Using Building Performance Simulation to Enhance Energy Efficiency Evaluations of Room Air Conditioners

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Abstract

This study compared fixed Cooling Seasonal Performance Factors (CSPF) calculated using a general outdoor temperature distribution to those calculated considering specific climates and the use of Room Air Conditioners (RAC). Results indicate that tailoring CSPF calculation to specific climates is key to better communicating RAC efficiencies to stakeholders. Additionally, using Building Performance Simulation (BPS) was proved as an innovative approach within this scope, since it can tailor CSPF calculation to specific hours when indoor conditions are more likely to demand cooling. This approach also highlighted equipment-related outcomes that static evaluations could not detect.

Highlights

- CSPF calculation should be tailored to specific climate and RAC usage conditions.
- Using static temperature profiles hinders CSPF outcomes.
- National standards may guide simulation-based approaches to calculate such temperature profiles.
- BPS results evidence equipment-related aspects hindered by current approaches.
- It is important to use RAC's full- and partial-load efficiencies to guide BPS-based results interpretation.

Introduction

Scientific literature is emphatic about the profound impact of buildings on worldwide energy use. Cooling is a key driver of such use, and projections indicate that cooling energy demand is expected to triple by 2050 (IEA 2018). Achieving efficient cooling is paramount in modern societies since cooling is linked to all 17 Sustainable Development Goals (SDGs) established by the United Nations (Khosla et al. 2020).

Along these lines, assessing and improving Room Air Conditioners (RAC) is essential. This technology faces a global demand increase driven by higher incomes, electrification, and urbanization, especially in emerging economies with hot climates (Park et al. 2020). Establishing and constantly updating Minimum Energy Performance Standards (MEPS) for air conditioning systems is crucial to increasing the energy efficiency of these systems and improving the status quo. However, a common problem concerning RAC usage worldwide is that historically their efficiency improvements were based on full-load operations. Such an approach does not show to consumers a realistic performance benchmark for variable-speed equipment (e.g., inverters).

Technological developments have placed seasonal metrics (e.g., Cooling Seasonal Performance Factors – CSPF) in a prime position to enhance RAC evaluation and consumer communication (Shah, Park, and Ding 2021). Such metrics are calculated according to part- and full-load RAC performance considering local temperatures over an entire year. These metrics better reflect the superior performance of variable-speed inverters over fixed-speed ones.

Although variable-speed RAC and seasonal performance indicators are predominant in mature markets (Shah, Park, and Ding 2021), developing countries have recently implemented seasonal metrics. The Kigali Amendment to the Montreal Protocol mainly influences this trend, having shifted the global cooling market to deploy more energy-efficient technologies (Park et al. 2022).

A seasonal metric was recently released in the Brazilian market by Ordinance 269/2021 (INMETRO 2021). This requirement is aligned with the Model Regulation Guidelines developed by the United for Efficiency Initiative (U4E) (UN 2019), which recommended using ISO 16358 to calculate CSPF. Such a calculation relies on country-specific bin hours of outdoor air temperature. This and similar initiatives are vital to achieving global sustainability targets given the growing demand for RAC, especially in developing economies with hot climates (Shah et al. 2017).

The National Institute of Metrology, Standardization, and Industrial Quality (INMETRO) has publicized all measured data for all equipment it has evaluated. Its database includes cooling/heating capacity and the associated energy use in three scenarios: full load at 35°C, partial load at 35°C, and partial load at 29°C. By providing public access to these indicators, INMETRO has enabled further calculation of seasonal metrics considering broader representations of outdoor temperatures (i.e., climate-specific indicators).

Although innovation has occurred along the central topic of this study, the scientific literature indicates a knowledge scarcity about CSPF in tropical climates (Karali et al. 2020). Variations in climate profiles (i.e., outdoor temperature binning) adopted worldwide may lead to non-negligible divergences. For instance, international experience shows a 5°C reduction in the

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lowest temperature bin used in Europe, compared to those observed in China and Japan (Shah, Park, and Ding 2021).

