A Comparative Energy Efficiency Analysis Between Inverter-Driven and Conventional Air Conditioning Systems

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Abstract: ***The strong demand for energy efficiency in buildings and industries has driven the search for more sustainable and technologically integrated air conditioning systems. This study conducts a comparative analysis of energy efficiency in air conditioning systems, considering the integration of electrical and mechanical parameters based on data from manufacturers and technical literature. Adopting a literature review approach, the research examines publications from 2015 to 2025 in databases such as SciELO and Google Scholar, focusing on studies that provide efficiency parameters such as COP, EER, and SEER. The analysis reveals that VRF and chiller systems excel in energy performance, largely due to the use of inverter compressors and intelligent controls, while split and rooftop systems, though simpler in design, demonstrate lower efficiency under partial loads. The importance of automation, the adoption of BLDC motors, and the use of new environmentally friendly refrigerants in reducing electricity consumption and greenhouse gas emissions are also highlighted. It is concluded that the integration of electrical and mechanical components, combined with automation and predictive maintenance technologies, represents the primary pathway toward energy optimization and sustainability in the HVAC sector, underscoring the need for future experimental studies to validate the theoretical findings in practice.***

Keywords: Energy efficiency; Air conditioning; Electrical and mechanical integration; Automation; Sustainability.

1. INTRODUCTION

The air - conditioning sector, which accounts for a significant portion of electricity consumption in residential, commercial, and industrial buildings, has become one of the main targets of studies aiming at optimizing energy performance and reducing operating costs. According to Wagner (2019), efficient control of the operation of air - conditioning equipment is one of the determining factors for the rational use of electricity, as poorly sized or non - automatically controlled systems result in significant energy waste.

Energy efficiency in the context of air - conditioning involves an integrated analysis of electrical, mechanical, and thermal variables. Alves (2019) emphasizes that implementing efficiency plans in refrigeration systems requires not only the appropriate selection of equipment but also an understanding of the interactions between thermal load, electrical power, and thermodynamic performance. This balance between electrical consumption and mechanical performance is essential for achieving sustainable and reliable operation. Similarly, Rosa and Lopes (2022) highlight that the performance of VRF systems directly depends on the compatibility between electrical and mechanical components, requiring a detailed evaluation of efficiency parameters under different operating conditions.

Air conditioning systems are essential not only for thermal comfort in built environments but also for industrial processes that rely on strict temperature and humidity control. According to Blasius, Schmid, and Rossi (2019), the thermo - energetic behavior of buildings is closely related to the interaction between the thermal envelope and air - conditioning equipment, which reinforces the importance of a systemic and interdisciplinary analysis. Thus, understanding the integration between the electrical and mechanical subsystems becomes essential for designing more efficient systems that align with energy sustainability standards and policies.

The importance of energy efficiency is also directly associated with environmental and economic impacts. Excessive electricity consumption for air - conditioning purposes contributes to the increase in greenhouse gas emissions and the depletion of natural resources. Reis (2016) emphasizes that the application of energy - efficiency measures can significantly reduce operating costs in large - scale projects such as hotels and industries while contributing to the reduction of the carbon footprint. Otão (2018) adds that improving efficiency in industrial air - conditioning systems requires a joint approach between automation, maintenance, and performance analysis.

In this scenario, public policies and efficiency programs, such as PROCEL, have been encouraging the adoption of cleaner technologies and the modernization of refrigeration and air - conditioning systems across the country. Paiva et al. (2020) note that energy audits in public and private institutions are fundamental for identifying waste and proposing high - impact corrective measures, especially in the context of artificial air - conditioning systems. Such initiatives reinforce the strategic role of electrical engineering in building a more rational and sustainable energy model.

Given this context, the general objective is to comparatively analyze the energy efficiency of air - conditioning systems, considering the integration between electrical and mechanical parameters, based on data provided by manufacturers and technical literature. The specific objectives are: to describe the main electrical and mechanical parameters that influence the energy efficiency of air - conditioning systems, to compare the performance indices (COP, EER, and SEER) between different types of systems based on technical information from suppliers, and to discuss the implications of energy efficiency for the sustainability and operating costs of air - conditioning installations.

2. THEORETICAL FRAMEWORK

2.1 Energy Efficiency in Air - Conditioning Systems

Energy efficiency is a concept widely used in electrical and mechanical engineering, which consists of the rational use of energy to perform a function with the lowest possible consumption without compromising the system's performance (Otão, 2018). According to Alves (2019), energy efficiency in air - conditioning systems is directly associated with the ability of equipment to convert electrical energy into useful work, optimizing the refrigeration process and reducing waste. In this context, regulatory bodies such as the National Electric Energy Agency (ANEEL) and the National Electric Energy Conservation Program (PROCEL) establish parameters and incentive programs to promote the continuous improvement of the energy performance of air - conditioning equipment, ensuring the minimum efficiency standards required by the national market.

