UNIVERSITY OF SAO PAULO
ENERGY GRADUATION PROGRAM
INSTITUTE OF ENERGY AND ENVIRONMENT

DANILO FERREIRA DE SOUZA

A contribution to energy efficiency in motor-driven systems

Sao Paulo
2024

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Corrected version

Ph.D. Thesis presented to the Graduate Program in Energy of the Institute of Energy and Environment of the University of São Paulo for the Doctorate degree in science.

Area of Concentration: Energy Technology

Supervisor: Prof. Hédio Tatizawa Ph.D.

Co-Supervisor: Ildo Luís Sauer Ph.D.

Sao Paulo
2024

PUBLISHER’S CATALOGING-IN-PUBLICATION DATA

Souza, Danilo Ferreira de.
A contribution to energy efficiency in motor-driven systems. /DaniloFerreira de Souza; orientador: Hédio Tatizawa. -- São Paulo, 2024.
180f.: il; 30 cm.
Thesis - (Doctorate degree in Science) – Graduate Program in Energy - Instituto de Energia e Ambiente da Universidade de São Paulo

1. Life Cycle Analysis. 2. Energy Efficiency. 3. Sustainability. I. Títle.

Prepared by Maria Penha da Silva Oliveira CRB-8/6961

Name: SOUZA, Danilo Ferreira de

Title: A contribution to energy efficiency in motor-driven systems

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Approved (*Summa Cum Laude*) on April 04, 2024.

Supervisor: Prof. Hédio Tatizawa Ph.D.

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Examination Committee

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To my grandmother Rita and my
grandfather Cícero, who have always shown me
the best through their example. My mother,
Ivete, a teenager when I was born, has always
endeavored to do her best for me.

ACKNOWLEDGEMENTS

I want to express my gratitude to the Federal University of Mato Grosso and the Brazilian Ministry of Education for allowing me to take a leave of absence from my professional duties, enabling me to dedicate myself specifically to the development of scientific research.

I sincerely thank Prof. Hédio Tatizawa for his trust and willingness to supervise me. His commitment and dedication to maintaining the best possible working conditions have significantly contributed to the progress of our research. Professor Hédio has consistently offered me support, always striving to ensure the successful development of our projects. Beyond being an exceptional advisor, he is also a great friend.

I am deeply grateful to Prof. Ildo Sauer for his co-supervision, ongoing support, and friendship. His keen eye in identifying the research problems addressed in the papers presented here has been invaluable. Furthermore, his contribution to my intellectual development cannot be overstated. The "Energy and Society" course taught by Prof. Ildo ignited my interest in the social appropriation of energy throughout the journey of Homo sapiens.

I sincerely thank Prof. Aníbal Traça de Almeida and Dr. João Fong for their warm welcome in Portugal and for agreeing to supervise me at the Institute of Systems and Robotics at the University of Coimbra. Their provision of excellent material conditions and comprehensive intellectual support has been instrumental in developing my research.

This research was composed through the assembly of various papers. Throughout this journey, numerous researchers have contributed to the published findings. Therefore, I extend my gratitude to those who have been part of this achievement: Emeli Guarda, Welitom Ttatom, Pedro Paulo Fernandes da Silva, Francisco Marino Salotti, Arnaldo Kanashiro, João Lourenço, Carlos Arias Hernandez, and Eduardo Mendes.

Professors Elcio Brito and Maria Lídia provided profound support in the course PEA5733 – Automation and Society, for which I am deeply grateful.

Raphael Diegues and Alexandre Gallo supported me in implementing the Ph.D. scholarship from CNPq. This scholarship was crucial for the smooth progress of my research. I am grateful to them.

During my undergraduate studies in Electrical Engineering at UFMT, I had several opportunities crucial to my professional development. Without them, I ’wouldn’t have reached where I am today. I thank my Internship Supervisor at ITAIPU Binacional - Henrique Ribeiro, and Mrs. Mariza Mezomo. To the Internship Supervisor at Eletronorte, Wlamir de Jesus. And to the Internship Supervisor at UFMT, Mr. Antônio Coelho.

From a young age, I had the opportunity to work, and I always remember those who gave me my first professional opportunities. I am grateful to the couples Marcos Luciano Ferri and Paula Adriana Jassniker Ferri from Eletrônica Paulista and Gilberto Guedes de Souza and Luciana da Costa Jorte from Produtora Infinity, as they believed in me. They should feel represented in this achievement.

I am grateful to two special friends who, besides helping me develop my English skills, which were essential for the execution and internationalization of this research, have offered me the most genuine friendship, Dr. Richardson Abraham-Adejumo, and Lars Eirik Frantzen.

The Graduate Energy Program (PPGE) at the University of São Paulo (USP) has consistently provided excellent conditions for the successful development of this research. Therefore, I am grateful to the staff who supported me with administrative tasks at PPGE: Renata Boaventura, Raphael Diegues, Mirtes Staduto, and Adriana Pelege.

While researching at the University of Coimbra, I made great friends who made my days wonderful. Thank you for your companionship and friendship: Evandro Garcia, Jônatas Manzolli, Luiz, Habibu, Lucélio, Matheus, Carlos, Rodolfo, Joana, Erika, Cláudia, Lourenço, Nuno Quaresma, and Sr. Coelho.

A special person is Maria do Socorro Almeida (SOS), who, despite always being far away, has been a constant presence in my life and has followed me throughout my entire Ph.D. journey with the best words for me.

The professors Mário Kawaphara and Teresa Irene Ribeiro Malheiro believed in me. They gave me a letter of recommendation for my master's degree in 2012. I will never forget this gesture of trust, and completing this Ph.D. is my way of saying thank you.

I would like to extend my gratitude to my colleagues from the Electric Machines Laboratory at IEE/USP. They supported me through various stages of my master's and doctoral studies. These colleagues include Francisco Salotti, Fernando Gava, Abraão Garcia, Antônius Quirino, Álcio (BUDAs), Luís Caires (Lulão), and the late Professor Sabinus (IN MEMORIAM).

To my friends in Sao Paulo, who make my visits to the ‘‘Concrete ’Jungle’ always a chance for ‘' Meetings and Farewells’: Nilton Amado, João Lopes, Sérgio Santos, the Vaiser Family (Adolfo, Simone, Maria, Henrique, and Luana), Angélica and Fazzi, Thiagão, Gallo, Kauê.

Hélio Sueta and Milton Shigihara are great partners in research on accidents involving lightning strikes and people. They are not only great friends but also excellent professionals.

I deeply thank the Zaqueo and Pitaro families, who have always warmly welcomed me, graciously opening their homes to me. To little Pietro, who gave me a glimpse of one of the most enchanting stages of childhood—my best thoughts and deep wishes for a successful and loving journey, and may my best wishes always accompany him.

My aunts Elane and Bel and my uncle Carlusco have always rejoiced in my achievements.

To my friends who are advocates for raising awareness about the dangers of electricity: Edson Martinho, Meire Biudes, Vinicius Ayrão, João Cunha, Sérgio Santos, Márcio Bottaro, Orestes, and Walter Aguiar.

To my great friends Walter Aguiar, Vinicius Teixeira (Broog), Evandro Silva, and Gabriel Konzen, who are always there for me at all times and anywhere.

To the Vaiser family and friends at OSE, Flavia, and Edmilson, thank you for the opportunity to contribute to the magazine and engage in scientific dissemination.

To the friends of the Association of Electrical Engineers of Mato Grosso, AMEE, who fight for the entire category. Especially those who have taken on the organization's leadership in recent years: Lauro Leocádio and Adriana Dussel.

To my friends in the Energy Processing group, my colleagues in the Department of Electrical Engineering, and the Faculty of Architecture, Engineering, and Technology - FAET at UFMT.

To my friends Kenny Kawaguchi and Walter Martins, who brought many of the images in this thesis to life.

To friendship dinners with Claudio, Jozanes, Milton and their families.

The Coordination for the Higher Education Improvement Coordination - Brazil (CAPES) - Finance Code 001, for their support in facilitating my period at the Institute of Systems and Robotics (ISR) of the University of Coimbra (UC) between 2023 and 2024.

To Santander Bank for funding my Ph.D. internship at the Institute of Systems and Robotics (ISR) of the University of Coimbra (UC) in 2022.

To the National Council for Scientific and Technological Development (CNPq) for awarding the Ph.D. scholarship through Project 870814/1999-0, Process 142323/2020-9, enabling the completion of this Ph.D.

To the National Electric Energy Agency (ANEEL) for Project number 00390-1086/2018 (ENEL) – 'Integrated Evaluation of Distributed Generation, Demand Management, Monitoring, Network Quality, and Performance, Aiming at the Optimization of Investments and Tariff Regulation in the Underground Network,' for their support in conducting and publishing the studies that comprise this Ph.D.

To the São Paulo Energy Company (CESP) for their support in conducting and publishing the studies that make up this Ph.D. under Project number 00061-0054/2016 – 'Analysis of the Efficiency of Complementary Energy Storage with Hydroelectric Plants, Using Electrochemical and Hydrogen Storage Technologies'.

To the state's workers who, by paying their taxes, fund a public university of excellence.

"No matter how complex or affluent,
human societies are nothing but subsystems of
the biosphere, the Earth's thin veneer of life,
which is ultimately run by bacteria, fungi, and
green plants."

Vaclav Smil

ABSTRACT

SOUZA, D. F. **A contribution to energy efficiency in motor driven systems**. 2024. 180 p. Ph.D. Thesis – Graduate Program in Energy, University of Sao Paulo, Sao Paulo, 2024.

The advancement in the energy efficiency of electric motors is a crucial element for improving efficiency in industrial processes. Electric motors are fundamental to modern society across all sectors of the economy. This thesis first presents historical research on the key elements that have driven changes in electric motor efficiency from 1945 to the present day. The research results demonstrated cumulative performance gains of more than 10% in some cases, while discrepancies were observed between the efficiencies declared by manufacturers on nameplates and the values measured through standardized testing. Brazilian energy efficiency policies were analyzed, demonstrating substantial gains in the efficiency of drive systems and alignment with international standards. Additionally, the thesis explored the impact of Industry 4.0 technologies on the management of building pump systems, presenting promising possibilities for optimization through advanced control and supervision, enabling significant efficiency gains. Furthermore, life cycle studies were conducted to assess the environmental impact of Permanent Magnet Synchronous Motors and Synchronous Reluctance Motors compared to induction motors. These studies indicated that, although more efficient during the use phase, these motors might have a higher environmental impact during production and disposal. The analysis shows that even at the brink of the theoretical limits of electric motor efficiency, the main efficiency bottlenecks lie in the driven load and the system as a whole. Therefore, there is room for improvements in the efficiency of drive systems, especially when considering the total product life cycle. The thesis concludes that there is a critical need to continue exploring technological advancements and to implement stringent regulatory policies that promote energy efficiency and sustainability, in harmony with global sustainable development goals and the growing energy demands. Research gaps for future investigations were identified and presented.

Keywords: Energy Efficiency; Electric Motors; Sustainability Policies; Industry 4.0; Life Cycle Assessment.

RESUMO

SOUZA, D. F. **Uma contribuição para a eficiência energética em sistemas acionados por motores elétricos**. 2024. 180 f. Tese de Doutorado – Programa de Pós-Graduação em Energia, Universidade de São Paulo, São Paulo, 2024.

O avanço na eficiência energética dos motores elétricos é um elemento central para a melhoria de eficiência nos processos industriais. Os motores elétricos são fundamentais para sociedade moderna em todos os setores da economia. Esta tese apresenta primeiramente uma pesquisa histórica sobre os principais elementos que proporcionaram as mudanças na eficiências dos motores elétricos desde 1945 até a atualidade. Os resultados da pesquisa demostraram ganhos de desempenho acumulados de mais de 10% em alguns casos, ao mesmo tempo em que foram observadas discrepâncias entre as eficiências de motores elétricos declaradas pelos fabricantes nas placas, e os valores medido por meio de ensaio padronizado. As políticas de eficiência energética brasileiras foram analisadas, demonstrando ganhos substanciais na eficiência dos sistemas motrizes e alinhamento com padrões internacionais. Além disso, a tese explorou o impacto das tecnologias de Indústria 4.0 na gestão de sistemas de bombeamento de edifícios, apresentando possibilidades promissores de otimização através de controle e supervisão avançados, possibilitando ganhas de eficiência significativos. Adicionalmente, foram realizados estudos de ciclo de vida para avaliar o impacto ambiental dos Motores Síncronos de Ímã Permanente e Motores Síncronos de Relutância em comparação aos motores de indução, indicaram que, embora motores mais eficientes na fase de uso, podem ter maior impacto ambiental na produção e no descarte. A análise demonstra que, mesmo à beira dos limites teóricos de eficiência dos motores elétricos, os principais gargalos de eficiência estão na carga acionada e no sistemas como um todo. Portanto, há espaço para melhorias na eficiência dos sistemas motrizes, especialmente ao considerar o ciclo de vida total do produto. A tese conclui que há uma necessidade crítica de continuar explorando avanços tecnológicos e de implementar políticas regulatórias rigorosas que promovam a eficiência energética e a sustentabilidade, em sintonia com os objetivos de desenvolvimento sustentável global e as crescentes demandas por energia. Lacunas de pesquisas para futuras investigações foram identificadas e apresentadas.

Palavras-chave: Eficiência Energética; Motores Elétricos; Políticas de Sustentabilidade; Indústria 4.0; Avaliação de Ciclo de Vida.

FIGURE LIST

SUMMARY

1 INTRODUCTION

The need for mechanical power was one of the fundamental demands that drove the process of humanity's productive transformation, as it revolutionized the life of sapiens, making him, previously an animal in nature, not very different from the others around him, develop the possibility of building megacities (SMIL, 2020).

The process of producing mechanical power has gone through several phases. Domesticating animals represented an essential step in developing the automation process and increasing work productivity. This act was essential for there to be a change in the way of life, in which man went from being a hunter and gatherer to a farmer/pastor (WHITE, 1943) because by using other domesticated animals, sapiens were able to carry out activities without the need to use their muscular strength directly (ZEDER, 1982).

The production of mechanical power can be understood as one of the processes that was basically responsible for the first two great industrial revolutions. The first phase of the Industrial Revolution began in England around 1750-1760, lasting from 1820 to 1840, and was marked, in general terms, by the development and application of the steam engine in industrial manufacturing processes (MOHAJAN, 2019). The second phase of the Industrial Revolution was marked by the replacement of steam engines or gas engines with electric motors (LAMOREAUX; LEVENSTEIN; SOKOLOFF, 2013).

By the end of the 19th century, the new electric motors were more economical, required less maintenance, took up less space, ran more uniformly, and allowed for a cleaner environment (THOMPSON, 1887). In just one generation, following its introduction in the 1880s, the electric motor drive replaced the steam engine as the primary means of providing motive power (BALDWIN, 1988).

With the use of electric motors on a large scale, electrifying industrial plants, they gained greater flexibility, no longer needing to be close to a stream to use mechanical energy from water or a coal mine for direct use in the steam engine (DEVINE, 1983).

Today (21st century), electric motors are the driving force of modern industrial society. It is electric motors that drive household refrigerators, pump water for heating and conduct ventilation, make it possible to distribute compressed air and move loads on conveyors, and keep city water supplies flowing (SAIDUR, 2010).

Electric motors are responsible for around 70% of the electricity consumed worldwide in industry, corresponding to the consumption of 46% of the world's electricity

(INTERNACIONAL ENERGY AGENCY; WAIDE; BRUNNER, 2011). Three-phase induction motors - with squirrel cage rotor or Squirrel Cage Induction Motor - are responsible for more than 90% of total electricity consumption in electric motors (GARCIA et al., 2007). However, other motor technologies have been presented as economically viable options, especially for variable speed drives, such as Permanent Magnet Synchronous Motors (PMSM) and Synchronous Reluctance Motors (SynRM) (FONG et al., 2020).

To improve the energy efficiency of electrical equipment, minimum efficiency standards called Minimum Energy Performance Standards (MEPS) - energy labels - have been defined. This measure is seen as one of the main ways of supporting energy efficiency directly at the product level (DE ALMEIDA et al., 2017). The use of MEPS and energy efficiency labels is a way of supporting rational consumer choice and overcoming information barriers. These efforts are often mandatory but can also be voluntary (RUBY, 2015) and are updated over the years in line with improvements in building materials and equipment designs, thus aiming to manufacture increasingly efficient equipment commercially.

In the case of electric motors, MEPS have encountered barriers to their use. In some cases, these barriers have been due to a lack of knowledge on the part of users, while in other situations, they have been due to low levels of demand from entities such as building energy efficiency certifiers, insurance companies, residential building constructors, etc.

The energy efficiency indicators of electric motors have shown that this equipment is already close to the theoretical efficiency limits (BORTONI et al., 2019). The new SynRM and PMSM electric motor technologies have small energy efficiency gains, mainly reducing rotor losses when operating at synchronous speed (DE ALMEIDA; FERREIRA; BAOMING, 2014). And the current three-phase electric induction motors with squirrel-cage rotors combined with electronic variable speed drives (VSD) have already demonstrated substantial profits, soelectric motors are already highly efficient equipment (DE ALMEIDA et al., 2019). Thus, one of the challenges on the horizon concerns increasing the overall efficiency of the motor system, involving the entire drive process.

When reviewing the published literature on energy efficiency in motor systems, the following questions were identified as research gaps:

A. How has the efficiency of electric motors changed over time?
B. Are the reported efficiency values of electric motors written by manufacturers on the electric motor plate the same as those measured in standardized tests?

C. What has been the impact of energy efficiency policies for electric motors in Brazil? Have there been efficiency gains in motor systems? Are the current levels of energy efficiency for electric motors in Brazil compatible with international levels?
D. How can the overall energy efficiency of an electric motor-driven system be assessed using indicators?
E. What are the future trends for increasing energy efficiency in drive systems?
F. Permanent Magnet Synchronous Motors (PMSM) and Synchronous Reluctance Motors (SynRM) present themselves as the main substitutes for Induction Motors (SCIM). Has research been carried out assessing the impact of these technologies on all stages of the electricmotor's life? From production, through transportation and use, to disposal or recycling?
G. What is the environmental impact throughout the life cycle of PMSM and SynRM synchronous motor technologies compared to SCIMs?

1.1 General Objective

The general objective of this thesis is to investigate and contribute to the advancement of energy efficiency in motor-driven systems, focusing on technological improvements, sustainability policies, and life cycle assessment of electric motors.

Specific Objectives:

1. Historical Analysis and Technological Evolution: To examine the evolution of electric motors from animal harnessing to modern motors, assessing their transformations and impacts on energy efficiency.
2. Evaluation of Energy Efficiency Policies: To analyze energy efficiency policies in Brazil and their alignment with international standards, determining their effects on the improvement of motor system efficiency.
3. Case Study of Industry 4.0 Technologies: To explore the impact of Industry 4.0 technologies on the management of building pumping systems and assess future trends for increased energy efficiency.
4. Life Cycle Assessment of Electric Motors: To conduct a comparative life cycle assessment of Permanent Magnet Synchronous Motors, Synchronous Reluctance Motors, and induction motors, focusing on environmental impact and energy efficiency.

The thesis unfolds structured, addressing various aspects of energy efficiency in motor-driven systems. Chapter 1 sets the stage with an introduction to the topic. Chapter 2 outlines the thesis structure, laying a clear roadmap for the reader. Chapters 3 to 9 each address a specific research gap identified in the field. These chapters are comprehensive explorations, each based on a research article, covering topics from the performance evaluation of induction motors, disparities in reported and actual motor efficiencies, to the impact of Brazilian energy policies on electric motors.

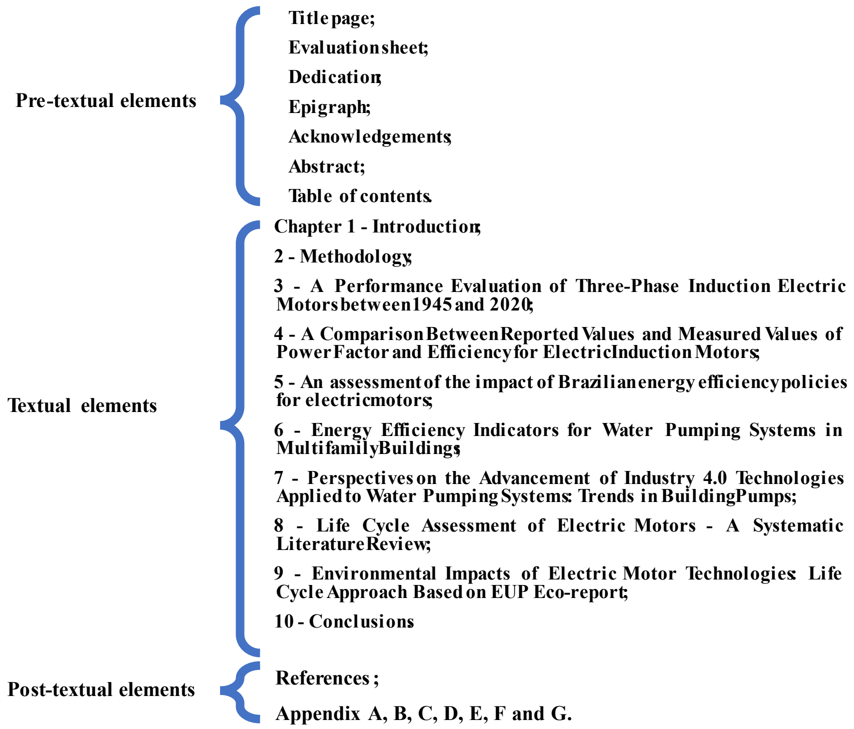
Further, they delve into energy efficiency indicators for water pumping systems, the role of Industry 4.0 technologies, and a systematic literature review on the life cycle assessment of electric motors. Each chapter presents an in-depth analysis, contributing unique insights to the field. The final chapter concludes these extensive studies. All the detailed papers corresponding to each chapter are included in the appendices, providing an exhaustive understanding of each topic covered.