In this panorama, the present study aims to target CSPF assessments to specific outdoor temperature bins while considering the most likely hours of RAC usage throughout the year according to national standard on households' thermal performance. Considering multiple key performance indicators (Krelling et al. 2023), national standards of building thermal performance may guide such an innovative approach by providing the most likely hours of RAC usage in residential buildings. Therefore, this study's innovation concerns moving from a static approach to calculating a seasonal energy efficiency metric (i.e., typical-year outdoor temperature binning) to a dynamic building simulation approach. In other words, by transferring information and consolidated practices from building sciences, CSPF calculation can be adjusted to temperature bins linked to real-world cooling needs, thereby providing more accurate and informative results.

Method

This section describes the approaches proposed to boost the calculation of Cooling Seasonal Performance Factors (CSPF) for Room Air Conditioners (RAC) in Brazil. First, details about the CSPF calculation considering 577 weather files across the country are presented. Then, the application of Building Performance Simulation within this scope is proposed and detailed.

Calculating CSPF considering weather files

The initial approach in this study involved CSPF calculation for 577 Brazilian climates. This metric was chosen because it has been recently implemented in Brazil by Ordinance 269/2021 (INMETRO 2021). The climates were obtained from the newest national database and included cities from all Brazilian states. This calculation also employed three categories for the bin hours selected:

- Entire days (24 hours)
- Daytime (12 hours)
- Nighttime (12 hours)

Selecting periods of the day was important in accounting for possible changes in RAC operation given the realities of different climates. In other words, each of the 577 climates was used to set specific bin hours that may indicate changes in occupancy and climatization use. Then, the method from ISO 16358-1 was applied to achieve climate- and usage-specific CSPFs (ISO 2013). The main difference between this and the classic approach is having one outdoor temperature distribution for each climate to calculate CSPFs according to ISO 16358-1.

Using Building Performance (BPS) Simulation to Calculate CSPF

The performance of a single-family residential building was simulated using EnergyPlus, considering the climates of four Brazilian cities: Curitiba, Florianópolis, Goiânia, and Macapá. ASHRAE 169 (ANSI/ASHRAE 2013) classifies their climates as 3A, 2A, 1A, and 0A, respectively. Building models were developed following the Brazilian building performance standard guidelines, NBR 15575-1:2021, which are thoroughly described in Krelling et al. (2023).

Building model

A representative design (Triana, Lamberts, and Sassi 2015) for low-income detached houses was adopted due to their significant presence in the national building stock. Envelope characteristics followed those defined for the reference model from NBR 15575, which is characterized by heavy and mostly uninsulated walls and roofs, and windows with a solar heat gain coefficient of 0.87 (Figure 1). As four climates were adopted in this study, a minor adjustment was made to the envelope simulated according to the requirements from NBR 15575. As shown in Figure 1, the roof requires additional thermal insulation (0.67 m²·K/W) in the hottest Brazilian climate zone. All the other envelope characteristics were the same, disregarding the climate tested.

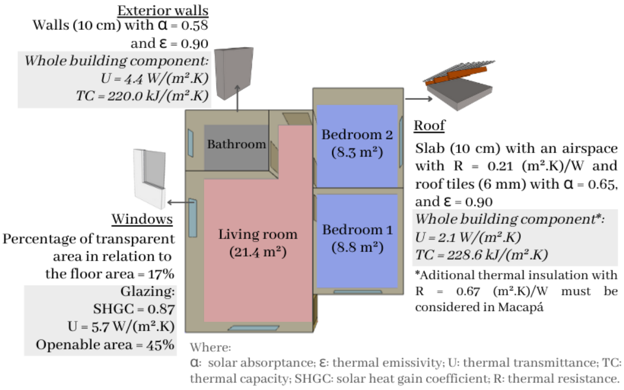

Figure 1: Representative single-family residential building with envelope characteristics from NBR 15575-1 reference model