The Brazilian Association of Technical Standards (ABNT) also plays an essential role through standards such as NBR 16401, which deals with the efficiency of air - conditioning systems in buildings, and NBR ISO 50001, focused on energy management in organizations. Rosa and Lopes (2022) reinforce that the application of such standards not only ensures compliance with technical requirements but also contributes to environmental sustainability and the reduction of operational costs. Therefore, energy efficiency transcends the economic aspect and assumes a strategic character, integrating into policies for mitigating environmental impacts and promoting technological innovation.

Among the main energy performance indicators are the Coefficient of Performance (COP), the Energy Efficiency Ratio (EER), and the Seasonal Energy Efficiency Ratio (SEER), widely used to evaluate the relationship between useful thermal capacity and consumed energy (Melatte, 2016). According to Higa et al. (2023), these indices allow measuring the degree of energy utilization of air - conditioning systems, enabling the comparison between technologies and the identification of improvement opportunities. Thus, the joint analysis of electrical and mechanical parameters becomes essential to understand the thermodynamic behavior and the impact of energy consumption under different operating conditions.

The evolution of air - conditioning systems follows the technological development of thermal and electrical engineering throughout the 20th century (Melatte, 2016). The first applications date back to the beginning of the last century, when mechanical refrigeration began to be used in industrial environments and, later, in commercial and residential spaces (Otão, 2018).

Reis (2016) emphasizes that technological advancement in compressors and refrigerants was decisive for the popularization of air - conditioning systems, making it possible to expand this type of equipment on a large scale.

Over the years, the systems have become more compact, efficient, and automated (Melatte, 2016). In harmony with Otão (2018), the incorporation of electronic control devices and high - efficiency motors has transformed air - conditioning into one of the most dynamic sectors of modern engineering. This evolution has enabled the emergence of hybrid technologies and intelligent solutions that automatically adjust the thermal load and electrical consumption according to the environmental conditions.

Currently, air - conditioning is an essential component of thermal comfort and productivity in built environments. Blasius, Schmid, and Rossi (2019) highlight that the integration between architectural envelopes and air - conditioning systems has been a growing field of research, seeking to simultaneously optimize energy efficiency and thermal comfort. In this scenario, innovations in automation, sensors, and remote control, as pointed out by Rocha et al. (2019), consolidate the concept of "intelligent air - conditioning", in which performance is continuously adjusted to reduce losses and improve overall consumption.

Air - conditioning systems can be classified into several categories according to the operating principle, application, and type of heat exchange used. Among the most commonly used models are Split systems, Multi - Split systems, VRF (Variable Refrigerant Flow), Chillers, Rooftop, and Fan Coil (Blasius, Schmid, and Rossi, 2019).

In accordance with Rosa and Lopes (2022), VRF systems stand out for offering individualized temperature control and greater energy efficiency, due to the ability to modulate the refrigerant flow according to the thermal demand of each environment.

Split and Multi-Split systems are widely used in small and medium-sized buildings, offering low installation costs and simplified operation. However, as Pin (2024) highlights, these models have limitations in terms of efficiency at partial loads and the control of multiple thermal zones. Chiller systems, recommended for large-scale industrial and commercial applications, provide better performance in continuous operation and allow integration with building automation systems (Higa et al., 2023).

In addition, Omido, Barboza and Júnior (2017) point out the potential of using alternative sources, such as geothermal energy, in hybrid air conditioning systems, offering a sustainable and highly efficient alternative. This integration of different technologies reflects the trend of diversification in the sector and the growing focus on sustainability and energy savings.

In general, the theoretical comparison between direct systems (such as Split and VRF) and indirect systems (such as Chillers and Fan Coil) shows that overall efficiency depends on the interaction between electrical, mechanical and environmental parameters. Therefore, the automation of these systems has been essential to reduce energy losses and optimize operational performance, reinforcing the need for a multidisciplinary approach between electrical, mechanical engineering and process control (Boaventura, 2016).

Several factors directly influence the energy performance of air conditioning systems. Environmental conditions, such as air temperature, relative humidity and altitude, affect heat transfer and cooling load. According to Reis (2016), an increase in ambient temperature raises electrical consumption and reduces thermodynamic efficiency, requiring greater effort from compressors and fans. The quality of the installation is also decisive, as improper sizing and deficiencies in thermal insulation can cause system overload and energy waste.

Preventive maintenance is another essential factor for operational efficiency. Periodic calibration of sensors, cleaning of filters and coils, and monitoring of the refrigerant fluid level contribute to maintaining the system's nominal capacity. According to Otão (2018), neglecting maintenance can result in up to 30% losses in overall efficiency, compromising the electrical and mechanical performance of the equipment. In addition, the quality of the refrigerants used directly affects performance, as properties such as viscosity and saturation pressure influence the heat transfer coefficient (Rosa; Lopes, 2022).

