metrics and the uncertainties.

To estimates the *CSPF*, two tests were conducted at full capacity or 100% of capacity factor, and half capacity or 50% of capacity factor. Figure 2 shows the cooling capacity, both full and half estimated at different outdoor temperature conditions as test result of ISO 16358-1. Note that for an outdoor temperature of 35°C the full cooling capacity value obtained was $Ø_{ful}(35) = 7090W$.

Table 3: Test results obtained by LPEA

Test results ISO 16358-1	Test results ANSI/AHRI 210.240
Full capacity $Ø_{ful}(35)=7090W$; $P_{ful}(35)=2332W$	A_2 - Full capacity $\dot{q}_{A,full} = 24083\frac{Btu}{h} equal\,to\,7058W; P_{A,full} = 2282W$
Half capacity $Ø_{haf}(35)=3572W$; $P_{haf}(35)=793W$	B_2 - Full capacity $\dot{q}_{B,full} = 27808\frac{Btu}{h} equalto 8150; P_{B,full} = 2035W$
Low temperature capacity. Theoretical correlations.	Ev – Intermediate capacity $\dot{q}_{E,int} = 12797\frac{Btu}{h} equalto 3751W; P_{E,int} = 682W$
Low temperature full $Ø_{ful}(29)=7636W$; $P_{ful}(29)=2131W$	B_1 - Minimum capacity $\dot{q}_{B,low} = 6926\frac{Btu}{h} equalto 2030W; P_{B,low} = 414W$
Low temperature half $Ø_{haf}(29)=3847W$; $P_{haf}(29)=725W$	F_1 - Minimum capacity $\dot{q}_{F,low} = \frac{9045Btu}{h} equalto 2651W; P_{F,low} = 352W$
Outdoor temperature bin distribution 20–35°C	US references outdoor temperature bin distribution 19.4°C (67°F) to 38.9°C (102 °F)
L_{CST}=5198W C_{CSE}=1039W	$\sum_{j=1}^{8} q(t_j) = 8584\frac{Btu}{h} equalto 2516W; \sum_{j=1}^{8} E(t_j) = 476W$
$CSPF$=5.00 W/W	$SEER = 18.02 Btu / \bullet Whequalto 5.28W / W$

In this point, the full power input was P_{ful} (35) = 2332W. With these results, the *EER* performance metric is calculated as 3.04. However, when the test sample is setting to operating at half condition, but at same outdoor temperature point, the half cooling capacity obtained was $Ø_{haf}$(35) = 3572W and the half power input decreased to P_{haf}(35) = 793W with an *EER* equal to 4.05. In this experiment, the half cooling capacity corresponds to 50% of full cooling capacity, but this was reached using the 34% of the full power input. These findings implicate that the test sample is more efficient operating at capacities different from the full condition, which represents the worst performance point.

In the Figure 2 when the outdoor temperature decreases to 29°C, which corresponds to low temperature cooling capacity, the theoretical results showed that the low temperature cooling capacity operating at a capacity factor of 100% is $Ø_{ful}$(29) = 7636W, the full power input decreases to P_{ful}(29) = 2131W, and the *EER(*29) increases mode to 3.58. This implies that not only the capacity factor influences the operation of the test sample, but also a lower value of the outdoor temperature affects the energy efficiency value. The test results demonstrate that lowering outdoor temperature from 35°C to 29°C in the same operation mode increases the efficiency by 17.8% approx.

Figure 3 shows the cooling capacity (full, intermediate, and minimum) estimated at different outdoor temperature conditions, as test result of ANSI/AHRI 210.240. Note that for an outdoor temperature of 97 °F (or 35°C) the full cooling capacity value obtained was $q_{A,\ full}$ = 24083 *Btu*/*h* (or 7058W). At this operating point, the full power input was $P_{A,\ full}$ = 2282W. With these results, the *EER* performance metric is calculated as 3.09. These results correspond to A_2 test following the ANSI/AHRI 210.240 recommendations. However, when the outdoor temperature decreases to 82°F (or 27.8°C), but the equipment is operating in full mode (which corresponds to B_2 test) the experimental results shows that the cooling capacity increases until $q_{B,\ full}$ = 8150W (or 27808 *Btu*), and the power input decreases to $P_{B,\ full}$ = 2035W. Under these conditions the *EER* reaches to 4.00. Note that, the B_2 test proposed by the ANSI/AHRI standard is like the low temperature cooling capacity test with a capacity factor of 100%