Building operation

Given the predominant preference for natural ventilation as an adaptation strategy in residential buildings (Ramos et al. 2021), NBR 15575-1 prioritizes a free-running operation mode. Thus, air conditioning is only used when natural ventilation cannot guarantee adequate indoor thermal conditions. To prevent overheating, such conditions are defined by operative temperature thresholds below 26 °C for Curitiba, Florianópolis, and Goiânia, and below 30 °C for Macapá. This variability in triggers for air conditioning use is defined in the national standard NBR 15575-1, based on previous studies regarding preferences for RAC use in different regions of Brazil (Ramos et al. 2021). The operation of windows or the air conditioning system is considered only for predefined occupied hours, adopting the internal heat gains illustrated in Figure 2.

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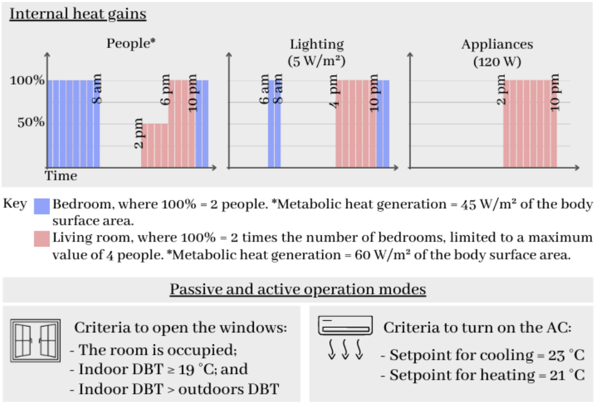

Figure 2: Operation of residential buildings according to NBR 15575-1

As a final step along these lines, CSPF was calculated using the results from BPS. For doing so, the hours in which air conditioning is likely used (i.e. thresholds of 26°C or 30°C as previously explained) guided this step. In other words, bin hours previously applied in the equations from ISO 16358-1 (ISO 2013) were adjusted according to the actual hours of RAC use in the households. Thus, besides having a general CSPF for the country (calculated with fixed bin hours from Brazil), this study also provides specific bin hours related to the thermal behavior of households in different climates.

Results

Selecting RACs to conduct further analysis

An initial analysis comprised the evaluation of 106 RACs labeled according to Ordinance 269/2021. As previously stated, specific measurements were publicized by the national agency, which enabled the CSPF calculation for 577 climate files that represent the broad variability perceived in Brazil. Figure 3 shows the results obtained from such analysis, with each boxplot representing the behavior of one specific machine. Machines are presented in decreasing order of the mean value obtained for the 577 climates tested.

This first step confirmed the broad variability that can be expected for RAC performance according to the climate in which they will be used. For instance, the minimum and maximum CSPF were 3.59 Wh/Wh and 15.60 Wh/Wh; the mean value was 6.75 Wh/Wh, and the standard deviation was 1.42 Wh/Wh.

Seasonal metrics adjusted to specific climates

A follow-up analysis was performed with this data, and two pieces of equipment were chosen for the simulation-based approach proposed in this study. This choice was based on the standard deviation of their CSPFs when considering all 577 Brazilian climates. Specifically, the chosen equipment demonstrated the largest and the smallest standard deviations observed (1.19 and 0.42 Wh/Wh). Figure 4 shows an overview of both machines. Although the minimum CSPF values were similar for both (5.26 and 5.17 Wh/Wh), expressive variations in the maximum CSPF were observed: 11.29 and 6.94 Wh/Wh. This initial result may indicate that while both machines appear similar when using static bins for outdoor temperature, such an approach may undermine RAC efficiency assessments for specific locations.