In this way, the analysis of environmental, operational and maintenance factors is essential to understand the variation in energy efficiency in real air conditioning systems. Recent studies, such as that of Pin (2024), demonstrate that energy management practices associated with predictive maintenance and automation can optimize performance, extend the service life of equipment and reduce the environmental impact of electrical consumption.

Air conditioning systems, although essential for thermal comfort and productivity, are among the biggest contributors to indirect greenhouse gas emissions. This occurs due to the high electrical consumption and the use of refrigerants with a high global warming potential, such as HFCs (hydrofluorocarbons) and HCFCs (hydrochlorofluorocarbons). According to Omido, Barboza and Júnior (2017), the gradual replacement of these compounds is essential to reduce environmental impacts and meet the targets established in international agreements, such as the Montreal Protocol and the Kigali Amendment.

The transition to eco-friendly refrigerants, such as R-32, R-290 (propane) and CO_2, represents an established trend in the sector, aligning energy efficiency and environmental sustainability. Higa et al. (2023) state that the adoption of these fluids, associated with the use of high-efficiency compressors and automation systems, significantly reduces gas emissions and electricity consumption. This technological change is also driven by environmental legislation and certification programs, which encourage the development of less polluting equipment with a lower impact on the life cycle (Rosa; Lopes, 2022).

Thus, energy efficiency and sustainability complement each other as pillars of an engineering approach aimed at the rational use of resources and the mitigation of the effects of global warming. The integration of technological innovation, public policies, and environmental awareness is pointed out as a strategic path for the future of sustainable air conditioning (Alves, 2019).

The modernization of air conditioning systems is strongly associated with the advancement of automation and intelligent control technologies. The incorporation of sensors based on the Internet of Things (IoT) allows for the continuous monitoring of electrical and thermal variables, enabling automatic adjustments of temperature, air flow, and operating power. Boaventura (2016) highlights that these solutions reduce waste and improve the overall performance of the systems, promoting the concept of adaptive and responsive air conditioning.

Another relevant innovation is the use of variable frequency drives (VFDs) to control motors and compressors. This technology adjusts the rotation of the equipment according to demand, reducing electricity consumption and increasing mechanical durability. Wagner (2019) observes that the dynamic control of electrical load is one of the main factors in improving the energy efficiency of modern installations, especially when integrated into automated supervision systems.

Concomitantly, current trends point to the development of green buildings, which integrate air conditioning systems with renewable energy sources, such as photovoltaic power generation. Reis (2016) emphasizes that the integration of solar panels and HVAC systems represents a promising strategy to reduce dependence on the electrical grid and promote energy self-sufficiency. The convergence of IoT, automation, and solar energy defines the new paradigm of sustainable air conditioning, where efficiency and innovation go hand in hand (Rosa; Lopes, 2022).

2.2 Electrical and Mechanical Aspects in Energy Efficiency

The electrical structure of an air conditioning system comprises the set of circuits, devices, and protections responsible for powering and controlling the equipment. The proper sizing of cables, circuit breakers, and protection devices is essential to ensure safety, performance, and energy efficiency (Rosa; Lopes, 2022). According to Higa et al. (2023), overloading in circuits or undersizing of conductors results in losses due to heating, increased current, and a decrease in the overall efficiency of the system. Therefore, the electrical design should be developed considering factors such as nominal current, voltage drop, and operating temperature of the conductors.

Nevertheless, the correct division of circuits and phase balancing are measures that reduce losses and increase the reliability of the power supply. In addition, the use of appropriate protection devices, such as thermomagnetic circuit breakers and time-delay fuses, prevents failures resulting from overcurrent or short-circuit, preserving both the equipment and the integrity of the electrical installation (Rosa; Lopes, 2022).

The quality of electrical energy, which directly influences the performance of air - conditioning systems, also needs to be highlighted. Voltage oscillations, harmonics, and phase imbalances can cause premature failures in motors and compressors, in addition to reducing the efficiency of electronic components. Concomitantly, the adoption of harmonic filters, stabilizers, and uninterruptible power supplies (UPS) contributes to the control of distortions and fluctuations, ensuring the operational stability and reliability of the electrical system (Boaventura, 2016).

Electric motors are the core of the operation of air - conditioning systems, being responsible for converting electrical energy into mechanical work in compressors, fans, and pumps. The most common types are induction motors, synchronous motors, and Brushless DC (BLDC) motors, each with specific efficiency and control characteristics. According to Wagner (2019), BLDC motors have higher efficiency and durability because they operate with lower friction and heating losses, in addition to allowing precise control of rotation and torque.

The motor efficiency classification follows international standards defined by IEC 60034 - 30, which establishes the categories IE1 (standard), IE2 (high - efficiency), IE3 (premium), and IE4 (super - premium) (Boaventura, 2016). Higa et al. (2023) highlight that higher - class motors can reduce energy consumption by up to 15%, positively impacting the total efficiency of the HVAC system. The higher initial investment tends to be offset by the lower operating cost over the equipment's useful life cycle.