2 THESIS STRUCTURE

To respond to the research gaps formulated, it was decided to use the Thesis model built from scientific articles. Thus, each of the articles was constructed to answer a research gap. The format and formalization of this study follow the rules in the document Guidelines for the presentation of dissertations and thesis at USP (FUNARO et al., 2020), i.e., prepared according to the Brazilian National Standards Organization (ABNT) standards.

Figure 1 shows the structure of how this thesis was organized.

Figure 1 – Thesis structure



Each of the following chapters is an expanded summary of the research article constructed to answer the identified research gap. The full paper has been placed in the appendix section.

3 A PERFORMANCE EVALUATION OF THREE-PHASE INDUCTION ELECTRIC 2 MOTORS BETWEEN 1945 AND 2020

This study was designed to answer the following identified research gaps: How has the efficiency of electric motors changed over time

During the latter part of the 19th century, the advent of the three-phase induction motor marked a pivotal increase in productivity, contributing significantly to the Second Industrial Revolution across Europe and North America. Today, these motors are the predominant consumers of electrical power in the industrial sector globally, accounting for about 70% of its electrical energy usage. In the 20th century, they witnessed a wave of technological advancements in electric motors, leading to notable enhancements in their performance. This study examines the evolution in the performance of squirrel-cage rotor three-phase induction electric motors (SCIMs), specifically models with mechanical outputs of 3.7 kW, 37 kW, and 150 kW and speed variants of two poles and eight poles. These motors were designed for low-voltage operation at 60 Hz. They were assessed over a period (1945 to 2020), revealing, in some instances, performance improvements exceeding 10%.

The evolution of insulation materials for electrical conductors has transitioned through various materials, from cotton and silk to modern-day varnish. Advancements in motor housing for enhanced cooling, better bearings, improved quality of active materials, and overall design have been instrumental in achieving these performance gains. The initial commercial two-pole SCIM, launched in 1891 with a mechanical output of 4.4 kW, had a weight-to-power ratio of 86 kg/kW. This ratio consistently decline over the following century, reaching 4.8 kg/kW by the 2000s. However, from 2000 to 2020, there was a notable uptick in this ratio, climbing to 8.6 kg/kW, reflecting the improved performance of SCIMs, which incorporated more active materials. Implementing the Minimum Energy Performance Standards (MEPS) for SCIMs has enhanced performance over the past thirty years. The data for this study were gathered through rigorous testing conducted at the Electrical Machines Laboratory at the Institute of Energy and Environment of the University of São Paulo, a facility with a longstanding tradition of testing electrical equipment, with records dating back to 1911. The full paper is available in Appendix A.

4 A COMPARISON BETWEEN REPORTED VALUES AND MEASURED VALUES OF POWER FACTOR AND EFFICIENCY FOR ELECTRIC INDUCTION MOTORS

This study was designed to answer the following written research gap: Are the reported efficiency values of electric motors written by manufacturers on the electric motor plate the same as those measured in standardized tests?

Manufacturers of electric motors typically highlight two critical parameters: the power factor and the overall efficiency of their products. Nevertheless, there is often a disparity between these proclaimed specifications and the actual performance outcomes when subjected to empirical testing. This discrepancy was the focus of an extensive evaluation involving 435 three-phase induction electric motors equipped with squirrel cage rotors. These motors, originating from 38 distinct manufacturing companies, were tested over two years, from 2015 to 2016. The assessment was conducted at the Laboratory of Electrical Machines at the Institute of Energy and Environment of the University of Sao Paulo, employing a series of standardized testing protocols to ensure the accuracy and reliability of results.

Similarly, when evaluating the efficiency of these motors, it was found that more than half, precisely 55%, showed efficiency below that advertised by the manufacturers but still within the maximum permitted tolerance limits. These findings highlight a worrying inconsistency on the part of the electric motor industry, underlining the need for more rigorous verification of the information provided by manufacturers to ensure that actual performance complies with expected standards.

The full paper is available in Appendix B.

5 AN ASSESSMENT OF THE IMPACT OF BRAZILIAN ENERGY EFFICIENCY POLICIES FOR ELECTRIC MOTORS

This study was designed to answer the following identified research gaps: What has been the impact of energy efficiency policies for electric motors in Brazil? Have there been efficiency gains in motor systems? Are the current levels of energy efficiency for electric motors in Brazil compatible with international levels?

During the zenith of the second industrial revolution, a technological innovation emerged as the linchpin of productivity: the three-phase induction motor. This machinery played a pivotal role in the industrial ascendance of Europe and the United States in the latter part of the 19th century. In our present era, the three-phase induction motor continues to be an indispensable component, constituting the principal load within the global electrical system and accounting for over 65% of Brazil's total electrical consumption.

In response to the increasing energy demand and the imperative of sustainability, Brazilian energy policy took a new direction toward enhancing electrical efficiency, following the electricity rationing the country experienced in 2021. This shift is encapsulated in the regulatory framework governing the operational performance of electric motors, with the issuance of the first legislative document occurring in 2002.

The study presents an empirical assessment of the alterations in efficiency and performance that three-phase induction motors with squirrel-cage rotors have undergone in the Brazilian market as a direct response to the implemented policies. This analysis encompasses a sample size of 435 motors, each subjected to standardized testing between 2015 and 2016. These motors, spanning a power range from 1 HP to 250 HP, were tested across four standardized velocities following the criteria outlined in three legislative documents: Presidential Decree No. 4,508/2002; Interministerial Ordinance No. 553/2005; and Interministerial Ordinance No. 1/2017.

The testing protocols adhered to rigorous standards, validated by the National Institute of Metrology, Standardization, and Industrial Quality (INMETRO) and further corroborated by the International Laboratory Accreditation Cooperation (ILAC), ensuring the integrity and reproducibility of the results.

The findings reveal a marked improvement in motor performance over the years, with 97% of the motors surpassing the performance benchmarks established by Decree No. 4,508/2002.

Furthermore, a notable 64% exceeded the performance criteria dictated by Ordinance 553/2005. Nevertheless, it was observed that only a modest 21% of the motors achieved performance figures that were in line with the more stringent requirements set out by Ordinance 1/2017. This expanded scientific treatise not only delineates the evolutionary trajectory of motor efficiency in response to regulatory standards but also underscores the ongoing challenge of aligning with the rigorous benchmarks of contemporary energy policies. The implications of these findings are critical for future policy formulation and emphasize the need for continuous technological innovation in the pursuit of sustainable energy consumption.

The full paper is available in Appendix C.

6 ENERGY EFFICIENCY INDICATORS FOR WATER PUMPING SYSTEMS IN MULTIFAMILY BUILDINGS

This study was designed to answer the following research question: How can the overall energy efficiency of an electric motor-driven system be assessed using indicators?

In the contemporary discourse on sustainability, particularly in urban development, the energy consumption of water pumping systems in residential buildings has come under scrutiny. Recognizing the critical role these systems play in the overall energy footprint of multifamily dwellings, this research endeavors to establish a comprehensive set of guidelines for the energy assessment of water pumping systems within such buildings.

The methodological framework of this study is structured around four pivotal procedures: firstly, it necessitates the determination of the efficiency metrics for electric motors utilized within these systems. Secondly, it requires the establishment of a benchmark for the efficiency levels of the pumps themselves. Thirdly, the methodology involves precisely calculating energy consumption across these systems. Lastly, it culminates in creating an efficiency scale, accompanied by a set of detailed guidelines that can be applied to both the design and assessment stages of water pumping systems.

The empirical findings of this research are illuminating; it was discerned that centrifugal pumps operating at an efficiency rate of 40% are associated with heightened energy consumption, a phenomenon that holds across all classes of electric motor efficiency. Notably, such pumps consumed 20% more electrical energy compared to their more efficient counterparts. This disparity in efficiency has a direct and significant impact on the overall energy efficiency rating of the water pumping system, with systems encompassing pumps of 40% efficiency being assigned the rating "Very Low—VL", spanning all motor efficiency classes from IE1 to IE5.

Conversely, at the higher efficiency threshold of 60%, the water pumping systems were designated with an "Average—A" energy efficiency level. This rating progressively ascended to "Very High—VH" as the pumps' energy consumption diminished in tandem with an increase in the energy efficiency classes of the motors.

The conclusion drawn from this study is unequivocal: for architects, designers, and industry professionals, the efficiency of pumps is not to be underestimated, as it is instrumental in determining the energy efficiency classification of the system. Furthermore, the study advocates for the routine evaluation of the energy efficiency of water pumping systems and calls for integrating these design guidelines to ensure that the systems are optimized for lower energy consumption. By adhering to these guidelines, not only is the operational efficiency of the building enhanced, but it also contributes positively to the broader objectives of energy conservation and sustainability within the built environment.

The full paper is available in Appendix D.

7 PERSPECTIVES ON THE ADVANCEMENT OF INDUSTRY 4.0 TECHNOLOGIES APPLIED TO WATER PUMPING SYSTEMS: TRENDS IN BUILDING PUMPS

This study was designed to answer the following research gaps: What are the future trends for increasing energy efficiency in drive systems?

The imperative for sustainable energy management in contemporary society has positioned the optimization of water pumping systems at the forefront of urban infrastructure efficiency debates. Given the substantial electricity demand attributed to water pumping for municipal supply, wastewater services, and high-rise residential buildings, there is a pressing need for innovative approaches to enhance energy efficiency. This study aims to bridge this gap by exploring the application of Industry 4.0 (I4.0) technologies to the water pumping systems of buildings, focusing on achieving superior energy efficiency and enhanced supervision and control mechanisms.

The study consists of a four-stage exploratory process. It first identifies the current I4.0 technologies. The subsequent phase involves mapping the potential for incorporating these technologies into the water pumping systems of buildings. To ground the investigation in empirical data, the study scrutinizes 16 scholarly articles published in academic journals from the year 2018 up to June 2021, extracting references to I4.0 technologies within these publications.

This rigorous analysis yields a compilation of eighteen distinct technologies, categorized based on twenty-two terminologies noted within the literature. The assortment of technologies is then classified according to their relevance and applicability to building water pumping systems: directly applicable, partially applicable, and applications yet to be identified.

The findings of this research are pivotal; they underscore the versatility of I4.0 technologies—initially developed for industrial applications—and their potential transference to the residential building water systems domain. The integration of these technologies can unlock numerous benefits. These include but are not limited to heightened energy efficiency, advanced user control interfaces, and a diminution in system downtime owing to predictive maintenance capabilities. Moreover, incorporating I4.0 technologies can significantly enhance water quality management and mark the transition towards 'Intelligent Pumping' or 'Pumping 4.0'.

In summary, the study not only underscores the untapped potential of I4.0 technologies in residential water systems but also serves as a clarion call for wider adoption. By embracing these technologies, stakeholders can drive forward the agenda of sustainable urban development, ensuring that the infrastructure underpinning our cities is both smart and energy-conscious.

The full paper is available in Appendix E.

8 LIFE CYCLE ASSESSMENT OF ELECTRIC MOTORS - A SYSTEMATIC LITERATURE REVIEW

This study was designed to respond to the following identified research gaps: Permanent Magnet Synchronous Motors (PMSM) and Synchronous Reluctance Motors (SynRM) present themselves as the main substitutes for Induction Motors (SCIM). Has research been carried out assessing the impact of these technologies on all stages of the electricmotor's life? From production, through transportation and use, to disposal or recycling?

Electric motors, which constitute more than half of the world's electricity consumption, have profound implications for global energy conservation efforts and climate change mitigation. The efficiency of these motors is a critical factor; however, a paradox emerges as higher efficiency often entails the utilization of additional materials. Current research trajectories are predominantly concentrated on the energy efficiency of motors during their operational phase, with insufficient attention to the complete life cycle, including the manufacturing and disposal stages. This comprehensive study undertakes a Systematic Literature Review (SLR) of 1,112 publications, sifting through to identify 20 that are quintessential to understanding the energy efficiency of electric motors.

The Squirrel Cage Induction Motors (SCIM) are prevalent in the discourse and celebrated for their cost-effectiveness, reliability, and efficiency. Notably, the past three decades have witnessed an enhancement in efficiency, primarily attributed to modifications in material consumption. While this evolution has altered the environmental footprint during the production and disposal stages, it has concurrently alleviated the impact during the usage phase. In the quest for even greater efficiency, the study highlights Switched Reluctance Motors (SRM) as viable contenders, offering better energy conservation with reduced material requirements compared to SCIM.

The study also casts light on Permanent Magnet Synchronous Electric Motors (PMSM) as the epitome of efficiency. However, they carry the burden of significant environmental impacts during both production and disposal. As an alternative, Synchronous Reluctance Motors (SynRM) stands out as competitive against SCIM with their smaller volume, heightened efficiency, and diminished environmental ramifications.

Life Cycle Assessments (LCAs) analyzed within the study reveal a spectrum of approaches regarding the life cycle stages considered, materials included, and categories of environmental impact. This variation underscores the need for a standardized, tiered framework for conducting LCAs of electric motors. According to the study, the use phase dominates the life cycle impact, accounting for the lion's share—over 90%. It is a salient point that even though the production and disposal of more efficient motors may have higher environmental impacts, their overall life cycle effects are generally reduced.

A limitation of this study is the geographic concentration of the analyzed LCA studies, all of which are European. These studies utilize primary energy mix from the electrical sectors of European countries or the EU mix. Therefore, these results should be interpreted with caution when considering other regions with substantially different primary energy matrices. This highlights a research gap for other regions.

The study concludes with an enumeration of seven critical research gaps that must be addressed to reduce the environmental impact of electric motors. These gaps span the spectrum of design, material selection, use-phase efficiency, end-of-life strategies, and the development of a comprehensive framework for life cycle analysis. This research contributes to a more nuanced understanding of motor efficiency and calls for a holistic view that encompasses the entire lifespan of electric motors, from the cradle to the grave.

The full paper is available in Appendix F.

9 ENVIRONMENTAL IMPACTS OF ELECTRIC MOTOR TECHNOLOGIES: LIFE CYCLE APPROACH BASED ON EUP ECO-REPORT

This study was designed to and address the following identified research gaps: What is the environmental impact throughout the life cycle of PMSM and SynRM synchronous motor technologies compared to SCIMs?

Electric motors are integral to industrial operations, and their energy efficiency is essential for climate change mitigation. This study evaluates the life cycle environmental impacts of three electric motor technologies: standard Squirrel Cage Induction Motors (SCIMs) at IE3 efficiency and the more advanced Synchronous Reluctance Motors (SynRMs) and Permanent Magnet Synchronous Motors (PMSMs) at IE5 efficiency. The EuP Eco-Report tool found that while SynRMs are operationally more energy-efficient than SCIMs, they have more significant environmental impacts during manufacturing due to higher material use. PMSMs are the most energy-efficient but have the highest environmental costs, especially during manufacturing and disposal, primarily due to the ecological hazards of extracting and recycling rare earth metals in their magnets.

The study begins by contextualizing the role of electric motors in global energy consumption and GHG emissions, emphasizing the significant electricity demand they represent in the industrial sector. It discusses the importance of energy efficiency in electric motors for sustainable development and the move towards higher efficiency standards, such as the European IE4 and the anticipated IE5 classifications.

The methodology is rooted in the Ecodesign Directive of the European Union and the MEErP framework, focusing on a life cycle perspective from manufacturing to end-of-life treatments. An 11 kW motor was chosen for its representativeness, and the bill of materials was provided by global manufacturing companies, ensuring the study's relevance to current market conditions.

The study dissects the environmental impacts during electric motors' manufacturing, use, and end-of-life phases. The manufacturing phase is detailed as energy-intensive due to material extraction and processing. In contrast, the use phase highlights the significance of motor efficiency in energy consumption, with IE5 motors demonstrating considerable energy savings over 15 years. Analysis of the end-of-life phase reveals the challenges in recycling materials such as electrical steel and permanent magnets, which are possible for non-noble uses in equipment that does not consume energy. However, it also indicates the high recyclability of most motor components.

The study concludes that despite higher production impacts, the environmental benefits of IE5 motors are pronounced during the operational phase. It emphasizes the necessity of life cycle analyses in selecting motor technologies, advocating for a move towards higher efficiency to mitigate environmental impacts. It underscores the importance of operational efficiency in motor design and selection to reduce the overall ecological footprint.

The full paper is available in Appendix G.

10 CONCLUSIONS

Based on the extensive and detailed survey conducted on the evolution, efficiency, and impact of electric motors, it can be concluded that humanity's journey towards optimizing mechanical motive power is both a reflection of technological advances and a testimony to socioeconomic and environmental changes. The domestication of animals, the emergence of the steam engine, and the subsequent adoption of electric motors marked significant milestones in how societies structure their industries and cities. The transition to electric motors not only intensified automation and productivity but also prompted a reconfiguration of urban and industrial infrastructures, with evident gains in energy efficiency and reduction of environmental impact.

Currently, the challenge focuses on the continuous search for improvements in energy efficiency, mainly through implementing performance standards such as MEPS and innovation in motor technologies, such as Permanent Magnet Synchronous Motors and Synchronous Reluctance Motors. The findings of this study suggest that, although electric motors are close to theoretical limits of efficiency, there is room for advances in the overall performance of the motive system, particularly when considering the entire life cycle of the product, from manufacturing to disposal.

Energy efficiency policies, particularly in the Brazilian context, have proven essential for achieving significant improvements in the performance of electric motors. The discrepancies between the efficiency values reported by manufacturers and those obtained in standardized tests underscore the importance of rigorous testing and effective regulation to ensure transparency and reliability for consumers.

The study also emphasizes that understanding and applying energy efficiency indicators are vital for assessing and improving pumping systems in buildings, directly impacting sustainability and energy savings. Furthermore, the integration of Industry 4.0 technologies presents itself as a promising frontier for optimizing pumping systems, with the potential to revolutionize management and energy performance.

From a broader environmental and economic perspective, the study on the life cycle of electric motors points to a complexity that transcends the usage phase, including the stages of production, transportation, and end of life. Although more efficient motors may demand more resources in their manufacturing and disposal, they tend to offset these impacts over their life cycle, contributing to climate change mitigation.

This thesis offers an analysis of the evolution, efficiency, and environmental impact of electric motors. It responds to research questions identified by exploring the historical changes in electric motors, uncovering performance improvements, and examining discrepancies between reported and actual motor efficiencies. Additionally, it evaluates the effectiveness of Brazilian energy efficiency policies and their alignment with international standards. The study also assesses the role of Industry 4.0 technologies in enhancing the energy efficiency of water pumping systems in buildings. Furthermore, it conducts a detailed life cycle assessment of different motor technologies, revealing the broader environmental impacts of more efficient motors. This research underscores the importance of comprehensive strategies encompassing technological advancements, rigorous policies, and life cycle considerations to achieve sustainable energy efficiency in motor-driven systems.

11 OTHER PUBLICATIONS

During the Ph.D. studies, some publications were produced. Here are the key publications by year, authored by Ph.D. candidate Danilo Ferreira de Souza.

11.1 Year 2020

1. Sustainable building works are safer than conventional constructions? The review (SILVA; GUARDA; SOUZA, 2021).
2. Should the three-pin plug cease to exist? (In Portuguese) (SOUZA, 2020).

11.2 Year 2021

3. Sustainable building works are safer than conventional constructions? The review (SILVA; GUARDA; SOUZA, 2021).

11.3 Year 2022

4. Interfaces between building inspection and work safety: application to a federal public building in Cuiabá/MT (FERREIRA DE SOUZA; MONTELARES DE CARVALHO KAISER, 2022).
5. Assessment of the conditions of electrical installations at residential construction sites: An analysis considering Regulatory Standard n.º 18 (CASTILHO DE MIRANDA et al., 2022).
6. Accidents of Electrical Origin, a Detailed Analysis of Statistics. Brazil Compared to Other Countries (MARTINHO; SANTOS; DE SOUZA, 2022).
7. An analysis of lightning deaths in Brazil 2010-2020 (DE SOUZA et al., 2022b).
8. STATISTICAL ANNUAL OF ACCIDENTS OF ELECTRIC ORIGIN 2022 - Base year 2021 (In Portuguese) (MARTINHO; MARTINHO; SOUZA, 2022).
9. Perception of safety with electricity (In Portuguese) (MARTINHO; JR.; SOUZA, 2022).
10. Analysis of Secondary Technical Training in Electrotechnics and the Bachelor's Degree in Electrical Engineering: Perspectives for the Construction of Professional Attributions (In Portuguese) (SOUZA et al., 2022).

11.4 Year 2023

11. An Analysis of Accidents of Electrical Origin in Brazil Between 2016 and 2021 (DE SOUZA et al., 2023a).
12. A Machine Learning Model for Lightning-Related Deaths in Brazil (DE OLIVEIRA MAIONCHI et al., 2024).
13. Irregular Electrical Cables (DE SOUZA et al., 2023b).
14. Accidents Leading to Electrical Shocks in Brazilian Electric Power Distribution: An Analysis (DE SOUZA et al., 2023c).
15. Application of optimization algorithms to determine the optimum amount of contracted demand (In Portuguese) (MARTINS JÚNIOR et al., 2023).
16. THE NEXUS BETWEEN OCCUPATIONAL SAFETY AND SUSTAINABILITY: AN ANALYSIS OF THE BRAZILIAN CASE BY REGULATORY STANDARDS (IN PORTUGUESE) (SILVA et al., 2023).
17. Irregular Low-Voltage Electrical Cables (DE SOUZA; AGUIAR MARTINS; MARTINHO, 2023).
18. Risk Associated with Upward Unconnected Leader in Human Beings (SUETA et al., 2023).
19. SNAPSHOT OF BRAZILIAN COMMERCIAL ELECTRICAL INSTALLATIONS (In Portuguese) (MARTINHO; MARTINS JR; SOUZA, 2023).
20. ELECTRICAL SAFETY AWARENESS (IN PORTUGUESE) (MARTINHO; MARTINS JÚNIOR; SOUZA, 2022).
21. STATISTICAL ANNUAL OF ACCIDENTS OF ELECTRIC ORIGIN 2023 - Base year 2022 (IN PORTUGUESE) (SOUZA et al., 2023).