After selecting these machines, further analysis was conducted using weather data from the cities chosen for this study. Figure 5 shows these results considering three possible schedules of RAC operation: all day long (24 h), daytime (12 h), and nighttime (12 h). The results for each city evaluated – Curitiba (CWG), Florianópolis (FLN), Goiânia (GYN), and Macapá (MCP) – are always presented in that order, which corresponds to the range of coldest (3A) to hottest (0A) climates observed in Brazil, according to ASHRAE 169 classification (ANSI/ASHRAE 2013). The dashed line in both graphics represents the seasonal metric for each RAC, according to the general bin hours established by Ordinance 269/2021. This indicator is 7.40 Wh/Wh for the first equipment, and 6.20 Wh/Wh for the second. It confirmed that the first RAC surpassed the second one in all the cities and schedules. For instance, while the mean CSPF for the first RAC is 8.50 Wh/Wh, it is 6.40 Wh/Wh in the second.

Other important outcome can be obtained from the machines tested. The first machine resulted in expressively larger CSPFs compared to a calculation using Brazil's general bin hours; this was especially true in colder climates. As shown in Table 1, the absolute CSPF values were 1.31 Wh/Wh up to 4.48 Wh/Wh, larger than the machine's standard values in Climates 3A and 2A. In contrast, the absolute variations for the second machine were 0.44 Wh/Wh up to 0.71 Wh/Wh. Employing a climate-specific perspective confirmed that in hotter cities (i.e., Zones 1A and 0A, both tested herein), general bin hours might overestimate CSPF values for RAC primarily used during daytime.

Seasonal metrics considering results from BPS

The final analysis in this study calculated CSPF considering the specific hours in which RAC are more likely to be used throughout the year. Such a prediction is enabled by building performance simulation (BPS) approaches, especially considering national standards with guidelines for evaluating residential building performance. These results are presented in Figure 6. A first and expected takeaway from this analysis is the increase in CSPF when comparing bedrooms to living rooms. Indeed, the national standard defines nighttime occupation in the former, and daytime occupation in the latter (as shown in the Method section). Similar results to those previously observed regarding day versus night operation were achieved.

Deepening this analysis to consider BPS results also produced important findings from the machine perspective. First, for the RAC with smaller CSPF values (i.e., the one with poorer performance under partial loads), BPS results did not add much value to the CSPF calculation. As shown in Figures 5 and 6 (b), all tested methods – daytime and nighttime bin hours, and expected RAC usage according to residential performance via BPS – resulted in similar values for the fixed seasonal metric (6.20 Wh/Wh) that was calculated with the general bin hours defined in Ordinance 269/2021.

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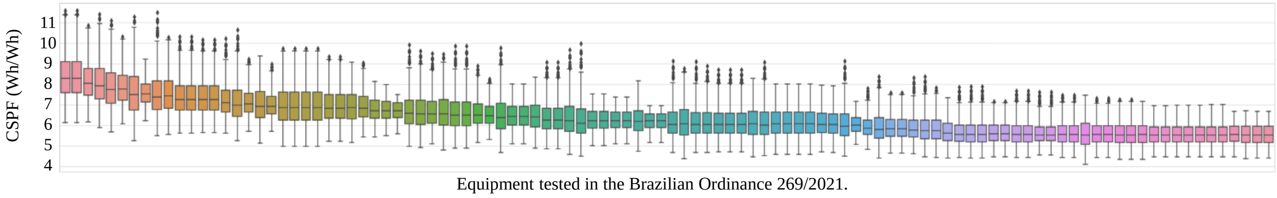

Figure 3: Overview of 106 Room Air Conditioners considering 577 Brazilian climates.

However, when it comes to better-performing RACs under partial loads, which is the case in Figures 5 and 6 (a), BPS results highlight important trends. First, it was observed that CSPFs for RAC installed in bedrooms (i.e., with nighttime expected usage) could be up to 1.95 Wh/Wh larger than those calculated assuming a full rest in night hours. Second, comparing these results with the general metric for the machine (7.40 Wh/Wh) yielded an increase of about 6 Wh/Wh. Finally, when comparing daytime operation of RAC in bedrooms versus living rooms, BPS notably highlights the times during which the RAC is more likely to be used. Consequently, the overall CSPF metric may be smaller than that of general bin hours considering daytime. This fact is influenced by including hours with milder conditions to calculate CSPF (when the RAC is likely off) in comparison with using only fixed hours to calculate CSPF. Our results indicate that CSPF calculated using BPS for Curitiba and Florianópolis (Zones 3A and 2A) could be 0.40 and 0.16 Wh/Wh smaller than CSPF calculated considering full daytime hours.