Speed control is another determining factor for the energy efficiency of motors. The use of variable - frequency drives (VFDs) enables the dynamic adjustment of motor rotation according to the thermal demand, avoiding continuous operation at full load. Alves (2019) notes that this control strategy contributes to reducing electrical consumption and minimizing mechanical wear, as the motor operates more stably and with lower current peaks. Thus, the integration of high - efficiency motors and VFDs represents one of the most effective solutions for the energy optimization of air - conditioning systems (Rosa; Lopes, 2022).

The power factor (PF) is an essential parameter in the analysis of electrical efficiency, as it expresses the relationship between active power and apparent power in a system. In air - conditioning systems, the PF tends to be reduced due to the presence of inductive loads, such as motors and transformers. A low power factor implies an increase in electrical current and, consequently, resistive losses in conductors. According to Reis (2016), correcting the PF is fundamental to reducing costs with reactive energy and optimizing the performance of the electrical installation, ensuring better use of the power supplied by the grid.

Power factor correction can be carried out by installing automatic or fixed capacitor banks, which compensate for the inductive reactive power of the system. Boaventura (2016) explains that the sizing of these banks should consider the load profile and seasonal consumption variations, especially in installations with multiple air - conditioning equipment. In more modern systems, the use of automatic controllers allows real - time adjustment of the compensation, avoiding over - correction and reducing losses due to reactance.

Electrical harmonics, mainly generated by electronic devices and frequency inverters, also affect the efficiency and lifespan of equipment. Rosa and Lopes (2022) highlight that an excess of harmonics causes heating in conductors, vibrations, and premature failures in motors and transformers. Mitigating these effects requires the use of active or passive filters, as well as proper grounding and load sectioning. Thus, controlling harmonics and maintaining the power factor close to unity are essential conditions for good electrical performance and the overall efficiency of air - conditioning systems (Higa et al., 2023).

Modern air - conditioning systems are increasingly incorporating automation and electronic control technologies, allowing for the precise monitoring of variables such as temperature, humidity, and pressure. The use of Programmable Logic Controllers (PLCs), digital sensors, and intelligent controllers enables the dynamic adjustment of operating conditions, optimizing electrical energy consumption and thermodynamic performance. According to Boaventura (2016), integrating automated devices into HVAC systems significantly reduces energy losses, as environmental variables are controlled in real - time according to occupancy demands and external conditions.

Automation also extends to communication between equipment through network protocols such as BACnet, Modbus, and Lon Works, which allow for the centralized management of air - conditioning functions. Rosa and Lopes (2022) highlight that using presence and temperature sensors distributed in different thermal zones increases efficiency and comfort, avoiding the unnecessary operation of units in unoccupied environments. Additionally, integration with Building Management Systems (BMS) enables the simultaneous control of lighting, ventilation, and refrigeration, increasing the potential for energy savings and operational sustainability (Higa et al., 2023).

Automation optimization is based on algorithms that continuously adjust the rotation of fans and compressors, air flow, and refrigerant volume. According to Rocha et al. (2019), this approach promotes a balance between thermal comfort and electrical consumption, eliminating overloads and reducing demand peaks. Therefore, applying automation to air - conditioning is established as a fundamental strategy for achieving energy efficiency in commercial and industrial buildings, ensuring precise operational control and simplified maintenance (Alves, 2019).

The vapor compression cycle, for its part, constitutes the central operating principle of air - conditioning systems and is composed of four main stages: compression, condensation, expansion, and evaporation. During the process, the refrigerant fluid continuously circulates between the system's components, such as the compressor, condenser, expansion device, and evaporator, transferring heat from the internal environment to the external one. According to Reis (2016), the efficiency of the cycle depends on the balance between pressure, temperature, and fluid volume, which defines the coefficient of performance (COP) of the equipment.

The types of compressors used in air - conditioning systems vary according to the application and the required capacity. Among the most commonly used are scroll, screw, and centrifugal models. Rosa and Lopes (2022) explain that scroll compressors are common in small and medium - sized systems due to their quiet operation and low maintenance cost. Screw and centrifugal compressors, on the other hand, are applied in large - scale industrial and commercial installations, offering greater efficiency in continuous operation and with variable loads. The mechanical performance of these components directly influences the electricity consumption and the overall thermodynamic efficiency (Higa et al., 2023).

The relationship between mechanical performance and electricity consumption is one of the main factors of analysis in air - conditioning engineering. Alves (2019) observes that mechanical failures, such as excessive vibrations, clearances, and misalignments, increase energy losses and reduce the service life of equipment. Operational efficiency, therefore, depends on the synergy between the electrical and mechanical subsystems, as well as on preventive maintenance and the quality of the components used. This proper integration is what enables achieving consistent results in energy efficiency and operational reliability (Otão, 2018).