11.5 Year 2024

22. Electrical storm warning systems: A case study at Arena Pantanal (RONCHI et al., 2024).
23. STATISTICAL ANNUAL OF ACCIDENTS OF ELECTRIC ORIGIN 2024 - Base year 2023 (IN PORTUGUESE) (MARTINHO et al., 2024).

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APPENDIX A

DE SOUZA, Danilo Ferreira; SALOTTI, Francisco Antônio Marino; SAUER, Ildo Luís; TATIZAWA, Hédio; DE ALMEIDA, Aníbal Traça; KANASHIRO, Arnaldo Gakiya. A Performance Evaluation of Three-Phase Induction Electric Motors between 1945 and 2020. **Energies**, v. 15, p. 2002, 2022. (DE SOUZA et al., 2022a).

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A Performance Evaluation of Three-Phase Induction Electric Motors between 1945 and 2020

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Abstract: In the late 19th century, the three-phase induction motor was the central element of productivity increase in the second industrial revolution in Europe and the United States. Currently, it is the main load on electrical systems in global terms, reaching approximately 70% of electrical energy consumption in the industrial sector worldwide. During the 20th century, electric motors underwent intense technological innovations that enabled significant performance gains. Thus, this work analyses the performance changes in squirrel-cage rotor three-phase induction electric motors (SCIMs) with mechanical powers of 3.7 kW, 37 kW, and 150 kW and speed ranges corresponding to two poles and eight poles, connected to a low voltage at a frequency of 60 Hz and tested between 1945 and 2020. The study confirms accumulated performance gains of above 10% in some cases. Insulating materials for electrical conductors have gone through several generations (cotton, silk, and currently, varnish). Improvements to the housing for cooling, the bearings, the quality of active materials, and the design were the elements that enabled the high gains in performance. The first commercial two-pole SCIM with a shaft power of 4.4 kW was marketed in 1891, with a weight/power ratio of 86 kg/kW, and until the 2000s, this value gradually decreased, eventually reaching 4.8 kg/kW. Between 2000 and 2020, this ratio showed a reversed trend based on improvements in the performance of SCIMs. More active materials were used, causing the weight/power ratio to reach 8.6 kg/kW. The MEPS (minimum energy performance standards) of SCIMs had an essential role in the performance gain over the last three decades. Data collection was via tests at the Electrical Machines Laboratory of the Institute of Energy and Environment of the University of São Paulo. The laboratory has a history of tests on electrical equipment dating from 1911.

Keywords: three-phase induction motor; squirrel-cage rotor; energy efficiency; motor performance

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Citation: de Souza, D.F.; Salotti, F.A.M.; Sauer, I.L.; Tatizawa, H.; de Almeida, A.T.; Kanashiro, A.G. A Performance Evaluation of Three-Phase Induction Electric Motors between 1945 and 2020. *Energies* **2022**, *15*, 2002. https://doi.org/10.3390/en15062002

Academic Editor: Ryszard Palka

Received: 10 February 2022
Accepted: 7 March 2022
Published: 9 March 2022

1. Introduction

The production of mechanical force was one of the fundamental human demands in the transformation process that took homo sapiens from an animal in nature like the others to the construction of megacities and technological mastery [1].

The process of producing mechanical force went through several phases. The domestication of animals represented an essential step in automation and the increase in labour productivity, necessary for changing the way of life from hunter and gatherer to farmer/shepherd [2]. With the use of other domesticated animals, homo sapiens could perform an activity without the need to use muscular strength directly [3].

The production of mechanical force was primarily responsible for the first two great industrial revolutions. The first industrial revolution began in England around 1750–1760, lasting until somewhere between 1820 and 1840, and was marked by the development and application of the steam engine in industrial manufacturing processes [4]. The second industrial revolution replaced steam engines or gas engines with electric motors [5].

In the late 19th century, new electric motors were more economical. They required less maintenance, took up less space, ran at a more uniform speed, and allowed a cleaner environment [6]. Within just one generation after its introduction in the 1880s, the electric motor drive had replaced steam as the preferred means of providing motive power (Figure 1) [7].

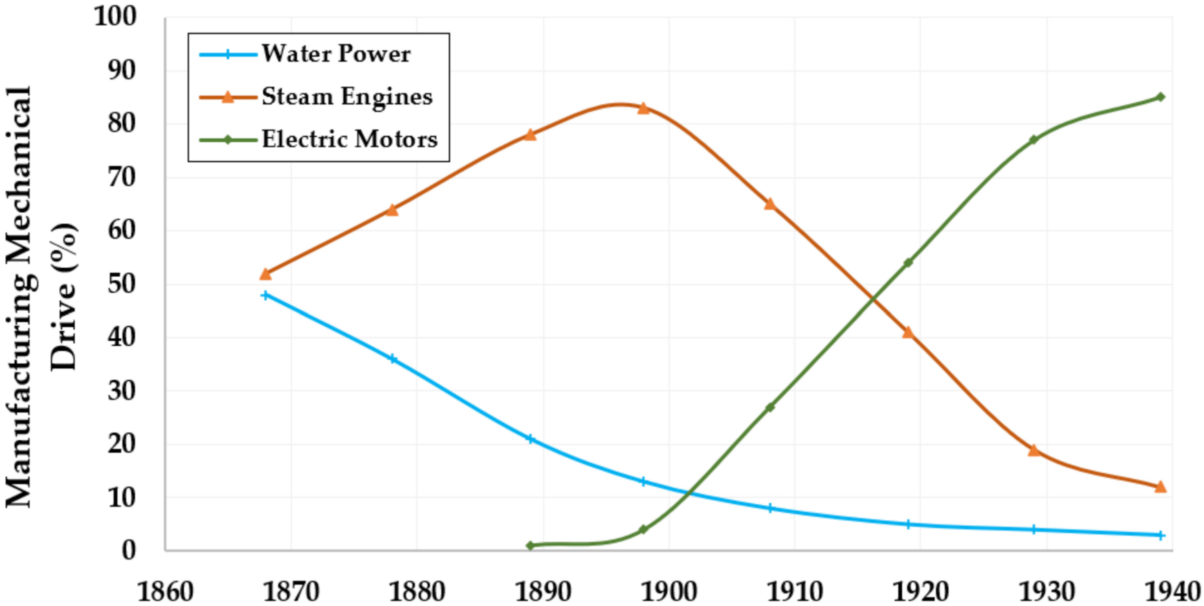

Figure 1. Percentage of mechanical drive manufacturing from hydraulic power, steam engines, and electric motors per year. Source: adapted from [7,8].

With large-scale electric motors electrifying industrial plants, the industrial plants gained flexibility. It was no longer necessary to be close to a stream in order to use mechanical energy from water or a coal mine for direct use of coal in a steam engine [9].

The mechanical force arising from water (Figure 2a) or steam engines (Figure 2b) was generally available from a single central axis and later, when subdivided, ran the entire length of the factory, with high losses in the gears and the emission of noise and vibrations throughout the industrial plant. In some cases, the engines served different industrial buildings. The connections made by belts and gears could drive hammers, presses, looms, and other machines, transferring mechanical energy horizontally between walls and vertically through industrial floors [10]. Due to the large distances and inevitable friction in these units, 60% to 80% of the transmitted energy was lost [11]. Everything required continuous lubrication by thousands of drip lubricators, with workers having direct access to the rotating parts, thus remaining exposed to high possibilities of work accidents [12].

Electric motors proved to be more efficient and more economical, and they reduced reliance on the complex mechanical shaft, pulley, and belt systems to distribute the mechanical drive from the central plant throughout the plant. The drive was located close to the load, and the energy was transferred by small electrical conductors [17] (Figure 2c).

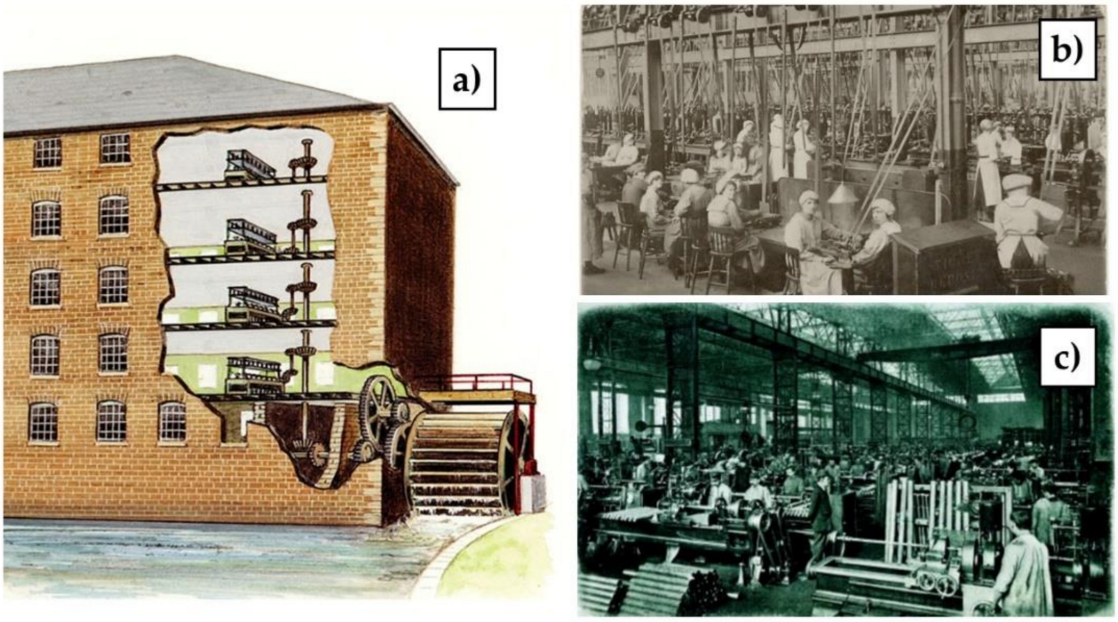

Figure 2. An industrial organization based on: (**a**) mechanical drive from hydraulic energy; (**b**) steam engines; and (**c**) electric motors. Source: [13–16].

The motors could reliably be fractionally coupled to the mechanical load with the electric drive, making it possible to establish an industrial flow in the manufacturing process. By splitting the mechanical drives, flexibility in maintenance was also gained, and islands with independent operation were possible. During a breakdown, it was not necessary to stop the entire plant. This freedom revolutionized industrial design and layout and provided the possibility of optimization in process control and better working conditions, leading to significant advances in productivity [8,18,19].

Currently (21st century), electric motors are the driving force of modern industrial society. Electric motors drive domestic refrigerators, pump water for heating, and drive ventilation, enabling the distribution of compressed air and the movement of loads on conveyor belts, in addition to keeping cities' water supplies flowing [20].

Several electric motor technologies have been developed. However, only three have become mainstream in industrial stationary electric drives. They are:

1. Direct-current motors, which were the first to be developed. Their applications are limited to situations in which speed control is essential, because by controlling the voltages applied to the rotor windings (armature) and the stator windings (field), it is possible to fine-tune the speed over a wide range. However, they are expensive, have high sparking caused by switching currents, and cannot be connected directly to the electrical grid, requiring a converter. They also have a high need for maintenance compared to other technologies.
2. Alternating-current synchronous motors, which are mainly reserved for high-load drives that require a constant speed. They are also expensive and require additional starting devices and electronic converters to feed the rotor winding (field) separately from the stator winding (armature). Synchronous motors are high-efficiency motors, as they have low rotor losses.
3. Cage rotor induction electric motors, which since their development have been the predominant choice in residential (single-phase), commercial, and industrial (three-phase SCIMs) environments. SCIMs correspond to about 87% of the total alternating-current electric motors used in the industry [21]. Several factors make SCIMs suitable for the broadest range of applications. Some of these are highlighted in Table 1.

Table 1. Characteristics of SCIMs.

Advantages	References
Low acquisition and maintenance cost compared to competing technologies;	[22–24]
The simple constructive characteristics make its manufacture simple compared to competing technologies;	[25,26]
Simple replacement due to a high degree of standardization of housings and connections;	[27,28]
Long service life;	[29,30]
A high degree of speed control using the variable speed drive (VSD), also enabling the saving of electrical energy;	[31,32]
Small dimensions can be used in compact places;	[33]
Does not produce sparking, making it easier to apply in classified areas (Ex areas);	[34–36]
High starting torque compared to other competing technologies;	[25,26]
Quiet compared to competing technologies;	[37–39]
There is no electrical contact between the rotor and the stator; the connection is made only by the bearings, thus giving high operating safety;	[25,26]
They can be powered directly by alternating current without the need for electronic converters;	[25,26]
Easy detection of faults of various natures (electrical, mechanical, thermal, and environmental)	[40–43]
Known production chain and easy access to the mineral resources necessary for the construction of SCIMs. They do not depend on high-volatility materials in the supply chain, such as, for example, the rare earth magnets present in permanent magnet synchronous electric motors (PMSMs).	[44–46]

SCIMs are seen as having undergone little change from their development to the present day, especially when compared to the obvious advances in electronics, communication, and information technologies. Hence, this research sought answers to the following questions:

I. What are the most significant changes that SCIMs have undergone throughout their history?
II. Has the performance of SCIMs changed since their development?
III. Has the volume of SCIMs changed over time?

2. Materials and Methods

Section 3.1 is a review of the literature that shows the historical development of SCIMs, focusing on the main technological innovations, material improvements, and various projects. The sources of information are technical documents from SCIM manufacturers or scientific articles that described the processes and the main events that caused the changes in the mass/power ratio between 1890 and 1990, contributing to answering question I.

In Section 3.2, a literature review is presented discussing the variations in performance between 1935 and 2012, contributing to answering questions I and II.

In Section 3.3, the primary data collected in the Technical Test Reports of the Laboratory of Electrical Machines of the Institute of Energy and Environment (IEE) of the University of São Paulo (USP) are presented and discussed.

Between 1945 and 1996, the Technical Test Reports were only available in printed form. Thus, it was necessary to digitize the data and collect them into a spreadsheet. Between 1997 and 2020, the Technical Test Reports were already available in digital format for processing and analysis.

The Laboratory of Electrical Machines of the IEE-USP has a technical collection of approximately 21,000 technical reports. For this analysis, reports with the following characteristics were considered:

(a) Three-phase induction electric motors with squirrel-cage rotor—SCIMs;
(b) Technical reports of new SCIMs;

(c) SCIMs tested according to current regulations, with the availability of test data at full load;
(d) SCIMs in which the nameplate data were made available by the manufacturer;
(e) SCIMs powered at low voltage (up to 600 volts);
(f) SCIMs for power supply at the industrial frequencies of 60 Hz or 50 Hz, tested at 60 Hz;
(g) SCIMs produced for continuous operation.

Using the conditions expressed in a–g, 359 technical reports of tested SCIMs with speeds corresponding to 2, 4, 6, or 8 poles, with a motor rated output power of 3.7, 37, or 150 kW, were collected for the evaluation of the change in performance between 1945 and 2020. The assessment seeks to answer the questions (I and II) that motivated this research, based on the data collected.

The results are organized into three different output power (kW) categories. The chosen groups include low power (3.7 kW), medium power (37 kW), and high power (150 kW). As the groups chosen to represent SCIMs are of significantly different dimensions, the production processes used in the manufacturing process and the standards of precision/quality of the materials are also different, even when dealing with the same equipment.

The number of poles of the electric motor determines the rotation speed, due to the arrangement and distribution of the electrical conductors of the windings located in the stator slots. In the SCIM market, historically, four speeds have been the most used. Between 80% and 90% of all the SCIMs sold have between 2 and 8 poles; therefore, this research evaluates them in this speed range. In fact, 4-pole SCIMs are dominant, representing between 45 and 70% of SCIMs [21,47].

Using the conditions expressed in a–g, 28 SCIMs with speeds corresponding to 2 poles and motor rated output powers of 3.7, and 4.4 kW were used to evaluate the change in the mass/power ratio between 2000 and 2020, seeking to answer the questions (I and III) that motivated this research, based on the data collected.

The National Institute of Metrology, Quality and Technology (INMETRO) accredits the Laboratory of Electrical Machines at IEE-USP, following ABNT NBR ISO/IEC 17025:2017 [48] under No. CRL 0011. INMETRO periodically carries out audits in accredited laboratories, aiming to guarantee the quality of the measurement results. INMETRO is a signatory to the mutual recognition agreements of the International Laboratory Accreditation Cooperation (ILAC) and the Inter-American Accreditation Cooperation (IAAC), thus following a world standard of quality and reliability.

This research, therefore, used data from standardized performance tests. This is because there may be differences between values measured in neutral laboratories and values reported by manufacturers [49], and when using the measured data, errors and uncertainties are reduced.

3. Results and Discussion

3.1. The Improvements in SCIMs

All the technological and theoretical bases for electric motor development were already advanced by the end of the 19th century. Direct-current motors were on the market, and alternating-current motors were in the full developmental stage, with research ongoing in Europe and the United States. The first patent for the electric motor with asynchronous technology was filed by the engineer Nikola Tesla [50] in 1888 and accepted in 1889 [51] in New York. The asynchronous motor became known as an induction motor, based on its working principle. However, Tesla's proposal was similar to the current single-phase auxiliary winding motors, operating with a wound rotor. The text that explained the working principle of the new electric induction motor was published by Nikola Tesla in 1988 with the title "A new system of alternate current motors and transformers" [52].

Parallel to Nikola Tesla's experiments in the USA were those of Galileo Ferraris in Italy. In 1885, Ferraris developed the idea that two out-of-phase currents could be used to produce two magnetic fields that could be combined to produce a rotating field, without the need for switching or moving parts, opening the door to AC electric motors [53–55].

The three-phase squirrel-cage rotor induction motor (SCIM) closest to the type we have today was developed by a German company AEG (Allgemeine Elektricitäts-Gesellschaft), headed by the Russian engineer Mikhail Dolivo-Dobrovolsky between 1888 and 1890 [56]. The electric motor developed by the Dobrovolsky team had very favourable characteristics such as high starting torque, more straightforward construction features, robustness in construction, and low maintenance needs. However, it also had the inconvenience of needing to be powered by a three-phase alternating-current system, which was not yet commercial. Until then, the available electrical systems were single-phase and two-phase systems. This type of supply does not provide efficient starting of the Tesla-mounted motor (starting torque practically non-existent), in addition to imposing some degree of vibration during operation. The SCIM has a high starting torque and does not need auxiliary windings and accessories such as a capacitor and a centrifugal starter, in addition to having a lower operating current compared to a single-phase motor. However, three-phase electric power generation, transmission, and distribution systems were quickly implemented with the objective of feeding the attractive SCIMs [57–59].

Dobrovolsky and the AEG company gained fame for the great invention. The artist Irene Ahrens created the illustration in Figure 3, which was exhibited in Berlin. The engineer appears in the sky, entering the Hall of Fame with his SCIM shown near his feet.

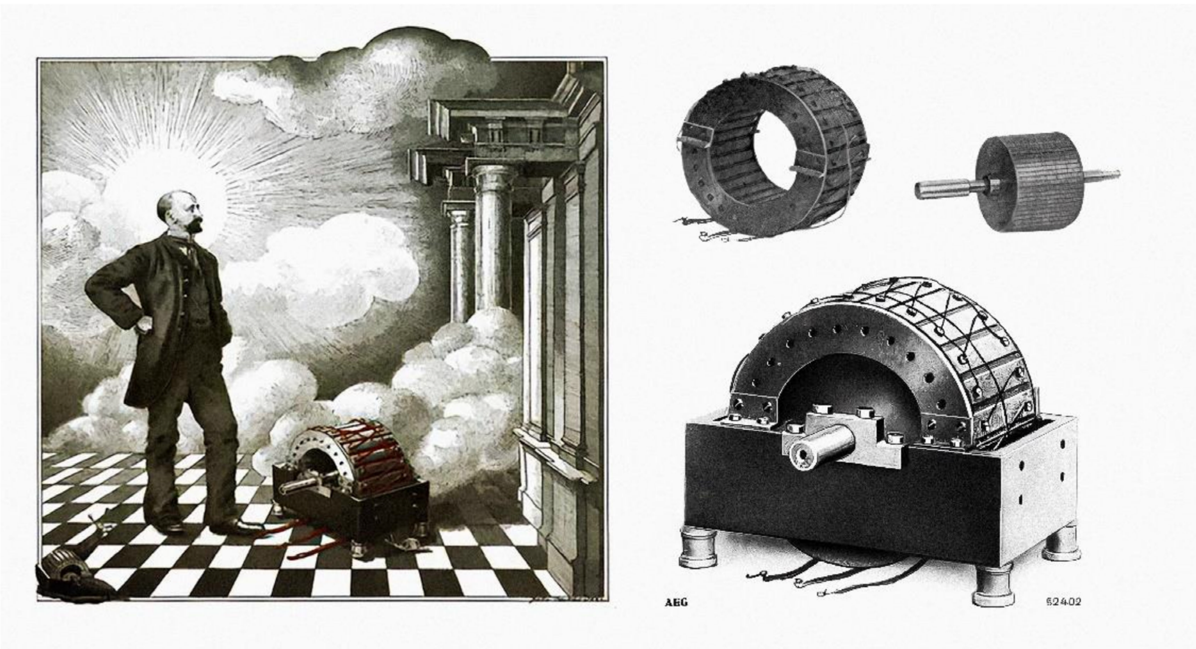

Figure 3. Mikhail Dolivo-Dobrovolsky entering the Hall of Fame with his SCIM. Source: [57,60].

In 1891, at AEG, Dobrovolsky coordinated the first serial production of SCIMs with shaft powers between 0.4 and 7.5 kW. The first SCIMs assembled had a performance of approximately 80% for the power range produced and very high mass by today's standards. The first commercial two-pole SCIM with a shaft power of 4.4 kW was marketed in 1891. These SCIMs had a mass/power ratio of 86 kg/kW, as shown in Figure 4.