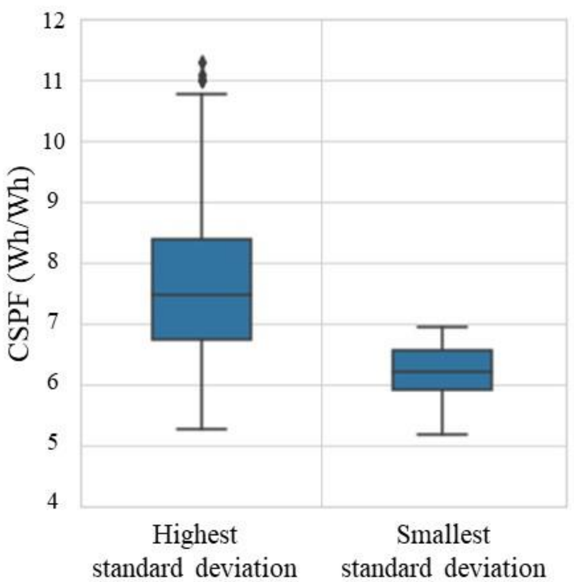

Figure 4: CSPF variability considering RAC with the largest and smallest standard deviations.

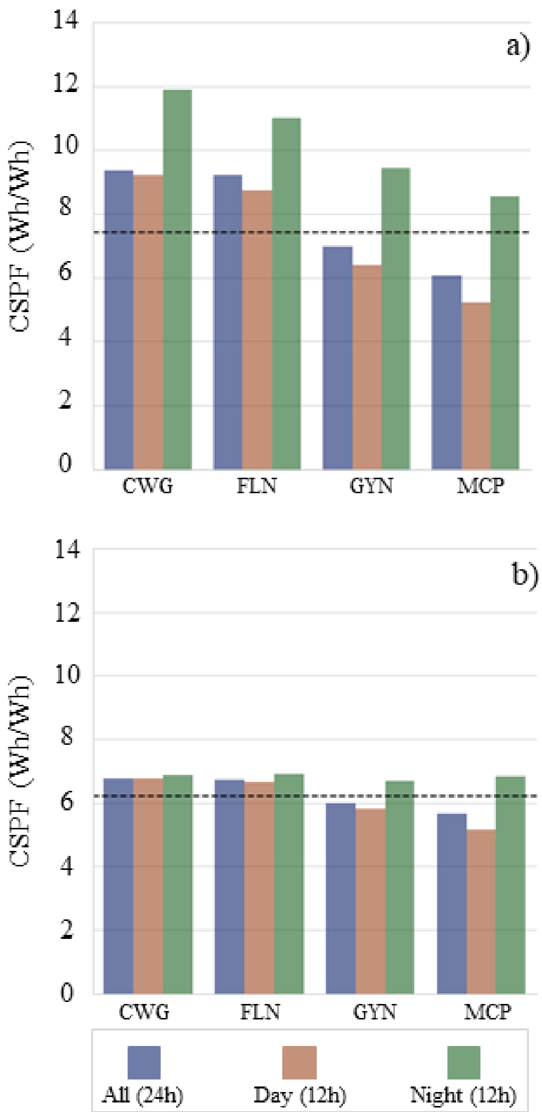

Figure 5: CSPF variability by cities evaluated and: a) the RAC with the largest standard deviation, and b) the RAC with the smallest standard deviation.

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Table 1: Variation in the CSPF calculated for the scenarios tested and the fixed value for each RAC.