Figure 2: Cooling capacity evaluated at different outdoor temperature. Test result of ISO 16358-1

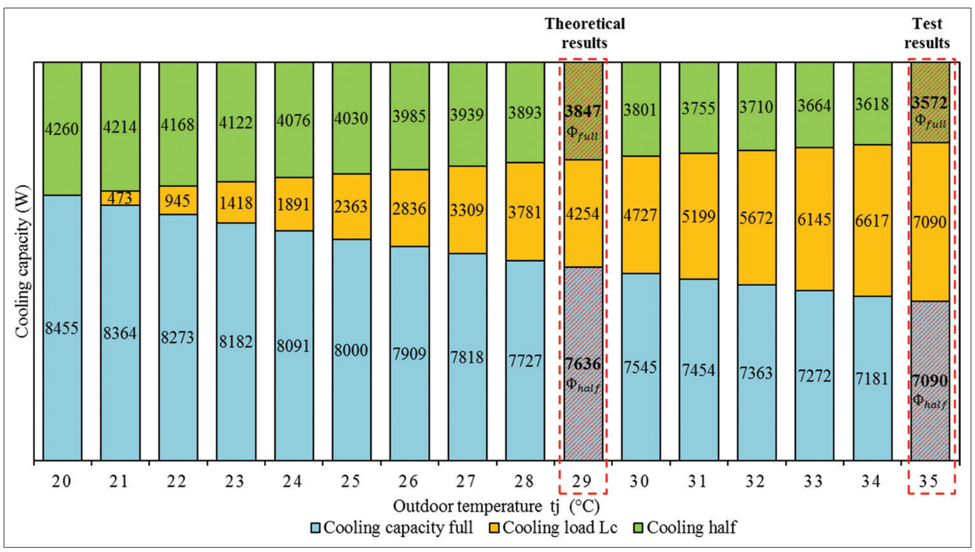
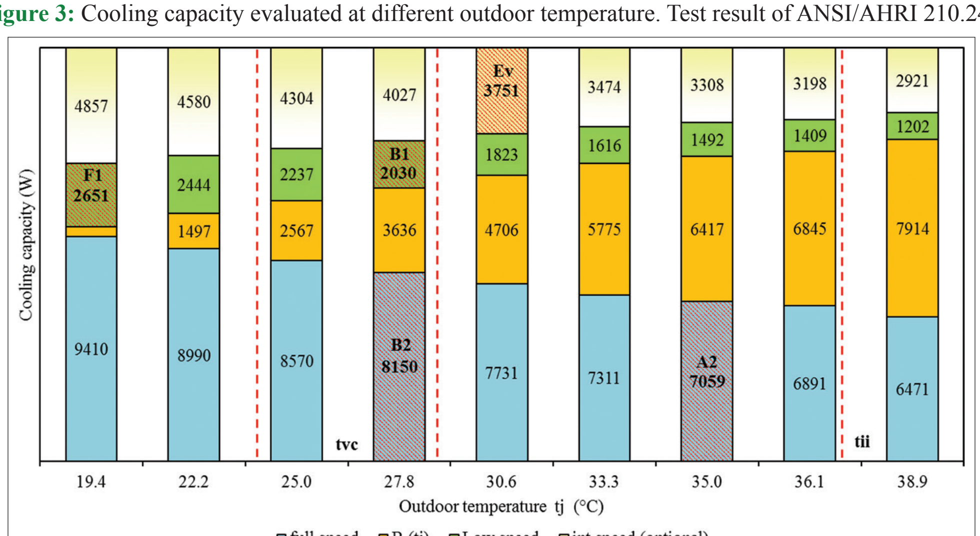


Figure 3: Cooling capacity evaluated at different outdoor temperature. Test result of ANSI/AHRI 210.240



and evaluated at 29°C, as presented by committee ISO. In this case, the main difference is a slightly lower outside temperature equivalent to $\Delta T = 1.2K$.