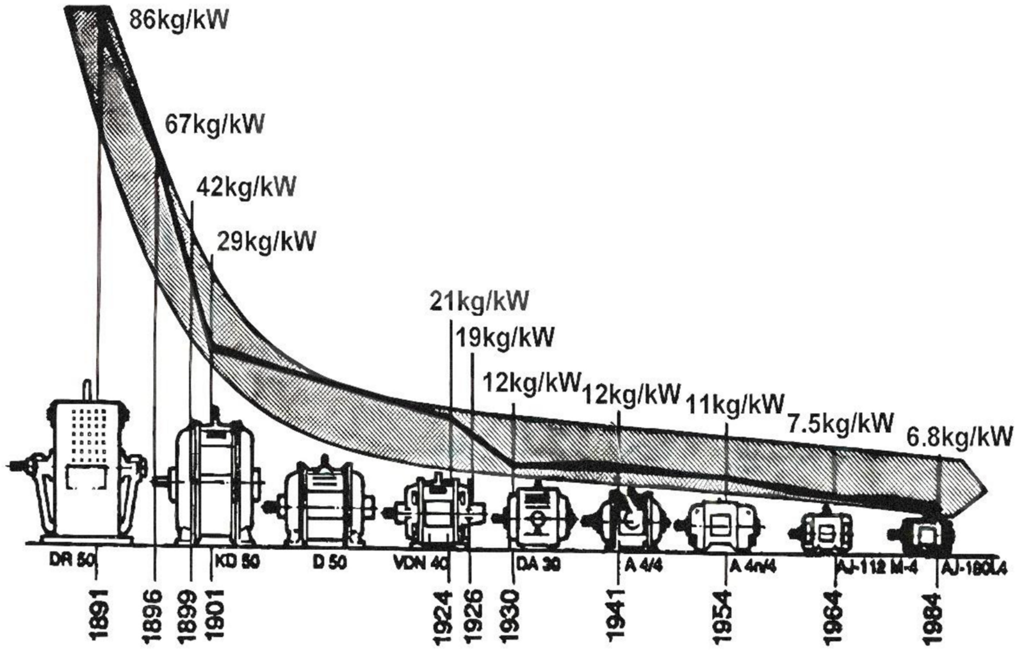

Figure 4. Improvements in SCIM mass/power ratio between 1891 and 1984. Source: [61–63].

The company AEG published the famous image represented in Figure 4, which shows the mass/power ratio from the first SCIMs manufactured by the company in 1891 to the SCIMs manufactured in 1984. The optimization of materials for electrical, magnetic, and mechanical purposes, combined with solid technological innovations, made it possible to reach a ratio of 6.8 kg/kW in 1984, representing only 8% of the total mass of the two-pole SCIMs with an axle power of 4.4 kW produced in 1891, as AEG's first commercial units.

The concept of the SCIM has not changed since the beginning of its commercialization; however, the volume has changed considerably (Figure 4).

The technological progress of SCIMs has been remarkable, stimulated by strong competition and by processes, technological innovations, and improvements in materials. According to Browning (1997) [64], the changes in the mass/power ratio resulted in better operational characteristics, even more excellent reliability, versatility, and longer life.

Browning (1997) [64] identified the following improvements in SCIMs:

- The change from open housing to closed housing;
- The change from plain bearings to anti-friction bearings. (In 1945, 35–40% of SCIMs used plain bearings);
- The change from cotton-insulated wires to varnished wires in the stator windings;
- Construction of the squirrel-cage rotor using copper or cast aluminium bars.

The adoption of industry standards has played a significant role in the progress of SCIMs [28,64]. An example is the thermal classification of insulating materials, which first appeared in 1898. In 1911, standardization by the AIEE Standards (now IEEE—Institute of Electrical and Electronics Engineers) established temperature limits for SCIMs. The 1915 edition of the AIEE Standards included definitions of insulation classes A, B, and C and the materials assigned to those classes. In 1929, the first SCIMs built to NEMA standards were made available on the market, setting standard dimensions and operating characteristics for specific ratings for the first time. Users were given the ability to directly replace SCIMs via the concept of stock electric motors for quick replacement in case of failure [64].

It is possible to observe in Figure 5 the tremendous technological innovations that were decisive in reducing the mass and volume of SCIMs.

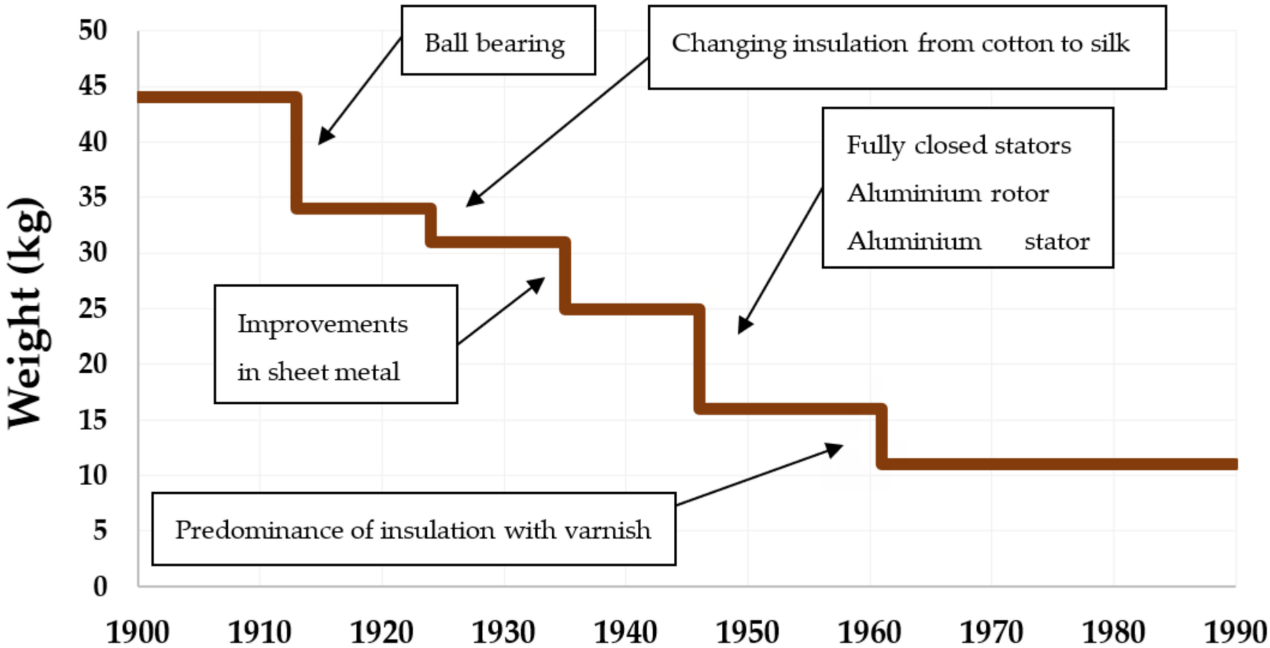

Figure 5. Chronology of 0.75 kW SCIM mass reduction between 1900 and 1990. Source: [65–68].

At the beginning of the 20th century, the first major technological innovation was the development of ball bearings, replacing the traditional plain bearings that were bulky, heavy, and required lubrication with oil. With the new bearings and the reduction in friction losses, the mass and volume of the SCIMs decreased considerably.

Between 1913 and 1940, there were gains in the quality of materials, improving compaction and making it possible to reduce the volume of copper and iron used in SCIMs and to reduce losses. In the 1940s, rotors previously built using iron sheets began to be developed using cast aluminium, adding more mass reduction, as shown in Figure 5. In addition, in the 1940s, with successive advances in metallurgy, SCIM housings could be built in an increasingly closed way and could maintain the cooling of the windings located in the stator.

In the early 1960s, a series of advances in insulation systems were instrumental in reducing the volume of SCIMs. Between 1960 and 1970, SCIMs went through five generations of materials used to construct insulation for electrical conductors. In the first SCIMs, the insulation was composed of paper, and later cotton. Then, insulation with varnish predominated until the present day. Figure 6 shows in white the area necessary to accommodate electrical conductors of the same metallic volume inside the stator magnetic package slot for different insulation technologies [63].

The first significant innovation in SCIM insulation systems was the replacement of the double layers of cotton between the conductors and the sheets with two layers of silk, allowing a reduction of approximately 59% of the groove area in the metal sheets (ferromagnetic material) of the stator. The second major innovation was the introduction of varnish used in conjunction with silk, giving an area reduction of over 2%, as shown in Figure 6. Subsequently, improvements in the quality of silk and varnish allowed an area equivalent to be reached of only 22% of the space required for the same electrical conductor using cotton as an insulator.

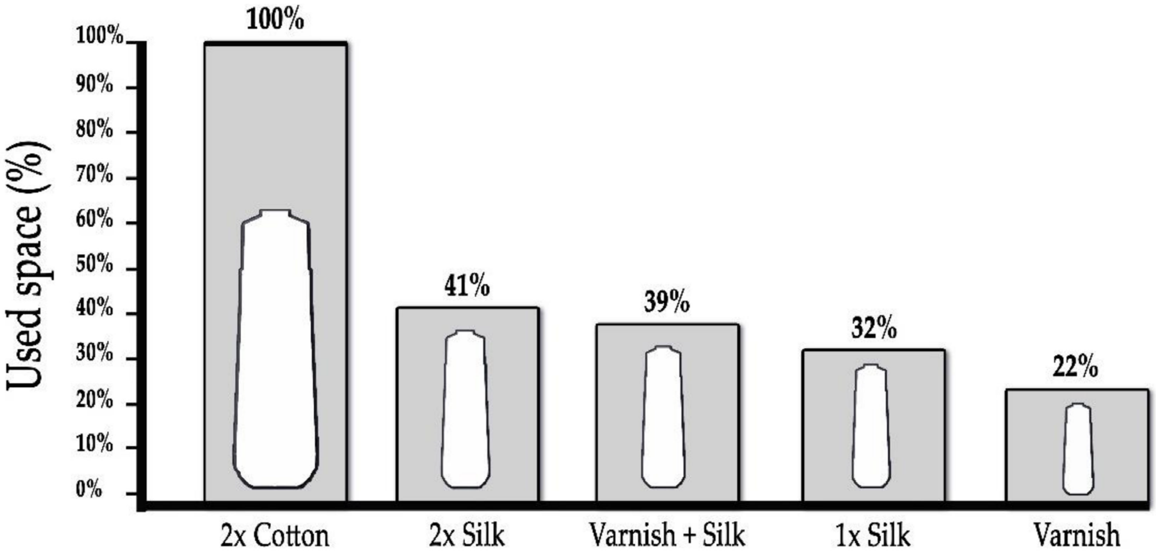

Figure 6. Space used by different insulation technologies for the same SCIM output power. Source: adapted from [63].

Successive technological innovations and improvements in electrical, magnetic, and mechanical materials achieved significant volume compaction in SCIMs between 1903 and 1974 [28], as illustrated in Figure 7a. Figure 7b shows the changes in appearance and frame dimensions of SCIMs of different powers from the open construction of 1904 to those used in the 1970s, similar to today's drip-proof and fully fan-cooled SCIMs.

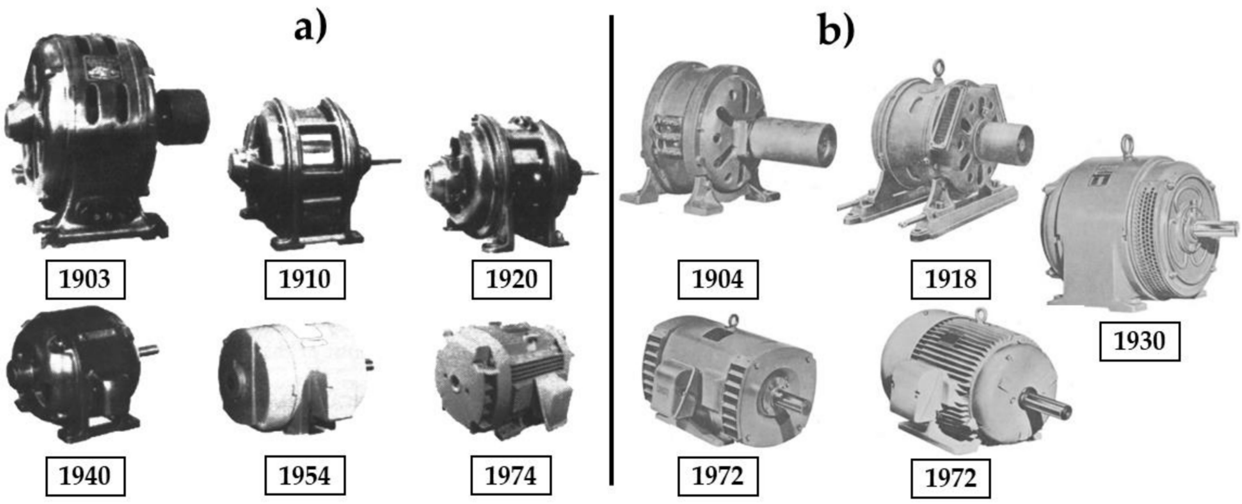

Figure 7. Dimension trends and housing changes of 11 kW 4-pole SCIMs between 1903 and 1974. (**a**,**b**): the changes in appearance and frame dimensions of SCIMs of different powers from the open construction of 1904 to those used in the 1970s. Source adapted from: [28,53].

Figure 7a presents SCIMs designed for operation at 220 volts and 11 kW, built by General Electric (GE). In Figure 7a, it is possible to observe the changes in the NEMA 404 housing over the years, and two significant innovations are evident in the images of SCIMs between the years 1920 and 1954: axial extension of the rotor at the rear and the closed housing, seen from 1954 and made possible by the improvement in insulation systems, enabling the transfer of heat from the windings to the outside.

Figure 7b shows a small SCIM (1904) built without a fan and considered to be "self-ventilated" by the semi-open housing. As early as 1918, SCIMs used a fan attached to the shaft for cooling. In 1930, the 15 kW SCIM already had a more efficient fan and could adopt a more closed design. In 1972, the engines were already drip-proof. Figure 7b shows 18.5 kW and 45 kW SCIMs. They could be fully enclosed (45 kW), allowing a reduction in SCIM dimensions. As a result of the improved insulation between the conductors and between the conductors and the ferromagnetic material of the sheets, the temperature of the winding wires and the groove walls became more homogeneous, as they were closer together with a thinner insulating layer. The temperature of the set decreased, and for this reason it was possible to increase the power considerably for the same housing. The stator slot was significantly reduced for the same power, and the magnetic section between the slots could be increased. There was also an improvement in the ferromagnetic material, an increase in the magnetic flux, and a consequent decrease in the number of turns per stator coil for the same electrical voltage.

According to Alger and Arnold (1979) [28], to avoid hot spots in the centres of long cores, radial ducts were introduced in the stator and impellers in the rotor operating as fans, creating the airflow through the stator channels. Therefore, the rating given to the NEMA 404 frame with an axle height and length of 25.4 cm and 31.1 cm, respectively, was increased with respect to mechanical power from 5.5 kW in 1897 to 75 kW in 1974, as shown in Table 2.

Table 2. Mechanical power increments in the same frame from 1898 to 1974. Source: [28].

Years	Motor Rated Output Power (kW)	Operating Temperature
1898–1903	5.5	40 °C Thermometer
1903–1905	7.5	40 °C Thermometer
1905–1914	11	40 °C Thermometer
1914–1924	15	40 °C Thermometer
1924–1929	18.5	40 °C Thermometer
1929–1940	22	40 °C Thermometer
1940–1956	30	50 °C Resistance
1956–1961	37	50 °C Resistance
1961–1966	45	50 °C Resistance
1966–1974	75	80 °C Resistance

The reduction in the volume of SCIMs also made it possible to reduce their costs, intensifying the electrification of industrial plants. For example, in 1890, a 3.7 kW SCIM weighed approximately 450 kg and cost about USD 900, and in 1957, a SCIM of the same power weighed around 50 kg and cost USD 110 [64]. Thus, the relationship between value and mass remained practically the same. However, as mass reduced significantly, the price of the SCIM reduced considerably, since the cost of an SCIM is fundamentally a function of the quantity and quality of materials used.

The company Hitachi produced three SCIMs of 3.7 kW in 1910, and in 2010 the total production was already 40 million SCIMs. The company recorded the significant advances that SCIMs have made over more than 100 years in this period. Hitachi divides advances in electric motors into three distinct periods. Between 1830 and 1890 is the period of inventions, from 1930 to approximately 1950 is the period of scientific initiatives, and between the 1950s and the present day is the period of industrial initiatives [69].

Various technical and technological developments have made Hitachi SCIMs smaller and lighter over the 100 years from 1910 to 2010. Figure 8 presents the leading technologies used by Hitachi that made it possible to reduce the mass of the first SCIM, with a power of 3.7 kW (four poles) manufactured by the company in 1910 with a mass of 150 kg, to approximately 20% of the mass in 2010 (30 kg).

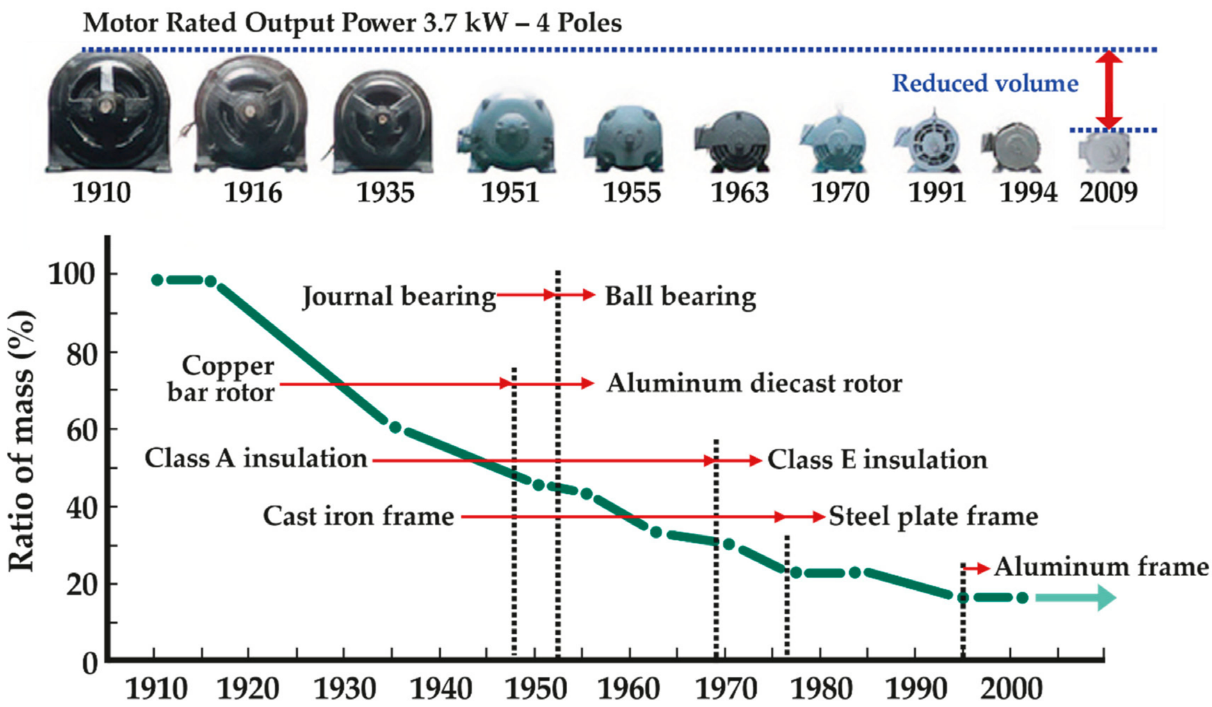

Figure 8. Hitachi SCIM mass changes for 3.7 kW (4 poles) SCIMs. Adapted from [69].

The main changes recorded were the use of aluminium in the rotor in the late 1940s. Later, in the 1950s, bearings improved, moving from sliding technology to ball bearings. In the late 1960s, improvements were made with the application of new insulation classes of varnishes on the wires. In the mid-1970s, cast iron frames gave way to lighter sheet steel frames. In the 1990s, aluminium structures closed the cycle of major technological innovations in Hitachi's first 100 years (1910–2010).

Reduction of Volume and Losses of Ferromagnetic Materials in SCIMs

The first electrical devices to use ferromagnetic materials were developed in the second half of the 19th century. Knowledge about these materials, such as their structure, was absent; as a result, the development of the projects was based on trial and error [70].

For SCIMs to thrive, they needed to advance in generating, transmitting, and distributing electrical energy via alternating current (AC) [71]. Charles Proteus Steinmetz was hired by General Electric (GE) (by Thomas Alva Edison) to improve the AC distribution system. He developed the complex representation of variables sinusoidally in time, which is still in use today [72]. Steinmetz deepened his studies of ferromagnetic materials to better compete with Westinghouse, which manufactured the induction motors invented by Tesla.

The first concepts regarding losses in ferromagnetic materials, traditionally known as iron losses, were developed by Steinmetz [73]. Via understanding how the losses behaved with changes in the intensity of the magnetic field, the General Electric induction motors became competitive, due to the reduction in the volume of material used [74].

Steinmetz's secret was to use increasingly thin sheets. The eddy current losses depend on the square of the sheet thickness, the hysteresis losses, and the square of the magnetic field strength [75]. Steinmetz's discoveries led to more efficient rolling mills that produced thinner and thinner sheets.

Understanding the ferromagnetic losses (hysteresis and eddy current) was decisive for selecting increasingly thin sheets to assemble the stator and rotor magnetic package. Thus, it was possible to impose a greater magnetic flux density in the package of sheets, approaching the limit of the magnetic saturation of the plate. This knowledge contributed to reducing the volume of SCIMs to approximately one third of the initial volume between 1891 and 1901 (Figure 4).

Subsequently, the development of ferromagnetic materials focused on reducing iron losses through heat treatment of the materials and the "doping" of silicon to increase the resistivity of the composite [76], thus enabling the intensification of the magnetic field and consequently reducing the volume of the SCIMs for a defined power.

To better understand the reason for the volume reduction of SCIMs over time, as shown in Figure 4, regarding the reduction provided by the improvement in ferromagnetic materials, it is possible to model the volume of SCIMs from the increase in the intensity of the magnetic field in their structures. This imposition of increasingly intense magnetic fields was one of the main reasons for the reduction in the volume of electric motors since their development.