City (Climate)	Variation in the CSPF (Wh/Wh)					
	1st RAC: largest standard deviation			2nd RAC: smallest standard deviation		
	24h	Day	Night	24h	Day	Night
CWG (3A)	+1.94	+1.79	+4.48	+0.56	+0.55	+0.67
FLN (2A)	+1.82	+1.31	+3.59	+0.51	+0.44	+0.71
GYN (1A)	-0.41	-1.01	+2.03	-0.20	-0.41	+0.48
MCP (0A)	-1.33	-2.18	1.13	-0.56	-1.06	+0.61

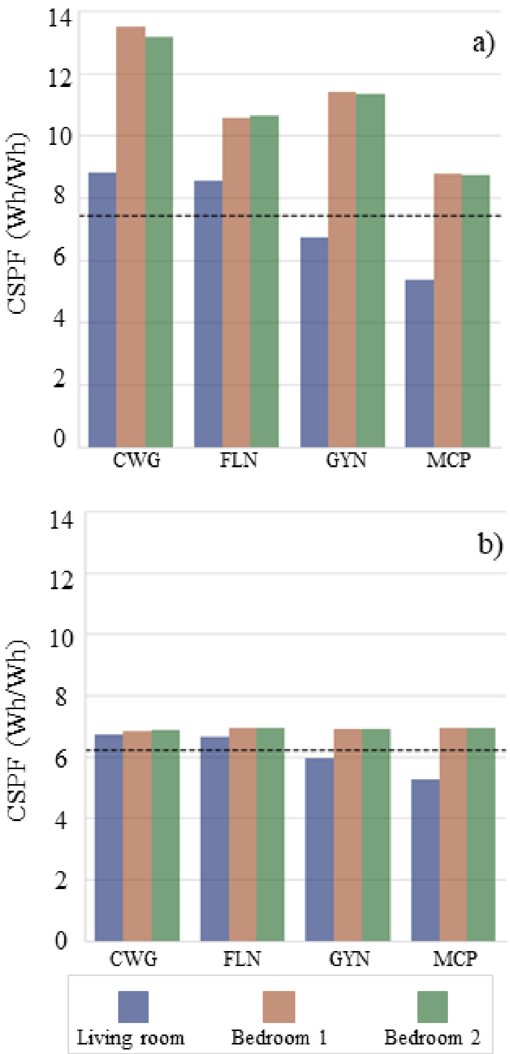

Figure 6: CSPF considering BPS results and: a) the RAC with the largest standard deviation, and b) the RAC with the smallest standard deviation.

Discussion

Consumers with predictable usage patterns (e.g., only during the night) are likely to be misinformed about their RAC efficiency when general bin hours for a country are used in the calculation. Our results confirmed underestimated values of seasonal performance metrics for RAC with different expected efficiencies, especially for nighttime use in colder climates.

Changes in absolute values comparing a country's general seasonal metrics to climate-specific indicators highlighted some equipment-dependent uncertainties. For instance, our results showed that machines more likely to have variable performance across different climates might also result in bigger variations compared to standard CSPF values. In other words, consumers in such locations may choose a specific RAC because of its smaller cost, relying only on the fixed CSPF value. The fixed CSPFs for both machines tested in this study (6.20 and 7.40 Wh/Wh) differ from the possible variations considering climate-specific metrics. On the one hand, the second machine is about 20% more efficient than the first when fixed CSPFs are compared. On the other hand, considering Curitiba's climate (Zone 3A) and nighttime operation, the CSPF in these machines changed from 6.87 Wh/Wh to 11.88 Wh/Wh – representing almost a 73% increase. Therefore, with better communication of RAC energy efficiency, consumers would be given appropriate guidance to purchase the best solution for their needs.