According to the testing scheme, the ambient conditions, and experimental test results, the intermediate test - Ev evaluated at 87 °F (30.6°C) following the ANSI/AHRI standard recommendations is comparable to the theoretical result from the low temperature cooling capacity test evaluated at 29°C in accordance with ISO standard. The test result shows that the AHRI result equals to $q_{E,\ int} = 12797$ *Btu/h* (or 3751*W*) in comparison to the ISO theoretical result from $\text{Ø}_{haf}(29) = 3847W$, which means a difference approx. to 2.4%. The small difference can be explained since the outdoor temperature of the "AHRI" standard is 1.2*K* higher compared to the ISO standard. This behavior corresponds to the thermodynamic and heat transfer laws in which while the ambient temperature increases, the cooling capacity decreases. Comparing the performance metrics, the *CSPF* = 5.00 with the *US–SEER* = 5.28, the experimental results demonstrate that the difference is low.

4.1. Results Sensitivity

This paper used the theoretical equations presented in the literature compared to the experimental results. The theoretical model aims at translating air conditioning performance metrics into regional metrics and indicate the efficiency improvement potential. Table 4 shows some theoretical performance metrics calculated using the experimental results obtained by LPEA. The theoretical functions and parameters were adapted from (Park et al., 2020).

As shown in Table 4, the average of the theoretical *US - SEER* was 5.12 *W*/*W* compared to the experimental *US – SEER* obtained by the LPEA that was 5.28 *W*/*W*, which means a difference approx. to 3.0%. Both the theoretical and experimental results allow us to conclude that the difference is negligible. In this way, the *CSPF* difference among the theoretical and experimental test result was approx. to 2.5%, concluding that the test results presented in this paper are aligned to the correlations proposed in the literature.

4.2. Policy Implications

A performance comparative analysis of the rated energy rating labeling regulations proposed in several regions as Australia/New Zealand, China, India, and the United States was developed. Table 5 shown the test results classify according to energy's labeling programs of different regions.

According to Table 5, the results of the performance metrics show that the variations of the calculation models proposed in the ISO 16358-1 and ANSI/AHRI 210.240 are not significant. In this case, this study concludes that both the *CSPF* and the *SEER* performance metric are approximate in numerical results, and even changing the tested sample the theoretical results allow extrapolating the data reaching the same conclusion. This paper concludes that the variations between the final test results and standards are negligible.

Both *CSPF* and *SEER* performance metrics are based on testing at several temperatures at both full and part loads and extrapolating this into a curve of performance that covers all temperature points. Since the part-load conditions and heating and cooling load hours are defined independently for each country, there is more variability in both the test conditions and the equipment response. For this study, the climatic curves proposed for each regulation labeling country were used.

Table 4: Theoretical performance metrics calculated using the experimental results obtained by LPEA

Performance metric	Function* #1	Function* #2	Average
US - SEER	$\mathrm{SEER_1} = d + \frac{a-d}{\left(1+\left(\frac{X}{C}\right)^b\right)}$	$\mathrm{SEER_2} = 1.039 \cdot X - 0.08$	$SEER = 5.12$
Predicted** $X = CSPF = 5.00$	$SEER_1 = 5.13$	$SEER_2 = 5.11$	
ISO - CSPF	$\mathrm{CSPF_1} = d + \frac{a-d}{\left(1+\left(\frac{X}{C}\right)^b\right)}$	$\mathrm{CSPF_2} = 0.962 \cdot X + 0.087$	CSPF = 5.13
Predicted*** $X = SEER = 5.28$	$CSPF_1 = 5.10$	$CSPF_2 = 5.17$	

*The theoretical functions and parameters were adapted from [24], **a=−0.752, b = 0.903, c = 972471, d = 350955, ***a = 1.728, b = 1.741, c = 15.127, d = 26.177

Table 5: Test results classify according to energy labeling programs of different regions

Region	Test result (Wt/We)	Rating of performance according to labeling regulation	Observation
Australia/NZ	FTCSP=4.22	2.5 stars	Very low efficiency
China	SEER=CSPF=4.15	3.8 <SEER (Wt/We) <4.4	Medium-low efficiency
India	ISEER=CSPF=4.07	4 stars	Medium-high efficiency
United States	SEER=5.28 equal to 18.02 (Btu/W.h)	Must meet the MEPS SEER >20 (Btu/W.h)	Do not accomplish MEPS

The performance rating varies significantly according to each region that issues its own labeling regulations. The test sample was classified according to the Australian and New Zealand labeling program, concluding that it is of very low efficiency. However, when the test result of the same test sample is classified according to the Indian regulation and certification labeling program, it is concluded that the equipment is classified as a medium-high performance. This behavior would be explained if the same test sample obtained very different results according to each performance metric. However, the results of seasonal efficiency are similar (*FTCSP* = 4.22 and *ISEER* = 4.07). In this sense, the responsibility for the energy efficiency classification is highly dependent on the governments of each region, who must harmonize the technical labeling regulations and energy savings programs, aiming at unifying and promoting the rational and efficient use of energy.