A mathematical expression that translates the volume/power ratio as a function of the imposed magnetic flux density can be deduced from the electromechanical energy conversion equation, where the phase-induced electromotive force is given by Cardoso et al. [70]:

$$E = 4.44fN_{eff}\varnothing \tag{1}$$

where f is the frequency (Hz), N_{eff} is the number of adequate turns in series per phase, and $\varnothing$ is the magnetic flux per pole (Wb).

Furthermore:

$$\varnothing = 2\frac{BLR}{p} \tag{2}$$

where B is the density of the magnetic flux in the air gap (T), L is the packet length (m), R is the radius of the air gap (m), and p is the number of pole pairs.

The electric current expressed as a function of the magnetic field in the motor air gap was expanded from the classical magnetomotive force equation FMM = NI = $\Re\phi$, and can be expressed as [70]:

$$I = \frac{\pi p l_g B}{3\sqrt{2}\mu_0 N_{eff}} \tag{3}$$

where μ_0 is the magnetic air permeability (H/m), p is the number of pole pairs, and l_g is the thickness of the air gap (m).

Ignoring any type of losses, the motor power will be given by $P = mEI$, where m is the number of motor phases.

Substituting E and I by their values expressed in Equations (1) and (3) results in:

$$P = \frac{\pi m p^2 l_g n}{3\mu_0} B^2 Vol \tag{4}$$

where $n = \frac{f}{p}$ represents the synchronous motor rotation in rps and $Vol = \pi R^2 L$ represents the motor volume.

Reorganizing Equation (4), it is possible to mathematically verify the volume/power ratio of SCIMs and other equipment that uses ferromagnetic materials, in proportion to the intensity of the internal magnetic field in Equation (5).

$$\frac{Vol}{P} = \frac{1}{K_m B^2} \tag{5}$$

with:

$$K_m = \frac{\pi m p^2 l_g n}{3\mu_0} \tag{6}$$

Equation (5) is inversely proportional to the magnetic flux density characteristic square, expressing a curve similar to that of Figure 4. It suggests that one of the primary explanations for the reduction in the volume (or mass) of SCIMs over the years was the more significant imposition of the magnetic field on its magnetic structure, as shown in Figure 9.

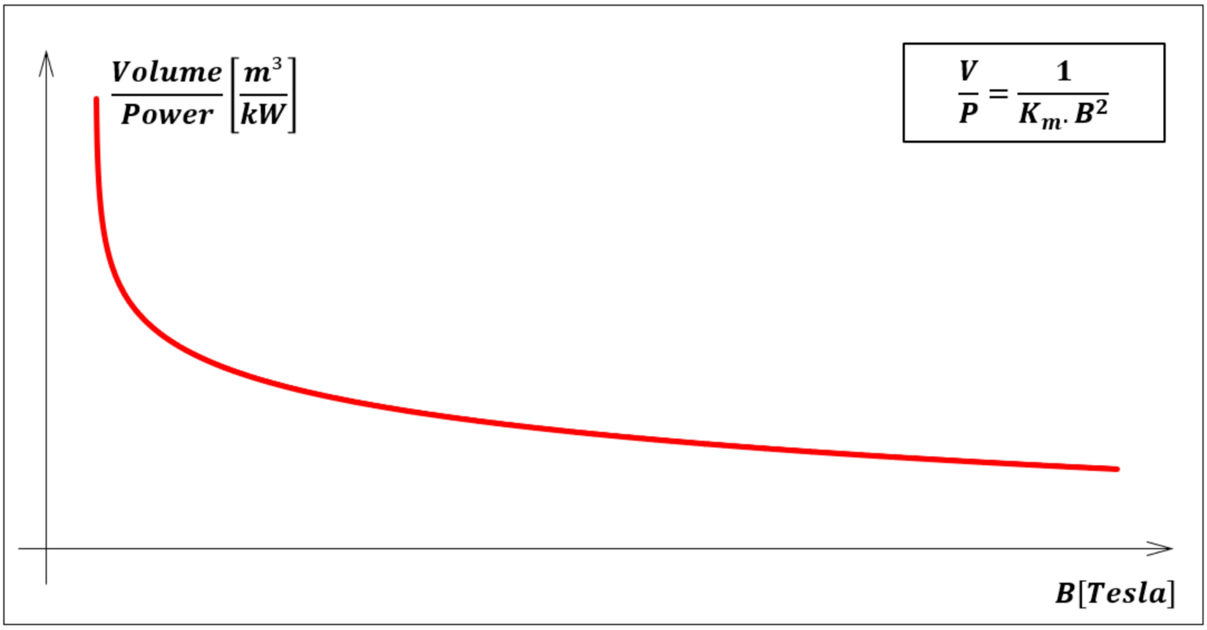

Figure 9. Density of the magnetic flux in the air gap and the volume of SCIMs.

Figure 9 represents the relationship between the improvement in the quality of the ferromagnetic material and the reduction in SCIM volume, considering the same output power. As a result of Equation (5), the curve is theoretical since it is impossible to design an electric machine with unlimited magnetic flux density (B) or a value of B very close to zero. Hence, the curve represents one of the essential reasons for the reduction in the volume of SCIMs from the first units to the present day.

It is estimated that for 110 kW electric motors, the losses in ferromagnetic materials represent, on average, 59% of the total losses [77]. The losses increase with increasing frequency of the electric voltage. These materials have also undergone improvements from the first electric motors to the current ones.

Since Michael Faraday demonstrated electromagnetic induction in 1831 [78], soft magnetic (ferromagnetic) materials have continued to evolve. When iron was the only soft magnetic material available, metallurgists and materials scientists experimented by introducing other elements to improve the efficiency of iron.

The main known losses in ferromagnetic materials are hysteresis and eddy current losses. Hysteresis losses occur through the coercivity of a magnetic material. Each time a material with magnetic characteristics completes an entire cycle of its magnetization curve, the area within this curve measures the energy lost in the magnetization process.

The second primary loss mechanism in soft magnetic materials is eddy currents. Eddy currents are closed electric current paths generated in a conductor whose source is a time-varying magnetic field. These current loops create a magnetic field in opposition to the change in magnetic flux (according to Faraday's law of induction). The energy losses caused by eddy currents scale approximately with the square of the operating frequency and are thus a significant cause of losses in alternating-current machines.

The development of silicon (electrical) steel in about 1900 was a notable event in the advances of soft magnetic materials [79]. Silicon steel still dominates the global soft magnet market and is the material of choice for large-scale transformers and electrical machines such as SCIMs. In 1900, Robert Hadfield, a metallurgist from England, and his team developed unoriented silicon steel by adding up to 3% of silicon to iron and increasing its electrical resistivity (ρ) [80].

The team led by the American metallurgist Norman Goss developed grain-oriented silicon steel in 1933, promoting grain growth along a crystalline direction. The most common applications for silicon steel are large-scale transformers (grain-oriented silicon steel) and electrical machines (unoriented isotropic silicon steel is preferred for rotating machines), for which the economical price is a great benefit [80].

Improvements in magnetic properties were also achieved, from the treatment of iron to minimize chemical impurities to the techniques of slicing the iron into thin sheets. Subsequently, silicon was used to increase the electrical resistance of iron and control the crystal orientation. Figure 10 presents the reduction in losses in the core of electrical machines in watts for each kilogram of ferromagnetic material, highlighting the predominant technological advances of each period.

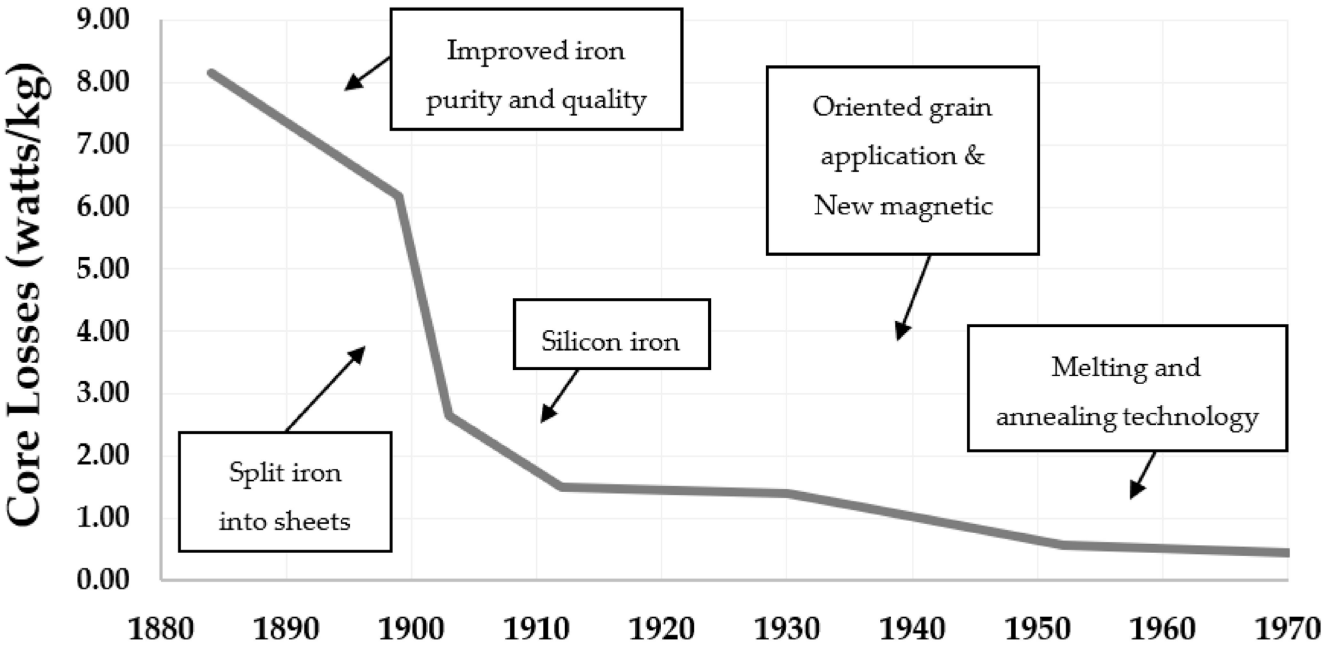

Figure 10. Changes in losses in the core of electrical machines (ferromagnetic material). Source: adapted from [7,76,81].

It is possible to observe in Figure 10 that between 1884 and 1970, the losses in the core of alternating-current electrical equipment reduced from 8.16 W/kg to 0.44 W/kg, which represents an approximately 95% reduction.

Figure 10 shows low frequencies (50 or 60 Hz) and a constant B (T) value, as both directly influence losses in ferromagnetic materials.

Today's primary soft ferromagnetic materials in electric motors are iron and ferrosilicon alloys (2022). However, materials with lower eddy current and hysteresis losses have been developed since the 1970s.

After the energy crisis of the 1970s, the first attempts to use amorphous materials for electric motors were recorded (1981). Mischler et al., demonstrated the low-loss potential of the amorphous stator in a laboratory environment [82].

In 1967, a new class of materials, amorphous alloys, was introduced [83]. In the mid-1970s, interest in amorphous alloys based on iron and cobalt increased, and these materials began to find applications [84]. However, only in 1988 did Hitachi researchers investigate Nb and Cu additives. They added an annealing step to amorphous alloys to produce small-spaced crystallites of iron or cobalt within an amorphous matrix material. The formation of isolated crystallites of transition metals reduced the eddy current losses of these materials compared to traditional amorphous alloys. Despite a higher initial cost than silicon steel, these advanced alloys can reduce the total lifetime costs of electric motors due to reduced losses.

Currently (2022), unique treatments involving thermal manipulation, laser bombardment, and other technologies continue to produce high-performance magnetic materials.

3.2. Changes in the Performance of SCIMS

It was not just the masses and volumes that changed. Successive changes in the performance of SCIMs occurred from the first commercially available versions to the mass manufacturing versions of today (2022).

Several technological advances explained the changes in the performance of SCIMs, from the technological innovations already mentioned to improvements in production processes and the purification of active materials. Sven Sjöberg [66] presented the reasons for the performance gains of SCIMs manufactured by the company ABB Motors after the great cycle of innovations that closed in the 1970s:

(a) Cutting tooling: improving mechanical precision and enabling the elimination of burrs;
(b) Laminated package: lamination mixing, lamination control before pressing, welding, or stator clasping. Quality assessment of raw material sampling before casting (rotor);
(c) Machining the outer surface of the stator core (generally not necessary): reduces surface roughness and improves tolerances;
(d) Stator winding: length of coils, type of winding, filling factor, insulation system, loops, and connections;
(e) Impregnation: good filling results and improvements in thermal exchanges;
(f) The casting of the rotor cage: filling of the slots and the closing rings of the cage, purity of the casting material, and balancing of the rotor;
(g) Alignment of the rotor shaft and machining of the outer surface of the rotor.

Sven Sjöberg (1997) presented the performance changes to SCIMs manufactured by ABB Motors between 1935 and 1996, as shown in Figure 11. According to Sven Sjöberg, performance changes did not result from any performance regulation but occurred due to materials improvements, technological innovations, and improvements in production processes [66].

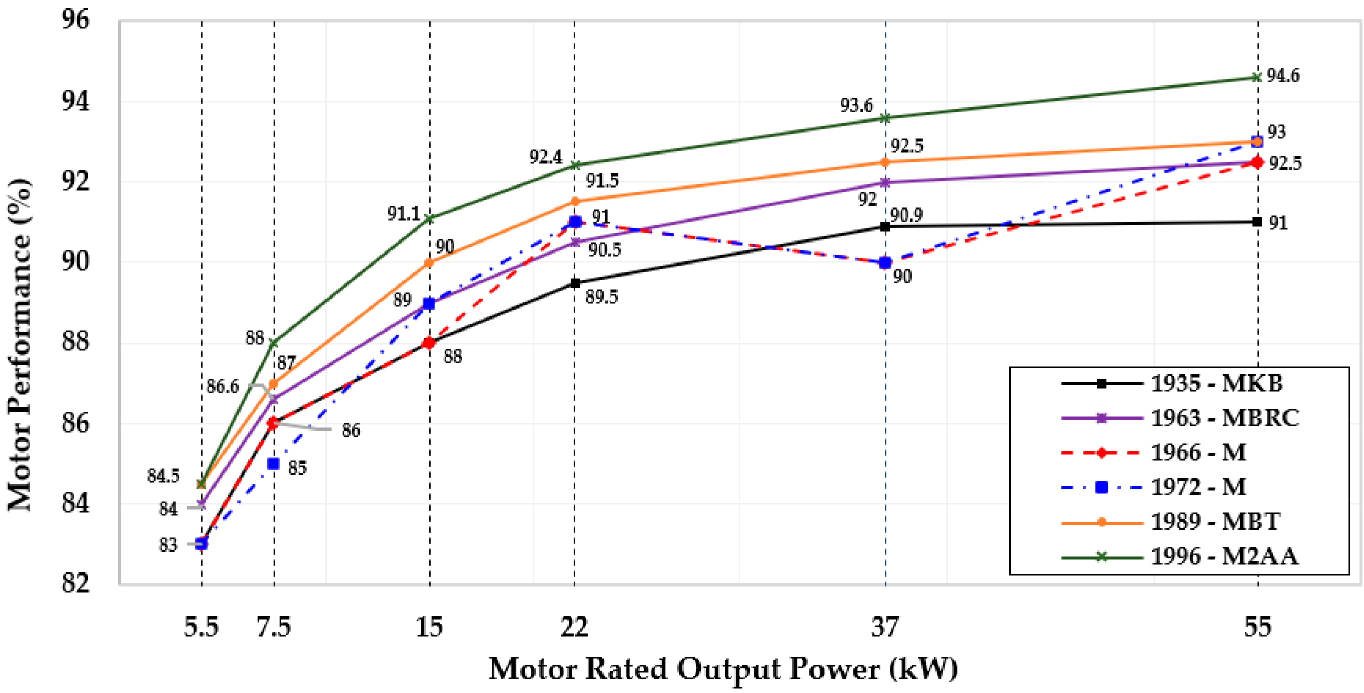

Figure 11. Changes to performance of 4-pole SCIMs between 1935 and 1996. Source: adapted from [65,66].

It is observable in Figure 10 that in the 1960s and 1970s there was a reduction in the average performance of SCIMs, considering a wide range of power. In some periods, the performances were inferior to those obtained by the industry in 1935. The researcher Sven Sjöberg, in his text, does not identify the elements that led to this temporary drop in performance between the 1970s and 1980s.

For the United States Department of Energy (DOE), the 1960s and 1970s were periods of global economic crisis, where SCIM manufacturers built lower-cost equipment compared to previous years. These SCIMs were less efficient, as shown in Figure 12, as they minimized the use of materials such as copper, aluminium, and steel. According to the DOE, these SCIMs had lower initial costs than previous projects. However, they consumed more electrical energy due to their inefficiency, so their use throughout the life cycle was more expensive [85].

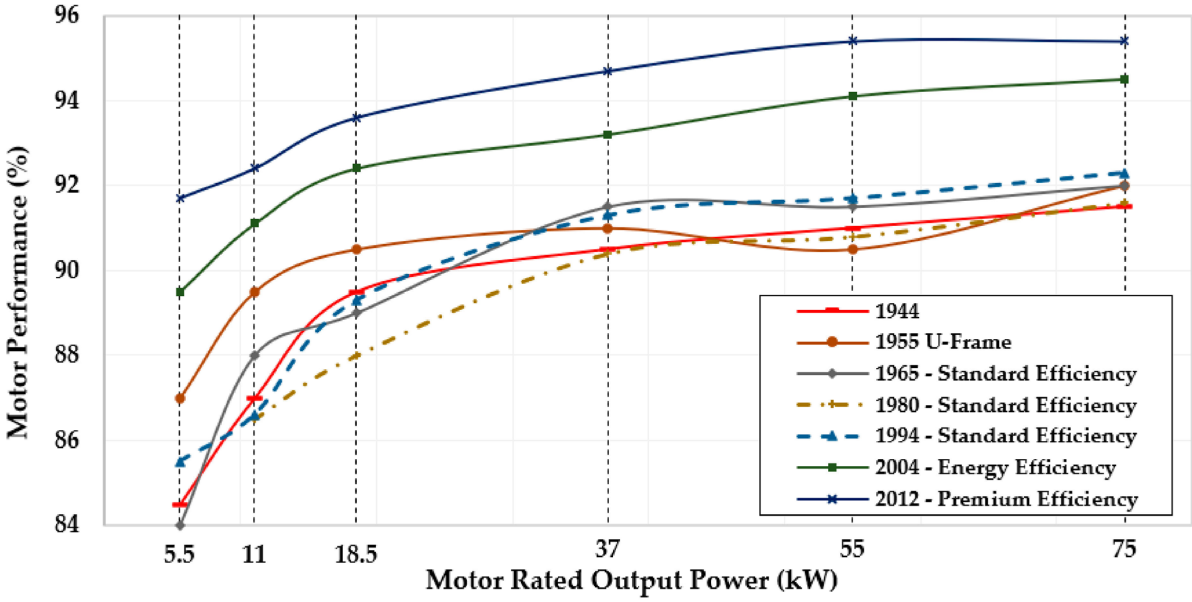

Figure 12. Changes to performance of 4-pole SCIMs between 1944 and 2012. Source: adapted from [85].

Figure 12 shows that the four-pole SCIMs manufactured and marketed in North America in the 1980s had even lower performance than SCIMs manufactured in 1944, which were the first officially registered by the DOE.

According to the DOE, less-efficient and more-compact SCIMs became possible with insulating materials that could withstand high temperatures. These SCIMs were designed to admit higher losses due to the increase in temperature in the coils located in the stator, making it possible to accommodate the winding wires in smaller frames without damaging the insulation [85].

Figure 13 shows the performance changes to four-pole SCIMs with motor rated output powers of 37 and 45 kW, operating at 50 or 60 Hz, at low voltage.

Figure 13 shows the average performance presented by Sjöberg and the DOE. The SCIMs showed a performance reduction between the 1960s and 1980s, and only the data provided by WEG (2015) showed a continuous increase in performance. Figure 13 illustrates the performance data available in the company's publications, beginning in 1960, which was the year the company was established. The data show performances below those obtained in the international market, with high performances recorded for 2010.

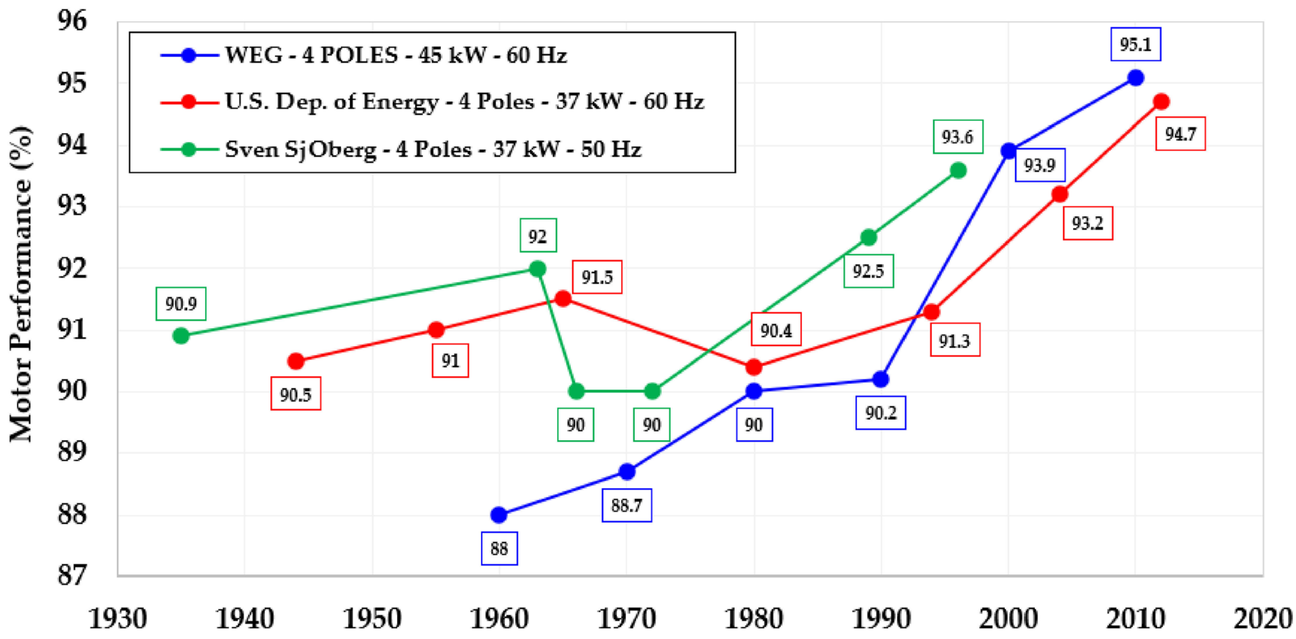

Figure 13. Changes to performance of 4-pole SCIM performance between 1935 and 2012. Source: adapted from [65,66,85].