Refrigerants play an essential role in the heat transfer process, determining the thermal efficiency and the environmental impact of air - conditioning systems. Among the most commonly used are R - 22, R - 410A, R - 32, and CO_2 (R - 744). Each one has specific thermodynamic properties that influence performance and energy consumption. According to Omido, Barboza, and Júnior (2017), the choice of refrigerant should consider parameters such as working pressure, heat capacity, and environmental impact, especially regarding the global warming potential (GWP) and the ozone depletion potential (ODP).

R - 22, widely used in old systems, is being replaced by more sustainable alternatives, such as R - 410A and R - 32, due to the restrictions imposed by the Montreal Protocol. Higa et al. (2023) explain that R - 410A, being a mixture of hydrofluorocarbons, has high thermodynamic efficiency, although it still has a moderate global warming potential. R - 32 is considered a more ecological option, with better thermal conductivity and less environmental impact. In larger systems, CO_2 (R - 744) has stood out as a natural, safe, and highly efficient refrigerant under high pressures, representing a promising alternative to synthetic substances (Rosa; Lopes, 2022).

The efficiency of heat exchange depends not only on the properties of the refrigerant but also on the design of the heat exchangers, the air flow, and the maintenance of the components. According to Reis (2016), deposits, dirt, and blockages in coils significantly reduce the heat exchange capacity, requiring more electrical power to achieve the same air - conditioning conditions. For this reason, the choice of the ideal refrigerant should be accompanied by proper operation and maintenance practices, ensuring maximum energy efficiency and the lowest emission of pollutants (Alves, 2019).

2.3 Comparative Analysis and Trends in Energy Efficiency

The use of manufacturers’ catalogs and technical manuals represents a primary source of information for comparative evaluation, as these documents present specifications such as power, air flow, nominal efficiency, and performance variation at different load ranges. Rosa and Lopes (2022) highlight that these materials enable the identification of the operating characteristics of systems in continuous or intermittent mode, as well as highlighting the differences between technologies with and without frequency inversion control. Thus, the technical data constitute a solid basis for comparing the electrical and mechanical efficiency between HVAC systems, especially when practical tests are not feasible (Higa et al., 2023).

Split and VRF (Variable Refrigerant Flow) systems represent widely used solutions in commercial and residential buildings, differing mainly in the way the refrigerant flow is controlled and the level of automation. The Split system is characterized by its simple construction, lower installation cost, and easy maintenance. However, it has limitations in terms of energy efficiency at partial loads, as the operation of the compressors is generally of the on/off type. Rosa and Lopes (2022) state that the performance of these systems tends to be lower when compared to VRF, especially in environments with significant thermal variation throughout the day. The VRF system, on the other hand, stands out for its ability to automatically adjust the refrigerant flow according to the thermal demand of each environment, providing greater flexibility and energy savings.

In terms of average electrical consumption, VRF systems demonstrate better performance, mainly due to the use of compressors with variable frequency drives (VFD), which modulate the rotation speed according to the cooling need. Alves (2019) emphasizes that this characteristic allows for a reduction of up to 30% in energy consumption compared to conventional systems. In addition, the seasonal efficiency (SEER) of VRF equipment tends to be higher, as the system adapts its operation to external conditions, avoiding energy waste during periods of lower thermal load (Higa et al., 2023).

Regarding installation and maintenance costs, the Split system requires a lower initial investment and is simpler in terms of parts replacement. On the other hand, the VRF system, although more expensive to install, offers lower long - term operating costs and greater durability, due to the reduction of start - up cycles and the intelligent monitoring of faults. Pin (2024) observes that the cost - benefit ratio of the VRF becomes more favorable in medium and large - scale projects, where energy efficiency and individualized temperature control justify the high initial investment. Thus, the VRF is established as the most efficient and adaptable solution for buildings with multiple thermal zones (Boaventura, 2016).

Chiller and Rooftop systems are widely used in commercial and industrial applications, standing out for their robustness and the ability to air - condition large volumes of air. The Chiller uses an indirect refrigeration cycle, in which the chilled water circulates to the air - handling units, allowing for the thermal control of large environments with high efficiency. In contrast, the Rooftop system, a direct - refrigeration system, is a compact alternative that integrates all components, i.e., compressor, condenser, and evaporator, into a single unit, usually installed on the roof of buildings. According to Reis (2016), the Chiller performs better in installations with continuous operation, while the Rooftop is more suitable for buildings with variable loads and intermittent use.

Efficiency at partial and full loads is one of the main differentiators between these two technologies. Rosa and Lopes (2022) point out that Chillers, especially those equipped with variable - speed centrifugal compressors, achieve higher coefficient of performance (COP) under partial - load conditions, resulting in a significant reduction in energy consumption. On the other hand, Rooftop systems, despite their simplicity and ease of maintenance, have less control flexibility and lower performance under load variations. Higa et al. (2023) add that, when integrated with automation systems, Chillers offer better thermal stability and optimized energy performance.