As shown in Table 5 for China's case, the performance metric was ranked as medium low-efficiency whereas in the United States the energy efficiency does not meet the minimum requirements MEPS. These findings allow us to conclude that China's labeling program is less demanding compared to that of the United States. Considering that China manufactures 70% of the global RAC production, it is in a privileged global position in which any decision made in labeling regulation affects the emissions of carbon dioxide on a large scale and global warming. Banning low-efficiency equipment strongly contributes to obtaining energy savings in countries that do not have strong policies or are transitioning to adopt their own regulations. In this sense, China must periodically update its regulations to avoid marketing its low-efficiency products in unregulated countries and, and it must also diversify the use of more efficient technologies. With a stringent energy labeling regulation program proposed in China to develop super-efficient technologies including the use of the low- global warming potential - GWP refrigerants, high efficiency systems shall be deployed in the rest of the world. China's Top Runner labeling program for the development and use of super-efficient equipment should not be optional.

Some governments in Asia, Africa, and South America are studying how to make the transition from energy policies based on ISO 5151 to the adoption of efficiency metrics that better represent the behavior and energy consumption of an AC variable type. However, the governments find difficulties with concerns regarding what the best technical standard would be and if the results differ a lot among them. In this case, the energy labeling policies for ACs are developed from there, since a table that classifies the equipment based on *CSPF* in theory should not be used to classify other types of performance metrics as *EER* or *SEER*. In addition, there are costs associated with the quantity and number of tests, which may be affected due to the adoption of one standard with respect to the other. From this perspective, these results help to make decisions and adopt public policies that can lead to energy savings in developing countries.

5. CONCLUSION

This study presented an energy efficiency analysis based on the *CSPF* as indicated by the standard ISO 16358-1, and the *SEER* according to ANSI/AHRI 210.240. A comprehensive analysis of the standard requirements, ambient conditions, and testing schemes was presented. The thermodynamics model to calculate the *CSPF* and *SEER* was presented. A deeper understanding of the experimental test results was developed, and this was compared to the theoretical correlations proposed in literature review. The sensitivity analysis concludes that the performance metrics *CSPF* and *SEER* are close values. In that sense, AC test methods and standards procedures for split system ACs variable type are reasonably well aligned.

Each region's climatic curve named as temperature bin distribution values has a high influence on the numerical result of both the *CSPF* and *SEER's* performance metrics. The higher the bin hours ponderation of the lowest temperature values, the higher the numerical value of the performance metrics. This explains why there are variations in the test results obtained for each region, using the same mathematical model to calculate the performance metric *CSPF*. Each region's government is responsible for issuing the temperature bin distribution which will be established in each labeling regulation program. From the point of view of the representation of the physical phenomenon, the *SEER* performance metric represents a behavior that is closer to the actual performance of the AC compared to the operation of the equipment finally installed. This is since it considers more test points of ambient conditions and capacity factor, which translates into a greater number of tests carried out. However, from the point of view of product certification, *CSPF* has a greater advantage due to the result is especially close to *SEER* but requires fewer tests. This implies lower product certification costs and shorter times in the declaration process.

Therefore, the energy efficiency rating is not affected by the technical standard used, but by the energy efficiency rating values issued by each government. In this sense, the recommendations are: (1) Unify not only the international standards, but also the methodology to establish the labeling and certification programs. (2) The labeling regulations of each region must be issued pondering the highest energy efficiency values of each product currently available. (3) Governments should consider innovative elements in the regulations to promote the change of older and less efficient ACs to achieve socio-economic and environmental benefits. (4) Each regulation must stimulate the use of refrigerants with a low carbon footprint (low-GWP), this being a key variable in the performance classification. (5) Promoting the development of regional testing laboratories to verify the energy efficiency values of products currently on the market of each region. (6) Banning low-efficiency products that do not comply with the international MEPS and (7) Periodically update the energy regulations to diversify the use of more efficient technologies. These findings could be useful for designing and developing better energy efficiency programs, leading to higher energy savings and carbon dioxide emission reductions.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided by the *Laboratorio de Ensayos para Equipos Acondicionadores de Aire* - (*LPEA*) at the researching group in energy managements (GENERGETICA), from the Vicerrectoría de Investigaciones, Innovación y Extensión of the Universidad Tecnológica de

Pereira, Colombia by financial support through internal project with code 8-22-2.