3.3. Changes in the Performance of SCIMs between 1945 and 2020

SCIMs and most of the electromechanical equipment developed in the 20th century underwent a series of improvements and refinements, from conception through the technological advances in construction processes, mainly in the improvement in the quality of the materials used.

Test results based on data from 1945 and 2020 were used to analyse the change in the performance of 359 SCIMs, with speeds corresponding to two, four, six, or eight poles, at a motor rated output power of 3.7, 37, 150 kW, in order to aid in answering the questions (I and II) that motivated this research.

Figure 14 shows the trends in performance of two-pole SCIMs over time, tested from 1945 to 2020.

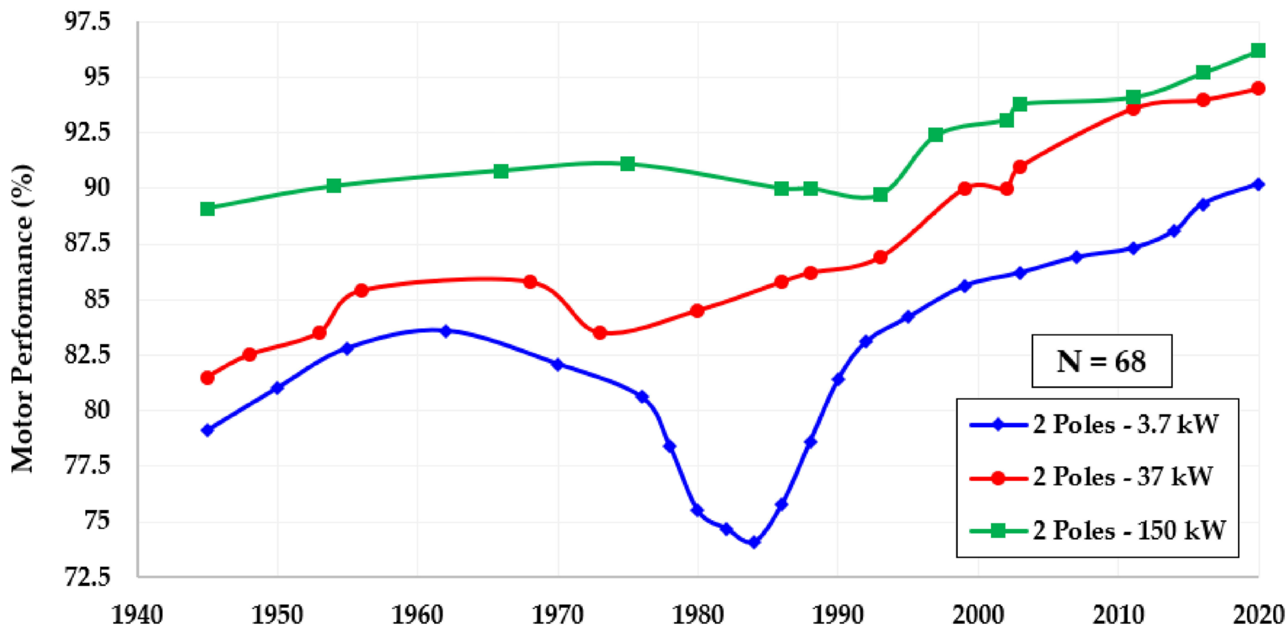

Figure 14. The average performance of 2-pole SCIMs between 1945 and 2020.

Figure 14 shows test results from 68 SCIMs organized into three output power categories and arranged over time. In the years in which results were obtained from more than one SCIM of the same speed and mechanical power, the average performance was calculated for the construction of the figure. In addition, in the years in which there were no SCIMs tested at the output power used in the analysis, the linear regression method was used between the adjacent years in which data were available, in order to construct the figure. The same considerations were applied to Figure 15 (four-pole SCIMs), Figure 16 (six-pole SCIMs), and Figure 17 (eight-pole SCIMs).

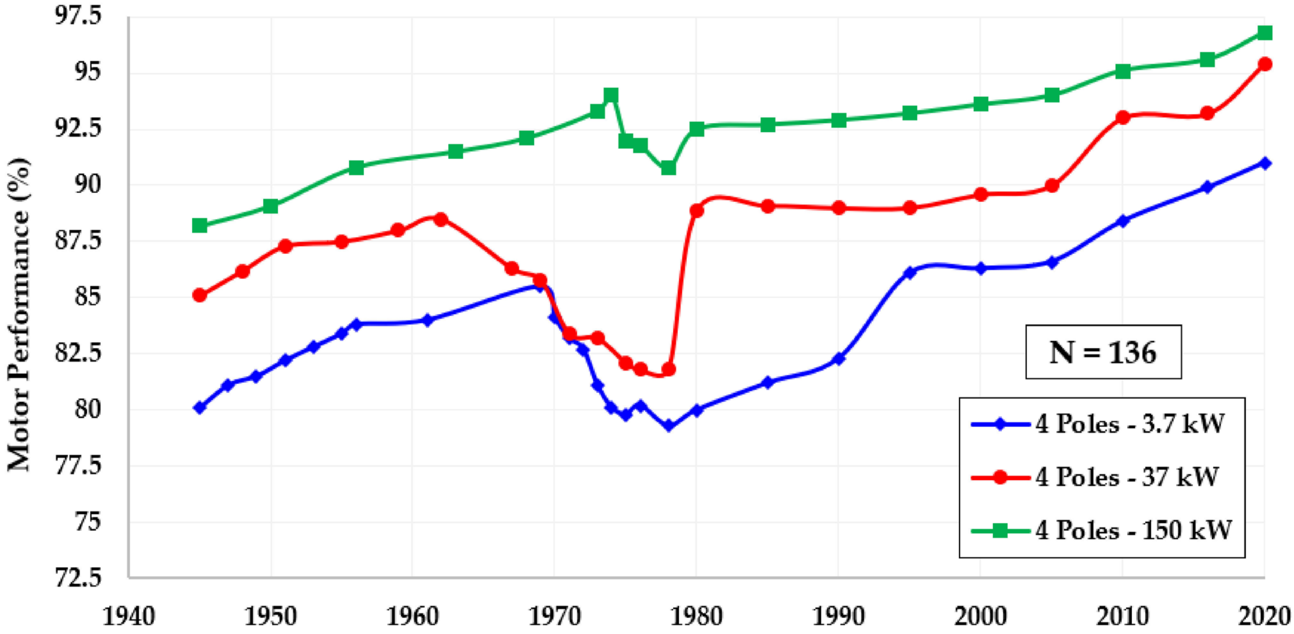

Figure 15. The average performance of 4-pole SCIMs between 1945 and 2020.

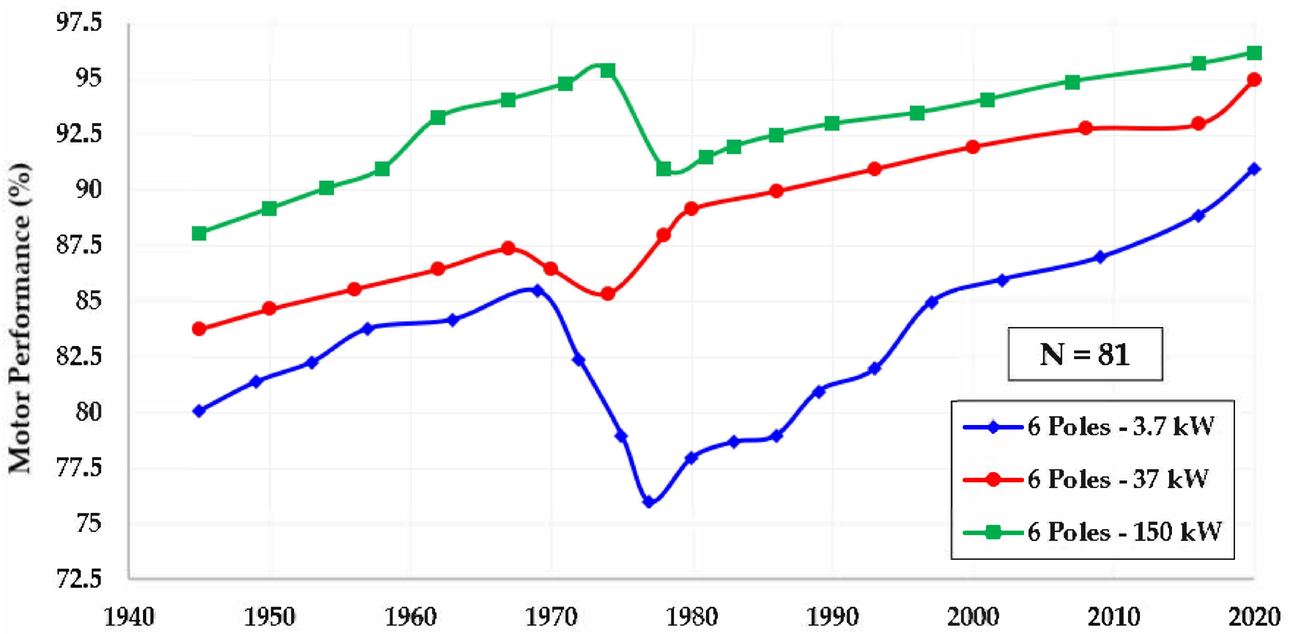

Figure 16. The average performance of 6-pole SCIMs between 1945 and 2020.

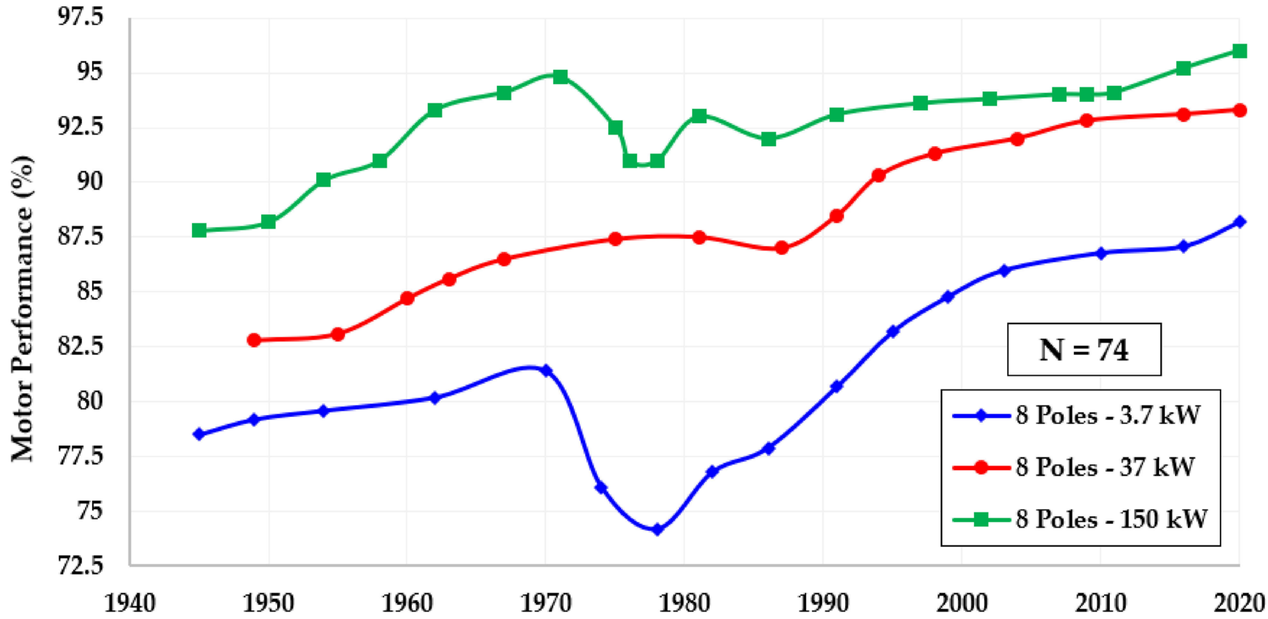

Figure 17. The average performance of 8-pole SCIMs between 1945 and 2020.

Table 3 presents the cumulative performance gain between 1945 and 2020 for the three analysed power values.

Table 3. The average performance of 2-pole SCIMs between 1945 and 2020.

Motor Rated Output Power (kW)	3.7	37	150
Performance (%) 1945	79.1	81.5	89.1
Performance (%) 2020	90.2	94.5	96.2
Accumulated gain (%)	11.1	13	7.1
Loss reduction (%)	53.1	70.3	65.1

Generally, high-power SCIMs are always associated with high performances. They are often subjected to more rigorous quality control routines by the manufacturers and users, who are concerned about the losses in this equipment because they are primarily the predominant industrial electrical loads. This fact results in SCIMs of higher power such as 150 kW having smaller performance gains over that time interval. Medium-power (37 kW) and low-power (3.7 kW) SCIMs are associated with high performance gains, with accumulated values of 13% and 11.1%, respectively, based on the analysed period. In other words, the reduction in losses in two-pole SCIMs between 1945 and 2020 was 53.1% for 3.7 kW, 70.3% for 37 kW, and 65.1% for 150 kW. The trends shown in Figure 14 and Table 3 for two-pole SCIMs are similar to those in Figure 15 and Table 4 for four-pole SCIMs, in Figure 16 and Table 5 for six-pole SCIMs, and in Figure 17 and Table 6 for eight-pole SCIMs.

Table 4. The average performance of 4-pole SCIMs between 1945 and 2020.

Motor Rated Output Power (kW)	3.7	37	150
Performance (%) 1945	80.1	85.1	88.2
Performance (%) 2020	91	95.4	96.8
Accumulated gain (%)	10.9	10.3	8.6
Loss reduction (%)	54.8	69.1	72.9

Table 5. The average performance of 6-pole SCIMs between 1945 and 2020.

Motor Rated Output Power (kW)	3.7	37	150
Performance (%) 1945	80.1	83.8	88.1
Performance (%) 2020	91	95	96.2
Accumulated gain (%)	10.9	11.2	8.1
Loss reduction (%)	54.8	69.1	68.1

Table 6. The average performance of 8-pole SCIMs between 1945 and 2020.

Motor Rated Output Power (kW)	3.7	37	150
Performance (%) 1945	78.5	82.8	87.8
Performance (%) 2020	88.2	94	96
Accumulated gain (%)	9.7	11.2	8.2
Loss reduction (%)	45.1	65.1	67.2

According to Table 4, the loss reduction for four-pole SCIMs was 54.8% for 3.7 kW power, 69.1% for 37 kW, and 72.9% for 150 kW between 1945 and 2020.

According to Table 5, the loss reduction for six-pole SCIMs was 54.8% for 3.7 kW power, 69.1% for 37 kW, and 68.1% for 150 kW between 1945 and 2020.

According to Table 6, the loss reduction for eight-pole SCIMs was 45.1% for 3.7 kW power, 65.1% for 37 kW, and 67.2% for 150 kW between 1945 and 2020.

The three curves (3.7 kW, 37 kW, and 150 kW) showed similar trends in the four figures presented (Figures 14–17), making it possible to separate three periods:

1. Between 1945 and the mid-1960s, SCIMs presented a curve indicating continuous increasing performance gains;
2. Between the 1960s and 1980s, SCIMs showed significant performance drops, in some cases reaching lower levels than the SCIMs marketed in 1945;
3. Between the 1980s and 2020, performance improvement dominated the scenario. It resulted in high levels of performance in the last years of the analysis, presenting a net result, from 1945 to 2020, of gains above 10% in average performance, corresponding to a worst-case reduction of losses of approximately 45%.

Several elements influenced these trends for each of the three periods described above. At first, between 1945 and the mid-1960s, an intensive process of technological innovation was identified, highlighting the following elements that directly influenced the performance gains of SCIMs:

a. Many SCIMs tested in the 1940s still had plain bearings. Sleeve bearings, compared to ball bearings, produce more noise, are larger and heavier, and generally provide greater friction, requiring oil lubrication;
b. In the 1940s, there was a transition from rotors made of iron bars to rotors made of cast aluminium bars. Aluminium has lower electrical resistivity and lower density, and is therefore lighter for the same power;
c. Advances in metallurgy allowed SCIM housings to be built more compactly, improving the safety of operation and maintenance workers, maintaining winding ventilation, and reducing masses and volumes;
d. The insulation system in that period underwent substantial advances, moving from the use of cotton as an insulator to silk, where a significant reduction in the size of the grooves was possible, reducing the size and volume of the SCIMs;
e. Due to the use of silk, it was also possible to insert more copper into the same slot, reducing the most significant losses in SCIMs (Joule losses in the stator winding wires);
f. Improvements in the manufacturing processes of SCIMs were remarkable in that period, whether due to advances in cutting tools or better machining of the active ferromagnetic materials of SCIMs;
g. Between 1884 and 1970, the core losses of AC SCIMS dropped from 8.16 watts/kg to 0.44 watts/kg, which represents an approximately 95% reduction.

In the second period, between the 1960s and 1980s, SCIMs showed significant drops in performance, making it possible to identify the influence of the following elements. In this period, insulation from varnish was developed. The varnish made it possible to withstand high temperatures without compromising the insulation. For this reason, SCIM designs emerged that admitted more significant losses in the stator winding wires due to increased temperature in the coils. Temperatures up to 180 °C, already standardized in the 1970s (Table 7), were observable in some SCIMs.

Table 7. Thermal class of insulation of electrical conductors. Source: [86].

Thermal Class (°C)	Designation Letter
90	Y
105	A
120	E
130	B
155	F
180	H
200	N
220	R
250	-

Cotton and silk operated only as electrical insulators. In contrast, the varnish used, in addition to being an electrical insulator, is a thermal conductor. This factor made it possible to accommodate the winding wires in even more miniature housings without damaging the insulation and to improve cooling with an increased transfer of heat produced mainly in the stator winding wires to the external surface, via the design of the fins on the housing.

When varnish is used to insulate the winding wire, it conducts the temperature rise resulting from the losses in the stator winding wires to the housing (Figure 18). In the process, the fins are designed to increase the contact area with air, thus improving the heat dissipation process and changing the geometry of the SCIM housing.

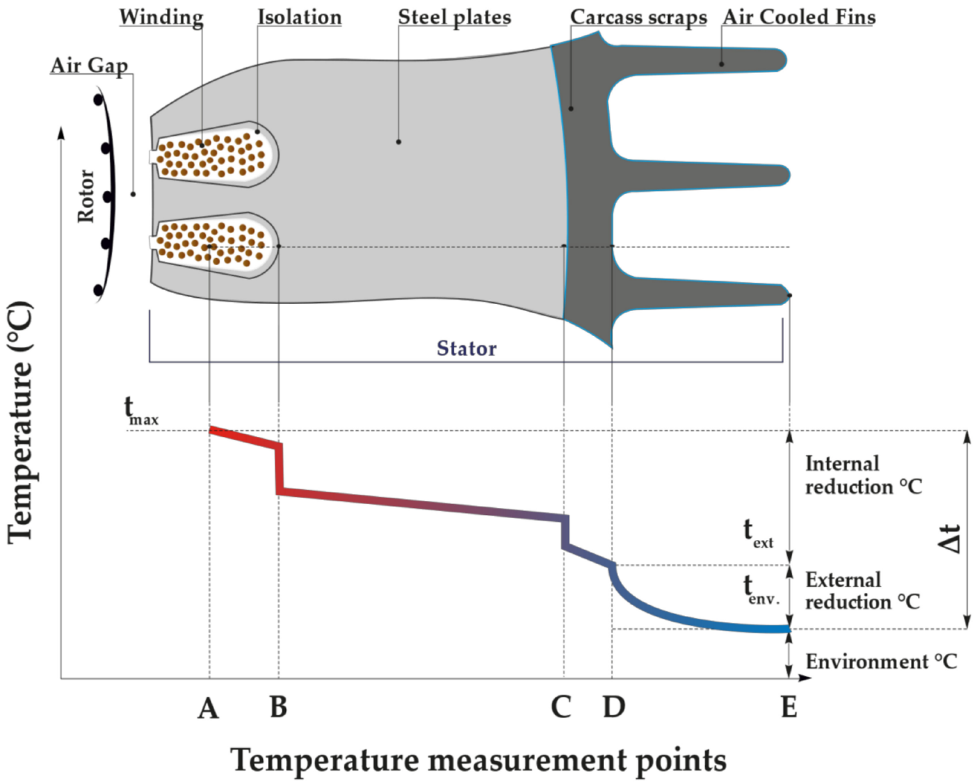

Figure 18. Stator temperature measurement points (A, B, C, D and E). Adapted from [87].

The temperature reduction in SCIMs between points A and E, expressed in Figure 18, can be described as follows:

A—the hottest point of the SCIM, inside the slot that generates the heat from the Joule losses of the stator winding wires;

AB—the temperature reduction resulting from heat transfer from the hottest point to the outer wires of the coil. As air is not a good conductor of heat, there must be no "voids" inside the groove. Therefore, the windings must be compacted and impregnated with varnish, filling the voids as much as possible;

B—the temperature reduction caused by the insulator inserted between the winding wires and the metal plates. It is common to use special paper or synthetic insulating foil to line the groove;

BC—the temperature reduction by thermal conduction in the SCIM core plates;

C—the temperature reduction in the contact between the core and the housing. Precision machining of the housing to reduce surface irregularities is essential in heat conduction;

CD—the temperature reduction by thermal conduction through the shell thickness;

DE—the temperature reduction due to the increase in the SCIM surface exposure caused by the fins.