External environmental conditions also have a significant influence on the energy performance of both systems. Alves (2019) explains that the efficiency of Rooftops is strongly affected by the temperature and humidity of the outside air, since the condensation process occurs directly in the external environment. Chillers, by operating with water as an intermediate fluid, maintain greater thermal stability, even under ambient temperature variations. Otão (2018) emphasizes that, in hot - climate regions, the use of Chillers with cooling towers and automatic fan - speed control represents a more efficient and long - lasting alternative. Therefore, the choice between the two systems should consider not only the initial investment but also the operating regime, the local climate, and the building's energy - consumption profile.

Analysis of electrical parameters is fundamental to understanding the performance and efficiency of air - conditioning systems. The main indicators include the nominal power (kW), the electric current (A), and the power factor (PF), which reflect the balance between the active power and the total power used. According to Reis (2016), equipment with improperly sized power or operation above the nominal current tends to have significant losses, resulting in conductor heating and a decrease in energy efficiency. The correct sizing of the electrical load and the compatibility between compressors, motors, and controllers are decisive for the overall performance of the system.

The behavior of the systems under load and voltage variations also directly affects the efficiency and operational stability. Rosa and Lopes (2022) highlight that voltage fluctuations can generate overcurrent and excessive heating, reducing the lifespan of the motors and compromising the system's performance. The stability of the electrical supply is, therefore, a critical factor for efficient operation, especially in installations with multiple compressors and fans. The presence of surge - protection devices and phase balancing helps to mitigate variations that affect energy performance (Otão, 2018).

Variable frequency drives (VFDs) and soft - start devices represent effective solutions for optimizing the electrical control of motors. These equipment allow the rotation of the compressors to be adjusted according to the thermal demand, reducing current peaks and electrical consumption. According to Alves (2019), the adoption of VFDs can result in up to 25% annual energy - consumption savings, in addition to reducing mechanical stress and improving the power factor. The integration of these resources into the automated control system consolidates the balance between electrical efficiency and operational stability (Higa et al., 2023).

Mechanical parameters directly influence the thermodynamic and energy performance of air - conditioning systems. Volumetric efficiency and thermodynamic efficiency are indicators that measure the compressor's ability to suck in and compress the refrigerant with the minimum of internal losses. Alves (2019) states that the reduction of volumetric efficiency is often associated with leaks, clearances, and component wear, which leads to an increase in electricity consumption and a reduction in cooling capacity. Thus, a detailed mechanical analysis is essential to ensure the balance between the effort of the electric motor and the expected thermal performance.

The type of compressor and the refrigerant used play a decisive role in the overall efficiency of the system. Rosa and Lopes (2022) report that scroll compressors have better performance for small - and medium - sized systems, while centrifugal and screw models are more suitable for high - capacity industrial applications. The choice of refrigerant influences thermodynamic properties such as saturation pressure and heat capacity, directly impacting the heat transfer rate and the COP. Omido, Barboza, and Júnior (2017) emphasize that replacing high - GWP refrigerants with more ecological options, such as R - 32 and CO_2, represents an important strategy to balance energy efficiency and environmental sustainability.

The relationship between the compression cycle and thermal dissipation is also decisive for the system's performance. Higa et al. (2023) explain that failures in heat dissipation in condensers and heat exchangers result in an increase in discharge pressure and, consequently, higher electrical demand. Efficient control of heat exchange, combined with the correct sizing of mechanical components, ensures operational stability and reduces energy consumption. Thus, the joint evaluation of electrical and mechanical parameters allows for an integrated understanding of the behavior of air - conditioning systems (Reis, 2016).

The overall efficiency of air - conditioning systems results from the combination of electrical and mechanical performance and should be analyzed from the perspective of total energy consumption and the economic return on investment. The theoretical calculation of annual consumption (kWh/year) allows estimating the energy impact of different technologies in operation. According to Rosa and Lopes (2022), this analysis should consider the number of annual operating hours, the load factor, and seasonal temperature variations. Such data enable identifying the operating cost and comparing the performance between equivalent systems under real - use conditions.

The comparison between the initial investment and the energy return is fundamental to determine the economic viability of air - conditioning technologies. Alves (2019) highlights that VRF and Chiller systems, although they have a higher initial cost, have a faster financial return due to savings in electricity consumption and a reduction in corrective maintenance. The calculation of the energy payback, i.e., the time required for the savings generated to compensate for the investment, is one of the main indicators of economic efficiency in air - conditioning engineering. In general, systems with automation and frequency inverters have a return between two and five years, depending on the usage profile and environmental conditions (Paiva et al., 2020).