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APPENDIX

Appendix A.1: CSPF overall results obtained by LPEA

Bin number	Outdoor temperature	Ref. bin hours	Sigma full (tj)	Pful (tj)	Lc (tj)	X (tj)	Fpl (tj)	Lcst	Cste
0	20	0	8455	1830.6	0	0.000	0.750	0	0
1	21	100	8364	1864.0	473	0.112	0.778	47267	9139
2	22	139	8273	1897.5	945	0.227	0.807	131401	25217
3	23	165	8182	1930.9	1418	0.344	0.836	233970	44580
4	24	196	8091	1964.3	1891	0.464	0.866	370571	70125
5	25	210	8000	1997.7	2363	0.586	0.897	496300	93301
6	26	215	7909	2031.2	2836	0.712	0.928	609740	113903
7	27	210	7818	2064.6	3309	0.840	0.960	694820	129009
8	28	181	7727	2098.0	3781	0.971	0.993	684421	126337
9	29	150	7636	2131.4	4254	1.000	1.000	638100	127756
10	30	120	7545	2164.9	4727	1.000	1.000	567200	121483
11	31	75	7454	2198.3	5199	1.000	1.000	389950	89784
12	32	35	7363	2231.7	5672	1.000	1.000	198520	49414
13	33	11	7272	2265.1	6145	1.000	1.000	67591	18309
14	34	6	7181	2298.6	6617	1.000	1.000	39704	11795
15	35	4	7090	2332.0	7090	1	1	28360	9328
							SUM	5198 (Wt)	1039 (We)
							CSPF	5.00 (Wt)/(We)	

Appendix A.2: SEER overall results obtained by LPEA

Bin. number j	Outdoor temperature	Frac. bin hours	q (tj)	Pi (tj)	BL (tj)	CLF (tj)	PLF (tj)	Q (tj)	E (tj)
1	67	0.214	9045	352	1460	0	1	312	15
2	72	0.231	8339	373	5109	1	1	1180	58
3	77	0.216	14684	23	8757	641	20	1892	155
4	82	0.161	13740	21	12406	661	20	1997	108
5	87	0.104	12797	19	16055	682	19	1670	71
6	92	0.052	11854	17	19704	703	15	1025	40
7	97	0.018	10910	15	23353	723	10	420	19
8	102	0.004	22077	2415	27002			88	10
							SUM	8584	476
							SEER	18.02 Btuh/We	
							SEER	5.28(Wt)/(We)	

Appendix A.3: Uncertainties of the cooling capacity test based on ISO 16491

Symbol	Value	Typical uncertainty	Factor	Standard uncertainty	Sensitivity coefficients	Contribution [W]
$\bullet_{i}^{n} P_{I,i}$	6677 W	33.38 W	2	16.69 W	1	16.69 W
h_{wl}	112.6 kJ/kg	112.6 kJ/kg	1.73	65 W	3,64E-04	0.02 W
h_{w2}	67.7 kJ/kg	67.7 kJ/kg	1.73	39.1 W	3.64E-04	0.01 W
w_r	5.84 9E-04 kg/s	5.84E-04 kg/s	1.73	5.8E-05	44877	1.51 W
$k_{s,p}$	2.6 W K^{-1}	0.52	1.73	0.3 W K^{-1}	7.3	2.19 W
$k_{s,i}$	17	3.4	1.73	1.96 W K^{-1}	2.1	4.12 W
T_{oam}	34.7°C	0.2 K	2	0.1 K	2.6	0.26 W
T_{iam}	27.3°C	0.2 K	2	0.1 K	19.6	1.96 W
T_{iscm}	25.3°C	0.2 K	2	0.1 K	17	1.7 W
Q_0	7095W	106.42 W	1	106.42 W	1	106.42 W
Expanded uncertainty: 220 W/3.1% of full cooling capacity - Coverage factor: $k = 2$						107.87 W