The reduction in copper mass meant that SCIM manufacturers were able to reduce the final cost of the equipment, since copper is the highest cost input in the construction of SCIMs. This trend was verified in the test reports of the analysed period. An increase in Joule losses (I^2R) in the stator winding wires was mainly observed in relation to previous decades. When the section of the copper conductors reduces, the total mass of the SCIM also reduces. The reduction in copper increased the Joule losses and consequently increased the operating temperature of the SCIMs. The heat generated internally could be more easily dissipated in the housing with varnish.

In the third period, between the 1980s and 2020, improvements in the average performance of SCIMs were evidenced mainly by the following observations.

Minimum performance level policies were applied in the world's largest economies between the 1990s and 2020. The policies that indicate the minimum energy performance of equipment are entitled "minimum energy performance standards (MEPS)," which specify minimum levels of energy performance for commercial purposes. The main objective of MEPS is to guide the performance of the equipment for the consumer and establish a minimum legal requirement for commercialization.

Government bodies usually institute MEPS policies. In the case of SCIMs, MEPS are divided into performance classes, allowing different levels that increase the requirement of a specific minimum performance value according to technological advances and market acceptance. Performance classes for SCIMs internationally are harmonized with the IE code in IEC 60034-30-1 [88], which is widely accepted as the global standard, making performance classes comparable across the various regional energy policy documents for SCIMs. The standard defines efficiency classes from IE1 to IE4 (Figure 19), where IE1 is the lowest, and IE4 is the highest. Similarly, in the United States, performance classes IE1 to IE4 are called Standard, High efficiency, Premium efficiency and Super-Premium efficiency, according to NEMA [89]. The new IE5 class has not been defined in detail; however, it is foreseeable in a future edition of the standard. For IE5 SCIMs, the goal is to reduce losses by about 20% compared to the IE4 class [88,90].

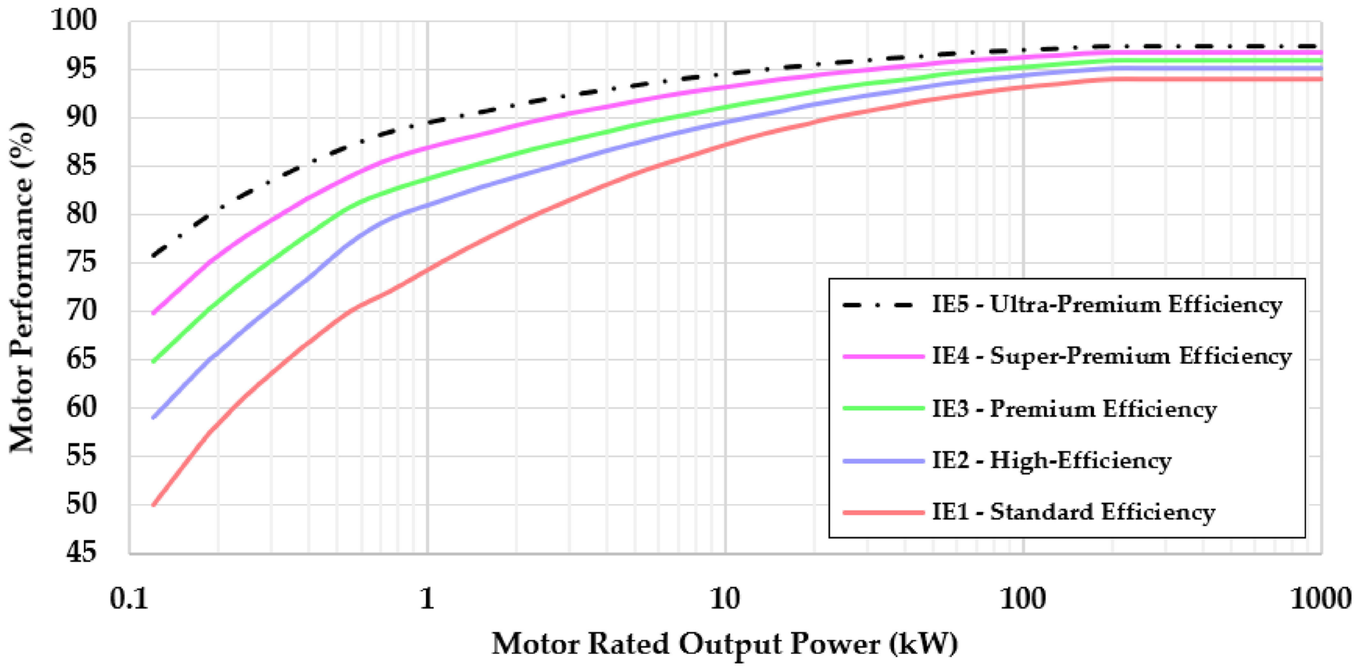

Figure 19. Efficiency levels in the IEC 60034-30-1 (2014) classification standard curves for 50 Hz, 4-pole SCIMs. Source: [88,90].

The SCIMs tested in 2020 were already IE3. Therefore, in the next few years, it should be possible to make another short jump in the performance gain of SCIMs.

The implementation of MEPS for SCIMs took place in the USA and Canada in 1997 and was later gradually applied in other countries, with modifications implemented by each energy agency of the various countries, but maintaining the harmonization as shown in Figure 20.

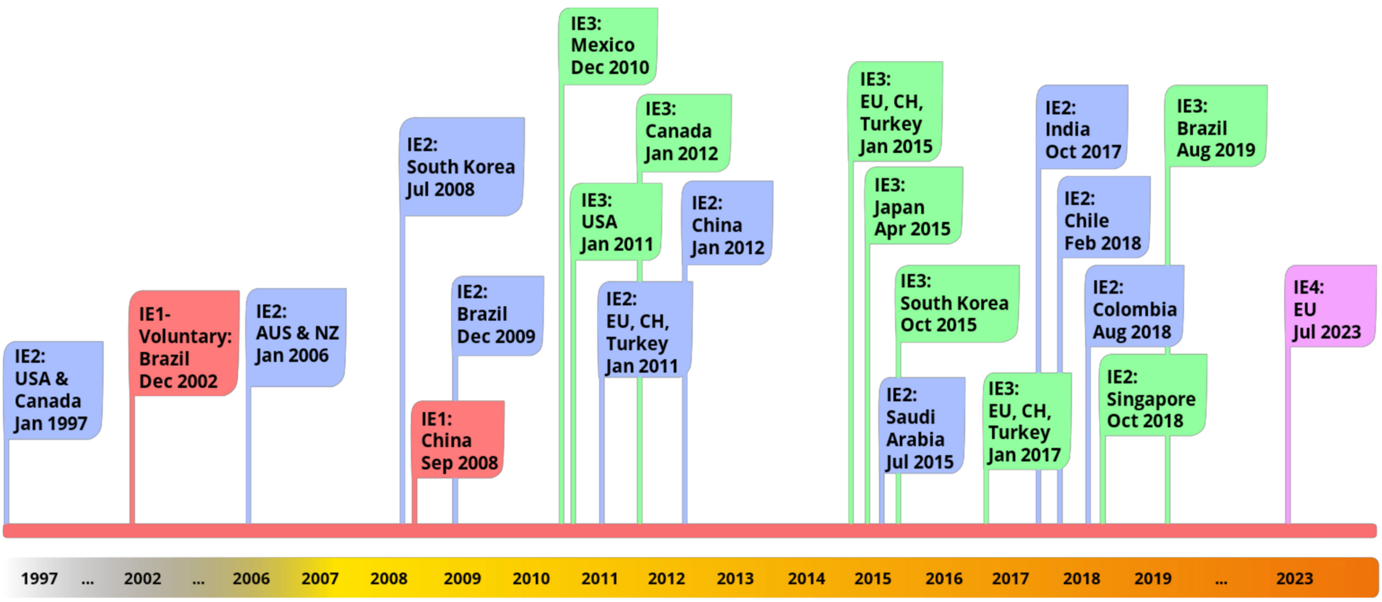

Figure 20. Timeline of global minimum performance standards for SCIMs. Source: [91–97].

To comply with the new legislation, which imposes higher performance indices, the central intervention of the manufacturers, verified in the test reports of the analysed period, was the reduction of Joule losses in the stator, because stator windings started to be built with more copper mass compared to previous decades. This movement also meant that the mass of SCIMs, which until then had decreased with time, began to increase, returning to the levels verified in the 1960s.

During this period, other secondary elements were observed that also influenced the improvement of the performance of SCIMs:

1. Advances in the design of SCIMs through the use of modelling software, enabling structural improvements in the coupling and a reduction in vibrations and noise;
2. Three-dimensional computational modelling of electromagnetic fields, enabling project optimization;
3. Advances in the processes of the casting of steel-silicon sheets;
4. Use of more efficient cooling systems (ventilation).

The three periods described led to profound changes in the mass/power ratio of SCIMs. The analysis presented in Figure 4 demonstrates the falling mass/power ratio and points to the lower levels in the following years needing to be updated. For this reason, Figure 21 was created to answer question III, which was one of the questions motivating this research.

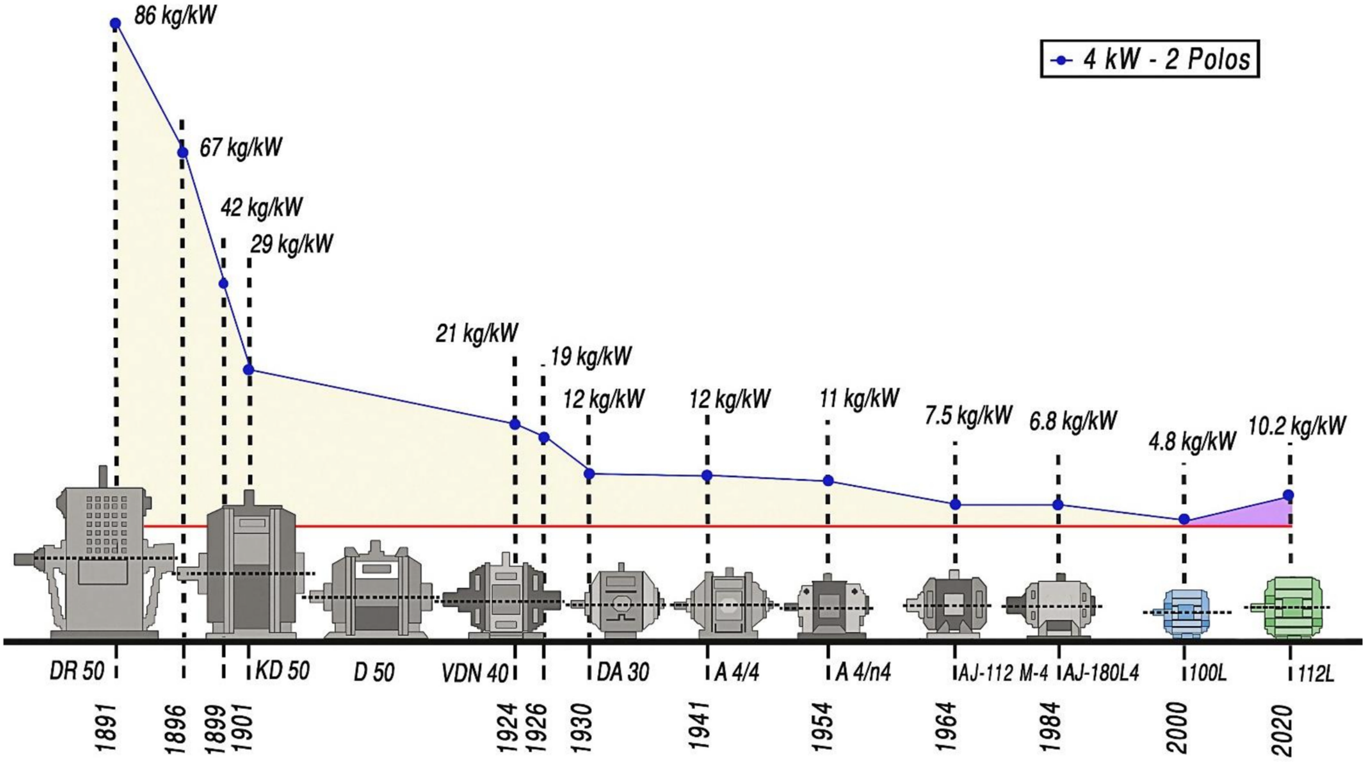

Figure 21. Changes to SCIMs in the mass/power ratio between 1891 and 2020.

The research relied on SCIM test data from 1945 to 2020. However, SCIM mass data was only available in technical reports from 1997 onwards. Before this date, few reports presented a record of the mass of the SCIM under test. Between 1945 and 2020, records of seven SCIMs with power and speeds compatible with Figure 4 and with mass records were discovered. The mass/power ratio found in these seven SCIMs was compatible with the data published by AEG. Thus, Figure 4, containing results between 1891 and 1984, was updated with data obtained in this research (Figure 21).

To create Figure 21, in 2000, 12 two-pole SCIMs with power between 3.7 kW and 4.4 kW were used, and in 2020, 16 SCIMs were used in the same power range and for the same speed. After calculating the mass/power ratio for each SCIM, the arithmetic mean was calculated for each of the two years under analysis.

A significant result verified in Figure 21 was the increase in the mass of SCIMs from the 2000s onwards, reaching the level of 10.2 kg/kW for the same power and speed, returning to levels verified in the 1950s.

The increase in mass was produced mainly by using conductors of a larger section, to reduce the block where the most significant losses in SCIMs are found, that is, the losses from the Joule effect in the wires of the stator windings.

The reduction in volume of an electrical machine can also result in challenges in keeping components cool. In the case of high heating, deterioration of the properties of most materials (such as insulators, coils, and sheets of ferromagnetic material) can occur, causing a reduction in the useful life of the equipment. This is one of the reasons that justify the average increase in the carcass of SCIMs in the last two decades.

There was also an increase in the lengthening of the rotor package, and consequently of the stator windings, significantly increasing the amount of material used in the construction of the high-efficiency motor, as seen in Figure 22.

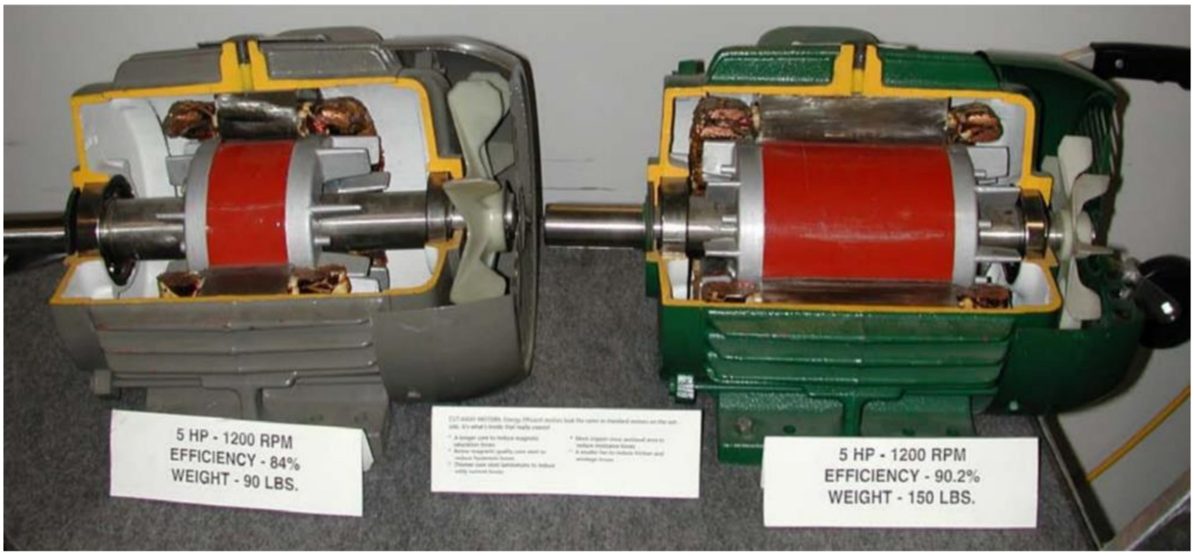

Figure 22. The difference in the material quantity between Standard SCIM and High-Efficiency SCIM. Source: [98].

In Figure 22, the most significant change made to increase the performance of a 5 HP (3.7 kW) electric motor from 84% to 90.2% was an increase in mass of 27 kg or approximately 33%, while maintaining the same carcass.

For performance gains superior to those shown in Figure 22, increasing the carcass to accommodate the new stator and rotor dimensions was necessary. Figure 21 shows that SCIMs went from a 100L housing in 2000 to a 112L housing twenty years later (2020).

The mass/power ratio depends on the power range and speed, so Figure 21 cannot be directly generalized to other power values without proper adjustments. However, the shape of the curve presents a similar trend for the other power ranges and speeds.

There is no forecast of a continuous increase in the mass/power ratio of SCIMs, as this has been optimized in recent years through technological innovations. Other viable technologies have been presented to reach the IE5 standard. Synchronous operation motors include permanent magnet synchronous motors (PMSMs) and synchronous reluctance motors (SynRMs). Synchronous motors employ a drive that can also control the speed, and they have introduced a series of improvements in motor drives, such as ease of automation, the possibility of pre-diagnosis, ease of application of intelligent sensors, the possibility of collection and analysis of electrical quantities, etc.

PMSMs, for the same power range (4 kW) and speed (two poles) as those shown in Figure 21 can present a mass/power ratio of approximately 4 kg/kW, with a performance above 93%, even for low power and a power factor above 0.95.

SynRMs, for the same power range (4 kW) and speed (two poles) as those shown in Figure 21 can present a mass/power ratio of approximately 7.5 kg/kW, with a performance above 92.8%, even for low power and a power factor above 0.95.

Synchronous operation electric motors do not have rotor losses, and this is one of the main reasons this equipment can raise the level of performance. Synchronous motors also have a smaller physical volume than traditional SCIMs and are touted as the immediate future of variable-speed motor drives. If the economic factor also becomes an attraction, synchronous motors may also be viable in fixed-speed systems.

For SCIMs to reach IE5, two possibilities are currently considered. One is the use of amorphous materials with high magnetic permeability to reduce core losses. Another is the use of copper to minimize losses in rotors traditionally constructed of aluminium.

The magnetic package of SCIMs can be particularly suited to amorphous laminations, as demonstrated by Hitachi with an 11 kW motor prototype that achieved IE5 efficiency [99]. The Hitachi prototype had a reduced size compared with a traditional SCIM and performance above 93% over a wide load range.

Traditional medium- and low-power SCIMs have a rotor constructed primarily of cast aluminium. However, since 2002, it has been possible to find, for some applications, SCIMs with rotors made with copper [100].

The copper squirrel-cage rotor enables a 15% to 18% reduction in total motor losses (this can represent an efficiency gain of 2 to 4%, depending on the power and number of poles) [101]. A copper rotor is made of electrical steel laminations in which the rotor bars and end rings are made of cast copper instead of cast aluminium. Copper is an excellent material for rotors because it has higher electrical conductivity than aluminium [102].

The use of the copper rotor can also support the resumption of size reduction and overall weight reduction of the motor, since the reduction in losses in the rotor allows the reduction of the total length of the rotor and consequently the stator.

3.4. Research Limitations

In this section, dealing with the limitations of this research, we make suggestions for future research activities on the theme of changes in the performance of electric motors, which will contribute to research in the area:

- Evaluate the changes that have taken place in the forms of SCIM projects, from manual calculations to the use of high-level computer simulation;
- Evaluate the improvements in the copper drawing process and the improvement in the purity of copper (stator) and aluminium (rotor);
- Evaluate the improvements in the design and machining of the ventilation of electric motors;
- Evaluate improvements in the electric drive process and coupling between electric motors and mechanical loads;
- Evaluate advances in metallurgy to produce increasingly accurate cuts, improving the quality of electrical machines.

4. Conclusions

It is common to read in the technical literature that "SCIMs have hardly changed in the last 100 years". However, current SCIMs are significantly different from the SCIM developed by Mikhail Dolivo-Dobrovolsky's team between 1888 and 1890. Therefore, this statement is only valid when referring to the SCIM's working principle. This research showed significant changes in the design, materials, and components that make up the parts of SCIMs.

The present research analysed the performance levels of SCIMs based on the results of tests carried out at the Laboratory of Electrical Machines of IEE/USP in the period between 1945 and 2020. SCIMs with powers of 3.7 kW, 37 kW, and 150 kW were used in a total of 359 electric motors. Regarding the performance levels, the results showed that the SCIMs presented a similar trend, and it was possible to identify three distinct periods in the historical timeline.

Between 1945 and the mid-1960s, SCIMs showed practically constantly increasing gains in performance. This was due to the various technological innovations in the period, mainly the use of oriented grains in the ferromagnetic material, the use of aluminium in the rotor, essential improvements in the projects, and the ventilation of the SCIMs.

Between the 1960s and 1980s, which was a period of cheap energy, manufacturers built cheap and relatively inefficient SCIMs, minimizing the use of materials such as copper, aluminium, and steel. The production of lower-performance, lower-volume SCIMs was made possible by developing insulating materials (particularly varnishes) that could withstand high temperatures. This allowed SCIMs to be designed with higher losses (particularly Joule losses in the stator winding), since the temperature rise due to losses could be transferred to the housing (the varnish is electrically insulating and thermally conductive) without damaging the insulation or reducing the expected motor life (Figure 18). In this period, the reduction in the performance of SCIMs was so high that, in some cases, the performance reached lower levels than for the SCIMs marketed in 1945.

Although these motors had lower start-up costs than previous designs, they used more energy due to their inefficiency.

From the 1980s to 2020, performance improvement dominated the scene again. The central aspect of this performance variation was the technology and materials used to construct the machines. It was possible to observe that the gains were significantly higher for minor power values, due to the large margin for improvements in materials and projects due to the low technical construction rigour.