In addition to the acquisition cost and electricity consumption, the cost - benefit analysis should include aspects such as the useful life of components, ease of maintenance, and environmental impact. Otão (2018) emphasizes that integrated solutions, based on high - efficiency motors and automated control, have greater durability and significantly reduce energy consumption over the life cycle. Thus, the overall evaluation of efficiency should consider both the technical performance and the financial and environmental sustainability of the system, guiding more assertive decisions in the air - conditioning sector (Reis, 2016).

3. METHODOLOGY

This research is characterized as an exploratory and descriptive literature review, focused on the comparative analysis of energy efficiency in air - conditioning systems from electrical and mechanical aspects. For this purpose, it was based on secondary sources obtained through scientific articles, dissertations, theses, and technical reports from manufacturers, selected according to criteria of relevance, currency, and reliability.

The analysis period covered publications between 2015 and 2025 to encompass recent studies on energy efficiency, automation, and optimization of air - conditioning systems. The main data sources used were the SciELO and Google Scholar platforms, as they are widely recognized databases in the field of Electrical Engineering and provide technical and scientific works on the topic.

Inclusion criteria were adopted that prioritized studies containing quantitative and qualitative information related to electrical and mechanical performance parameters, such as power, energy consumption, power factor, coefficient of performance, and Energy Efficiency Ratio. Works that describe energy evaluation methodologies, automation, and air - conditioning management in industrial, commercial, or institutional buildings were also included, as exemplified in the studies by Alves (2019), Rosa and Lopes (2022), and Higa et al. (2023).

As exclusion criteria, studies that did not present comparable technical data, purely theoretical approaches without an experimental basis, or those dealing with energy efficiency in sectors not related to air - conditioning were discarded. This filtering ensured greater consistency and analytical focus in the final sample of publications used.

The methodological process involved four main stages: initial selection of publications using keywords such as "energy efficiency", "air - conditioning systems", "electrical aspects", and "mechanical aspects"; exploratory and critical reading of the identified studies, focusing on the methodology and the energy performance results presented; comparison of efficiency parameters between different equipment and technologies, using technical data from manufacturers' catalogs and manuals; synthesis of the results, relating the evidence found in the literature to the integration between the electrical and mechanical dimensions of air - conditioning.

4. RESULTS AND DISCUSSIONS

The comparative analysis of air - conditioning systems was based on technical data from manufacturers' catalogs and manuals, considering parameters such as thermal capacity (BTU/h), electrical power (kW), coefficient of performance, and energy efficiency index. Table 1 summarizes the comparison between the main models of Split, VRF, Chiller, and Rooftop equipment, considering the nominal power, average electrical consumption, and seasonal efficiency.

Table 1: Theoretical Comparison of the Main Air - Conditioning Systems

System	Capacity (BTU/h)	Power (kW)	Average COP	Average EER (Btu/W.h)	Control Type
Split	18.000-36.000	2,5-3,8	3,1	10,6	On/Off
VRF	36.000-240.000	3,2-22	4,5	15,4	Frequency Inverter
Chiller	200.000-1.000.000	50-250	5,6	19,1	Proportional Control
Rooftop	60.000-300.000	8-30	3,6	12,3	Thermostatic

Source: Adapted from Alves (2019) and Rosa and Lopes (2022).

The results show that VRF and Chiller systems present the highest COP and EER values, reflecting greater energy efficiency under partial load conditions. While Split systems have satisfactory performance in small applications, their intermittent operation (on/off) reduces overall efficiency. According to Higa et al. (2023), the continuous modulation of compressors in VRF systems ensures stable operation, adjusting the refrigerant flow according to the thermal demand. Chiller systems, on the other hand, achieve better results in industrial installations due to continuous operation and the ability to utilize residual heat in heat exchangers.

The variation of EER between models also reveals the direct influence of temperature and ambient humidity. In accordance with Rosa and Lopes (2022), EER values can drop by up to 20% in regions with high humidity and an average temperature above 32∘C. Under these conditions, the efficiency of Rooftop systems is particularly affected, as condensation occurs in direct contact with the external air. Chiller systems, on the contrary, maintain more stable performance due to the use of water as an intermediate fluid, which reduces dependence on external climate variations (Reis, 2016).

The correlation between the electrical and mechanical performance of HVAC systems is decisive for overall efficiency. High - efficiency motors (IE3 and IE4), combined with frequency inverters, show lower current consumption and better power factor, and also reduce the mechanical wear of compressors. Alves (2019) highlights that electrical efficiency is only fully achieved when there is compatibility between the motor and the type of compressor used. This integration is mainly observed in VRF systems, in which BLDC motors and variable - speed compressors operate synergistically to adjust energy consumption to the actual thermal load.

In contrast, systems with simple induction motors present greater losses due to friction and starting current, which increases energy consumption and the wear of mechanical components. Otão (2018) observes that mechanical degradation, such as bearing clearances and dynamic imbalance, reduces volumetric efficiency and increases discharge temperature. Therefore, the integration between predictive maintenance and automated control is essential to maintain the balance between electrical and mechanical performance. Recent studies show that automation based on vibration and temperature sensors contributes to extending the service life and increasing the reliability of systems (Higa et al., 2023).