Another important outcome for the Macapá (Zone 0A) case is highlighted: the small variations between both machines may be considered in future trade-off or cost-benefits analysis. Although the first machine resulted in an expressively bigger efficiency indicator (7.40 Wh/Wh versus 6.20 Wh/Wh), this variability is minimized when daytime operation is expected (5.22 Wh/Wh versus 5.14 Wh/Wh, as shown in Figure 5). This outcome is a combination of climate and usage patterns of the RAC with its specific characteristics. For instance, the one with a smaller seasonal metric outperforms the other when full load occurs (COPs = 3.24 and 3.81 Wh/Wh, respectively). These COPs (Coefficient of Performance) were calculated considering the cooling capacity and the effective power input of each machine under full-load operation at 35°C. Such calculations were enabled by the database provided by INMETRO containing all the specific values observed for each machine.

Although adjusting the CSPF calculation to specific climate conditions is a feasible approach to reflecting RAC efficiency more accurately, using BPS along these lines can improve the calculation even more. Adding computer simulation outcomes to calculate CSPF is a promising way to tailor specific RAC to specific needs given local climate and usage patterns. Such an approach can also include building-related aspects that may lead to RAC use throughout the year. Indeed, outdoor temperature alone may not represent RAC needs since other environmental parameters (e.g., air velocities and solar radiation) in combination with envelope characteristics (e.g., window-to-wall ratios, walls and ceilings' thermal properties) are key factors for the indoor conditions. Such conditions impact RAC use nationwide, especially considering that most Brazilians prefer natural ventilation at home (Ramos et al. 2021). Thus, when the bin hours used to calculate CSPF are only based on outdoor temperatures, several underlying effects leading to RAC use are disregarded.

Our results also showed that BPS results were important within this scope since they highlighted equipment-related trends. On the one hand, machines with poorer overall performance may behave similarly, regardless of evaluation approach (including BPS results). On the other hand, machines with overall better performance, especially under partial loads, may have their efficiency misreported when static evaluations are applied. Therefore, this study evidenced that innovative BPS-based approaches will likely deliver valuable information to stakeholders. Importantly, deepening this analysis and proposing BPS use within this framework was only possible given the public results of RAC labeling carried out by the national institute. The Brazilian experience regarding publicizing such data may guide other policymakers towards similar strategies, enabling similar approaches worldwide.

Conclusion

The present study provides valuable insights into calculating Cooling Seasonal Performance Factors (CSPF) for Room Air Conditioners (RAC) in Brazil. First, the importance of considering local climates in the CSPF calculation was highlighted by comparing country-wide efficiency metrics calculated with fixed bin hours of outdoor temperatures to those calculated with typical data from specific climates. Using a general temperature distribution to calculate CSPF in a vast country like Brazil may hinder RAC performance given differences between colder and hotter climates. On the one hand, consumers from colder climates may expect poorer performance from their RAC when using only a general efficiency indicator as guidance as it may be inaccurate, especially for nighttime operations. On the other hand, consumers from hotter climates may expect better performance from their RAC, whose general efficiency indicator may be inaccurate, especially during daytime operations.

This study's key outcomes and innovations relied on including building performance simulation (BPS) under this framework. Determining the hours throughout the year in which RAC are more likely to be operating is a feasible approach to reaching more precise efficiency metrics. Our results indicated that even CSPF calculated to specific climates might be enhanced with such an approach. For instance, BPS results may guide the exclusion of outdoor temperature intervals in which the RAC is not being used. This approach will impact the final metric since the efficiency variability also depends on how each machine performs under full and partial loads.

This study's findings have implications for different stakeholders in this field, and may benefit policymakers, manufacturers, and consumers. Policymakers may use these results to improve evaluation approaches by moving from static climate consideration to climate-specific regulations. Manufacturers may produce and recommend RAC according to specific climate and usage needs. Consequently, consumers may be provided with better solutions for their problems and needs, possibly increasing user satisfaction and technology adoption levels. Future studies may consider the advances achieved herein to provide more detailed evaluations of different buildings and their envelope efficiency levels.

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