The comparative results also indicate that energy efficiency depends not only on the equipment technology but also on the quality of the installation, the adequacy of the electrical design, and preventive maintenance. VRF and Chiller systems stand out for their superior efficiency and operational flexibility, but require a higher initial investment and qualified professionals for operation and maintenance. According to Paiva et al. (2020), the lack of periodic calibration of sensors and expansion valves can compromise up to 15% of the nominal efficiency of the equipment. That is, energy management and performance control become indispensable components for the sustainability of the HVAC sector.

From a normative perspective, the ABNT NBR 16401 and ISO 50001 standards establish parameters that guide the sizing, operation, and maintenance of high - efficiency air - conditioning systems. Rosa and Lopes (2022) emphasize that compliance with these standards ensures not only energy efficiency but also thermal comfort and indoor air quality. In fact, certification labels such as PROCEL and LEED reinforce the importance of continuous measurement of efficiency and the incorporation of intelligent and sustainable technologies. In summary, the results indicate that maximum efficiency is achieved through the convergence of electrical design, mechanical control, and intelligent automation (Boaventura, 2016).

Technological trends in the air - conditioning sector are strongly associated with automation, digitalization, and the use of high - efficiency materials and components. The incorporation of intelligent sensors and automation systems based on the Internet of Things (IoT) has enabled precise control of variables such as temperature, humidity, and operating pressure. According to Higa et al. (2023), the integration of sensors and adaptive control algorithms allows for real - time regulation, ensuring the balance between thermal comfort and energy savings. This intelligent automation represents an evolution compared to manual controls, promoting greater stability and reduced electricity consumption.

The development of new refrigerants and BLDC (Brushless Direct Current) motors has also driven the energy efficiency of HVAC systems. Alves (2019) highlights that refrigerants such as R - 32 and CO_2 (R - 744) offer better thermal conductivity and lower global warming potential, gradually replacing more polluting substances such as R - 22. Meanwhile, BLDC motors have higher efficiency than traditional induction motors, reducing electrical losses and enabling more precise speed control. According to Rosa and Lopes (2022), the combination of BLDC compressors, frequency inverters, and intelligent sensors forms the basis of new - generation air - conditioning systems, which combine efficiency, reliability, and environmental sustainability.

5. CONCLUSION

During this research, a comparative analysis of energy efficiency in air - conditioning systems was carried out, considering the integration of electrical and mechanical aspects and based on technical data from manufacturers' catalogs and manuals. From the literature review and the analysis of electrical and thermodynamic parameters, it was observed that VRF and Chiller systems presented the best performance indices (COP and EER), especially under partial - load conditions. These results confirm the relevance of frequency inverter control technology, automation, and the appropriate selection of electrical and mechanical components in optimizing energy efficiency.

The integration of the electrical and mechanical subsystems proved to be a decisive factor for the overall performance of the equipment. High - efficiency motors (IE3 and IE4), BLDC compressors, and frequency inverters reduced over - current losses and increased the durability of the components. From a mechanical perspective, preventive maintenance and the dynamic balance of rotating assemblies had a direct impact on volumetric efficiency and operational stability. Moreover, the harmony between the electrical design, the thermodynamic cycle, and the electronic control devices represents the most promising path to achieving maximum efficiency and reliability in HVAC systems.

The results also reinforce the importance of comparative analysis as a tool for technical and economic decision-making. Comparing installation costs, energy efficiency, and financial returns allows for the identification of the most suitable technologies for each type of building.

VRF and Chiller systems, although they require a higher initial investment, offer significant energy savings over the life cycle, resulting in a lower environmental impact and better cost-benefit ratio. This approach highlights the need for incentive policies and certifications (such as PROCEL and LEED) to encourage the adoption of sustainable and energy-optimized solutions.

Regarding future trends, the study highlights the potential of technologies based on smart automation, IoT sensors, and artificial intelligence to improve the predictive control and maintenance of air - conditioning systems. Additionally, the development of new ecological refrigerants and high - thermal - conductivity materials points to a new generation of more efficient and environmentally responsible equipment. However, the limitation of the present study regarding the use of technical catalog data, which does not fully reproduce real - world operating conditions, should be recognized. Therefore, it is recommended that future research include computer simulations and experimental field measurements to empirically validate the theoretical results and improve the comparative models.

Furthermore, it was found that the energy efficiency of air - conditioning systems depends on the synergy between electrical design, mechanical performance, and automation. The application of advanced technologies and smart maintenance practices enables a significant reduction in electricity consumption and indirect carbon emissions, contributing to more sustainable and resilient buildings. Thus, the integration of electrical, mechanical engineering, and energy management emerges as an essential pillar for the future of efficient and environmentally responsible air - conditioning.

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