The reduction of losses in the SCIMs analysed in the period 1945–2020 was in all cases more than 40% for the three analysed output power values (3.7, 37, and 150 kW) and the four possible speeds (two, four, six, and eight poles). In the case of 150 kW SCIMs with a speed corresponding to four poles, the loss reduction in the period reached 72.9%, showing a significant advance.

The 37 kW SCIMs with a speed corresponding to 2 poles had the highest accumulated efficiency gain in the analysed period. They went from 81.5% average yield in 1945 to 94.5% 75 years later (2020), resulting in an absolute 13% performance gain.

The relationship between the mass and power of SCIMs presented two periods in the analysis performed. The first period was the 94% reduction between 1891 and 1984, from 86 kg/kW to 4.8 kg/kW, due to the various technological innovations discussed in this paper. The second period showed a decrease by 112.5% between 2000 and 2020, from 4.8 kg/kW to 10.2 kg/kW on average, due to the need to resume the performance increase.

In conclusion, continuous performance gains occurred during intense technological innovation, showing the importance of performance legislation for SCIMs. In the 1970s and 1980s, the search for lower-cost SCIM manufacturing reduced the equipment's performance. Thus, the self-regulation of the SCIM market, in terms of performance, did not show positive results in periods of low technological innovation. A return of the performance improvement was observed, mainly by the imposition of performance legislation, motivated by a global need to rationalize the final energy use and by sustainable energy considerations.

Author Contributions: Conceptualization, D.F.d.S., F.A.M.S., I.L.S. and A.G.K.; methodology, D.F.d.S., F.A.M.S. and A.G.K.; validation, D.F.d.S., F.A.M.S., H.T. and A.G.K.; investigation, D.F.d.S., F.A.M.S., A.T.d.A. and A.G.K.; resources, F.A.M.S., A.T.d.A., I.L.S. and A.G.K.; data curation, D.F.d.S. and F.A.M.S.; writing—original draft preparation, D.F.d.S., F.A.M.S., I.L.S., H.T., A.T.d.A. and A.G.K.; writing—review and editing, A.T.d.A., F.A.M.S., H.T. and A.G.K.; supervision, H.T. and A.G.K.; funding acquisition, I.L.S. and H.T. All authors have read and agreed to the published version of the manuscript.

Funding: National Electric Energy Agency (ANEEL): Project number 00390-1086/2018 (ENEL)—Integrated assessment of distributed generation, demand management, monitoring, quality, and performance of the network, aiming at optimizing investments and tariff regulation in the underground network, and Project number 00061-0054/2016 (CESP)—Analysis of the efficiency of complementary energy storage with hydroelectric plants, using electrochemical and hydrogen storage technologies; National Council for Scientific and Technological Development (CNPq): Project 870814/1999–0, Process 142323/2020–9.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the National Council for Scientific and Technological Development (CNPq) for the scholarship made available to the first author through the project 870814/1999–0, process 142323/2020–9, so that he could dedicate himself to his PhD research in this and related fields. The authors thank the researchers Walter Aguiar Jr. and Kenny Kawaguchi for their support in creating the figures for this paper, and the researcher Jefferson Oliveira for the discussions on electrical machine projects. Furthermore, the workers who worked since the foundation of the Laboratory of Machines of the IEE/USP and throughout their careers generated the database used in this research. The authors thank the researcher Richardson M Abraham-A for improvements in the translation of the manuscript. Moreover, the teacher Lars Eirik Frantzen made the text more friendly. The first author honors Mário Kawaphara and Mateus Rondina from the Federal University of Mato Grosso, for their teaching on SCIMs. The authors would like to thank the researcher José Roberto Cardoso from the Applied Electromagnetism Laboratory (LMAG/USP) for his contributions to the discussion in section (Reduction of Volume and Losses of Ferromagnetic Materials in SCIMs) of this paper. The authors are grateful for the reviewers' criticisms, which contributed to improving this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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APPENDIX B

SOUZA, D. F.; SALOTTI, F. A. M.; SAUER, I. L.; TATIZAWA, H.; KANASHIRO, A. G. A Comparison Between Reported Values and Measured Values of Power Factor and Efficiency for Electric Induction Motors. **IEEE Latin America Transactions**, v. 19, p. 173-181, 2021. (FERREIRA DE SOUZA et al., 2021).

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A Comparison Between Reported Values and Measured Values of Power Factor and Efficiency for Electric Induction Motors

Author: Danilo Ferreira de Souza
Publication: IEEE Latin America Transactions
Publisher: IEEE
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BACK CLOSE WINDOW

A Comparison Between Reported Values and Measured Values of Power Factor and Efficiency for Electric Induction Motors

D. F. Souza, F. A. M. Salotti, I. L. Sauer, H. Tatizawa, *Member, IEEE,* A. G. Kanashiro *Member, IEEE*

Abstract—**Two main features provided by electric motor manufacturers are power factor and efficiency. However, the values reported are often different from the measured values. Thus, this work presents the results obtained from testing 435 Three-phase Induction Electric Motors with Squirrel Cage Rotor from 38 different manufacturers tested between 2015 and 2016. The data were collected through standardized tests performed at the Laboratory of Electrical Machines of the Institute of Energy and Environment of the University of Sao Paulo. The values reported by the manufacturers were compared with the values measured in the laboratory. The results indicate that 58% of the values measured for the power factor of the motors were lower than those reported by the manufacturer. Similarly, 55% of the measured values for the performance were lower than the values reported by the manufacturer.**

Index Terms—**Efficiency, Power Factor, Tests on Electric Motors.**

I. Introdução

A eletricidade no Brasil é consumida predominantemente no setor industrial. Segundo a Empresa de Pesquisa Energética (EPE) [1], 37,56% de toda a eletricidade consumida no país é destinada ao segmento industrial. Para o Programa Nacional de Conservação de Energia Elétrica (Procel) [2], a predominância absoluta dos motores elétricos no consumo percentual industrial brasileiro, representando 68% da eletricidade consumida nas indústrias, são distribuídos entre cargas, como por exemplo: sistemas de bombeamento, ventilação, compressão, transporte, dentre outras [3].

De acordo com Garcia [4], os Motores de Indução Trifásicos com Rotor em Gaiola de Esquilo (MITRGE) são responsáveis por mais de 90% do consumo total de eletricidade em motores elétricos. Por este motivo, muitos países implantaram legislação de desempenho de motores elétricos, estabelecendo o rendimento mínimo dos MITRGE para cada potência de eixo padronizada e rotação [5]–[8]. Os motores podem ser classificados ainda por níveis de rendimento, informando ao comprador por meio de selos que definem basicamente o quão eficiente são os equipamentos [9]

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A simplicidade de sua construção faz com que consequentemente o custo de produção seja baixo, quando comparado a outras tecnologias motrizes [10], [11]. Os MITRGE também são conhecidos por exigir baixíssimos índices de manutenção, consistindo basicamente na lubrificação dos mancais e na limpeza do sistema de ventilação [3].

Os MITRGE, por não possuírem enrolamentos exclusivos para magnetizar o núcleo, utilizam energia reativa da rede para promover esta função. Assim, apresentam fator de potência abaixo do valor unitário, com corrente atrasada em relação à tensão [12]. O quão baixo é o fator de potência do motor elétrico depende de uma série de contribuições, por exemplo:

1) Carga mecânica aplicada ao eixo;
2) Simetria das tensões;
3) Número de polos;
4) Potência mecânica nominal;
5) Qualidade do material ferromagnético;
6) Densidade de fluxo magnético.

Para a correta medição do fator de potência, os itens 1 e 2 são contribuições controladas no laboratório de ensaio, na ocasião dos ensaios. Os itens 3, 4 e 6 são características construtivas que dependem do projeto e da especificação do usuário. O item 5 depende dos custos finais desejados e do controle de qualidade do fabricante por serem inerentes a seleção prévia da qualidade do material empregado. Cabe um esclarecimento quanto ao item 6 (densidade de fluxo) ser uma contribuição que afeta o fator de potência do motor durante a execução do ensaio e é também dependente do projeto. A densidade de fluxo magnético depende da tensão aplicada ao motor e do ponto de saturação previsto no projeto do equipamento, fato determinado pela curva de saturação do material ferromagnético empregado.

Desta forma, o fator de potência do MITRGE é um elemento importante para o dimensionamento da instalação elétrica que alimenta o referido equipamento; quanto mais próximo do valor unitário for o fator de potência, menor será a energia reativa capacitiva necessária para corrigir o fator de potência aos níveis de referência, sendo o valor mínimo regulamentado em (0,92) pela Agência Nacional de Energia Elétrica (ANEEL) do Brasil, na Resolução Normativa nº 414 [13].

Por este motivo, é importante conhecer o valor do fator de potência do MITRGE em condições nominais, devendo ser obrigatoriamente disponibilizado pelo fabricante em seu informativo técnico.

No caso do rendimento, se o valor medido for inferior ao valor efetivamente informado, o usuário do equipamento terá maior consumo de energia elétrica com o equipamento. Também haverá maior necessidade de investimentos públicos com a geração de energia elétrica, onde os custos dos empreendimentos são repassados aos consumidores. O rendimento dos MITRGE é ajustado na fase de projeto.

O rendimento é afetado pela seleção mais conveniente dos materiais utilizados na construção, como por exemplo, a qualidade da chapa ferromagnética selecionada que irá compor o núcleo do estator e do rotor, a moldagem dos enrolamentos com baixas perdas joule, uso de ventilador com aerodinâmica eficiente, rolamentos com baixo atrito, modelagem adequada das ranhuras onde serão alojados os enrolamentos do rotor e estator. O rendimento também tem a dependência das condições de alimentação, simetria das tensões e da potência mecânica.

Neste trabalho foi realizada a análise do fator de potência, e do rendimento em 435 MITRGE, comparando os valores fornecidos por 38 diferentes fabricantes com os valores medidos em laboratório por meio de condições controladas. Bem como, foi analisado os resultados e relacionados com as tolerâncias determinadas pelas portarias de controle do INMETRO.

II. Metodologia

Todos os dados de ensaios dos motores de indução trifásicos utilizados neste trabalho foram coletados no Instituto de Energia e Ambiente (IEE) da Universidade de São Paulo (USP). O Laboratório de Máquinas Elétricas do IEE-USP é acreditado pelo Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO) de acordo com a norma ABNT NBR ISO/IEC 17025:2017 [14] sob o nº CRL 0011. O INMETRO realiza periodicamente auditorias nos laboratórios acreditados, visando garantir a qualidade no resultado das medições. O INMETRO é signatário dos acordos de reconhecimento mútuo da *International Laboratory Accreditation Cooperation (ILAC)* e também da *Inter American Accreditation Cooperation (IAAC)*, seguindo, portanto, padrão mundial de qualidade e confiabilidade.

Todos os instrumentos utilizados nas medições no IEE são calibrados e aferidos com rastreabilidade à Rede Brasileira de Calibração (RBC), pertencente ao INMETRO.

O Brasil possui normativa própria para MITRGE que é a norma ABNT NBR 17094 partes 1 e 3 [15], requisitos para especificação e métodos de ensaio, respectivamente.

Os resultados dos ensaios de rendimento foram obtidos por meio de procedimentos de teste amplamente reconhecidos e aceitos pela indústria, e estão em conformidade com o método 2 da ABNT NBR 17094-3 [15], que é semelhante ao método B da norma *IEEE112* publicada pelo *Institute of Electrical and Electronics Engineers (IEEE)* [16], [17]. O método recomendado na norma brasileira para determinação do rendimento é o MÉTODO 2 devido a sua característica de apresentar baixa incerteza na determinação do rendimento e por apresentar repetitividade e reprodutividade dos resultados.

As incertezas de medição são calculadas conforme orientações internacionais estabelecidas nos documentos INTROGUM [18] e EA-4/02 [19]. Essas normativas são discutidas em comitês mundiais como uma tentativa de uniformizar o cálculo da incerteza de medição em diversas áreas do conhecimento.

De acordo com o MÉTODO 2 da norma NBR 17094-3:2018 [15], o rendimento é determinado pela adição de todas as parcelas de perdas, para cada solicitação de carga.

As perdas denominadas Joules, identificadas por I^2R que ocorre nos enrolamentos do estator, bem como nas barras do rotor. São corrigidas para uma temperatura igual à temperatura ambiente padronizada em (25°C), somadas à elevação da temperatura do motor, determinada pelo ensaio de aquecimento com carga nominal e calculada a partir da metodologia de variação da resistência do enrolamento.

Para determinar os valores de rendimento para diversos carregamentos, as parcelas que correspondem a cada perda são obtidas e separadas pelos seguintes ensaios:

1) Ensaio a vazio: Este ensaio é realizado utilizando-se fonte de tensão variável, trifásica, em frequência nominal conforme a NBR 17094-3 [15]. Na realização do ensaio, os dados são registrados para uma faixa de tensão desde 120% decrescendo até aproximadamente 20% da tensão nominal. Por meio de analisador de energia, é medido o valor da potência absorvida, composta pelas parcelas de perdas no ferro e perdas mecânicas (atrito e ventilação). Neste ensaio a NBR 17094-3 [15] considera que o motor, analisado pelo seu diagrama elétrico equivalente possua perdas no ferro (histerese e correntes parasitas), atrito e ventilação. As perdas no ferro são consideradas proporcionais à tensão da alimentação e são dissipadas essencialmente no estator. A perda no ferro do rotor é desprezível visto a baixa frequência induzida nesta parte do MITRGE e é considerada para efeito de cálculo do rendimento como perda suplementar dependente da condição de carregamento do motor. As perdas por atrito e ventilação são separadas por processo gráfico e consideradas invariáveis para qualquer condição de carregamento do motor;
2) Ensaio em carga: A NBR 17094-3 [15] orienta para a separação das perdas que são dependentes da condição de carga do motor estabelece que o ensaio para determinar o rendimento deva ser realizado após ter atingido a estabilidade térmica trabalhando com carga nominal. Para cada ponto de carga diferente são separadas as perdas joule no estator, joule no rotor e suplementar considerando que a temperatura do rotor tenha sido constante e igual ao valor médio entre o início e o final do ensaio. Para melhor obter a tendência da perda suplementar, o ensaio deve ser realizado preferencialmente em 6 pontos de carga, e não inferior a 5 pontos (cargas entre 25% e 150% da nominal), Após a separação das perdas suplementares, para cada ponto de carga, ela é linearizada por processo matemático utilizando método de regressão linear [15], esta etapa de cálculo faz um alinhamento dos pontos de rendimento obtido para toda a curva de carga medida.

O rendimento de um motor elétrico trifásico é a razão entre a potência de saída e a potência ativa de entrada, expressa em percentagem ou fração decimal. A ABNT NBR 17094-3 [15] regulamenta dez (10) diferentes formas de se determinar o rendimento dos MITRGE. Para o MÉTODO 2 - ensaio dinamométrico com medição indireta das perdas suplementares e medição direta das perdas joule no estator (I^2R), joule no rotor (I^2R), no núcleo e por atrito e ventilação, utilizado para execução dos ensaios desta pesquisa, a potência mecânica de saída é determinada como sendo a potência absorvida, ou de entrada, subtraindo todas as perdas já separadas nos ensaios em vazio e em carga.

Está apresentado na Fig. 1 uma das bancadas de ensaio dos MITRGE para até 25 CV. A referida bancada utiliza a metodologia de freio dinamométrico para aplicar carga mecânica no eixo do MITRGE no ensaio em carga.

Fig. 1. Foto de uma das bancadas de ensaio de MITRGE.

Este trabalho apresenta a comparação entre valores medidos e informados pelos fabricantes para o fator de potência e o rendimento de 435 MITRGE fabricados por 38 diferentes companhias brasileiras e internacionais. Os ensaios foram realizados entre 2015-2016 e os motores eram novos, sendo fabricados entre 2013 e 2016, sendo:

1) 129 motores de 2 polos;
2) 227 motores de 4 polos;
3) 61 motores de 6 polos;
4) 18 motores de 8 polos.

A análise foi realizada apenas para os motores alimentados em baixa tensão, até 600V, na frequência industrial de 60 Hz. Os motores foram divididos em 4 blocos de acordo com a velocidade determinada pelo número de polos magnéticos.

III. Resultados e Discussões

A. Dados de Placa Versus Valores Medidos – uma Análise do Fator de Potência

A Fig. 2 apresenta 129 resultados de ensaios de MITRGE, com potência de eixo entre 1 e 200 CV, com 2 polos. Os pontos marcados em verde referem-se a medições com resultados de fator de potência, igual ou superior ao valor nominal disponibilizado pelo fabricante. A linha horizontal em vermelho representa o valor nominal do fator de potência que é apresentado pelo fabricante, em percentual. Os pontos azuis representam resultados de medições inferiores aos valores informados pelos fabricantes. No eixo das ordenadas é apresentada a magnitude do desvio absoluto que é a diferença entre o valor medido e o valor informado pelo fabricante e no eixo das abscissas a potência nominal de eixo.

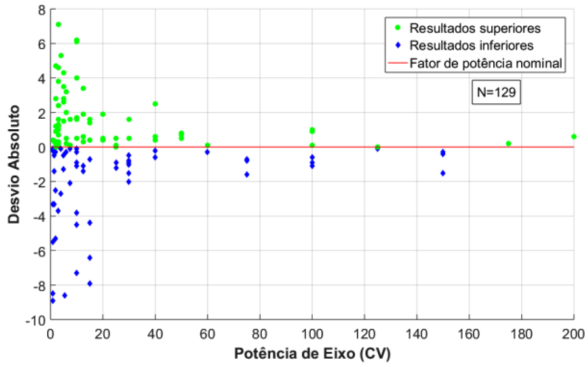

Fig. 2. Desvio absoluto dos valores de fator de potência para motores de 2 Polos.

Na Fig. 2 e nas demais que seguem, “N” representa o número de MITRGE ensaiados.

A Tabela I apresenta a avaliação estatística das medições do fator de potência dos 129 resultados de ensaio em relação ao valor disponibilizado no informativo técnico dos fabricantes. O percentual de resultados igual ou acima do registrado no informativo técnico foi de 56,59%, deixando, desta forma, 43,41% dos motores elétricos testados, com resultados de medições abaixo do valor apresentado pelo fabricante.

TABELA I
Análise Estatística do Fator de Potência para Motores de 2 Polos

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
56,59%	43,41%	7,1%	-8,9%	0,073%	2,71%

O “desvio máximo positivo” e “desvio máximo negativo” na Tabela I apresentam o desvio pontual unitário do resultado de ensaio que mais apresentou discrepância absoluta em relação ao valor nominal disponibilizado pelos fabricantes. Neste caso, o desvio máximo positivo de 7,1% e negativo de -8,9% mostram que existem diferenças entre os valores informados e os resultados das medições. Na Fig. 2 pode ser observado que os resultados apresentam maior desvio absoluto para os motores de menor potência de eixo. Este resultado é esperado, pois os motores de menor potência tem mais variabilidade no processo produtivo. Também é observado que os MITRGE com menor potência de eixo, possuem maior representação percentual no total de motores ensaiados, assim como é observado numericamente nas plantas industriais.

O desvio médio, expresso na Tabela I, trata da distância média entre os resultados dos ensaios e a média aritmética dos dados. Quanto maior for à dispersão dos dados, maior será o desvio médio. Como pode ser observado na Tabela I, (0,073%) de desvio médio é um valor baixo, indicando uma distribuição pouco dispersa.

O desvio padrão expresso na Tabela I é uma grandeza de dispersão dos valores de fator de potência medidos em torno dos valores informados pelos fabricantes nos informativos técnicos. Quanto menor o desvio padrão, significa que mais próximos os valores medidos estão dos valores informados.

Estão apresentados nas Fig. 3, 4 e 5 os desvios absolutos do fator de potência medido em relação ao informado pelo fabricante, para motores com velocidades de 4, 6 e 8 polos, respectivamente. As tabelas II, III e IV são apresentadas a análise estatística para as referidas velocidades de maneira similar à tabela I.

A Fig. 3 apresenta o desvio absoluto do fator de potência para 227 motores de 4 polos analisados. A referida análise apresenta maior quantidade de motores elétricos, como também, maior escala de potência de eixo com motores até 250 CV.

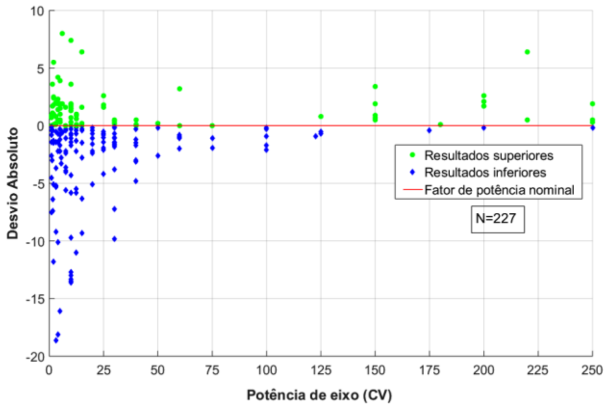

Fig. 3. Desvio absoluto dos valores de fator de potência para motores de 4 Polos.

A Tabela II apresenta o percentual de resultados igual ou acima do registrado no informativo técnico dos fabricantes em 39,21% do total de motores. Em 60,79% dos motores ensaiados foram obtidos resultados abaixo do valor apresentado pelos fabricantes, demonstrando, portanto, que uma significativa maioria dos resultados encontrados está abaixo dos valores nominais.

TABELA II
ANÁLISE ESTATÍSTICA DO FATOR DE POTÊNCIA PARA MOTORES DE 4 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
39,21%	60,79%	8%	-18,6%	-1,28%	3,9%

O desvio máximo negativo visualizado na Tabela II, foi de um motor elétrico ensaiado, cujo resultado foi 18,6% abaixo do valor informado pelo fabricante, o que demonstra elevada dispersão entre valores medidos e valores informados. Observa-se, entretanto, que a elevada discrepância não é representativa em função da quantidade total de motores para esta velocidade.

A Fig. 4 apresenta o desvio absoluto do fator de potência para 61 motores de 6 polos analisados. A referida análise apresenta escala de potência de eixo, com potências de até 180 CV.

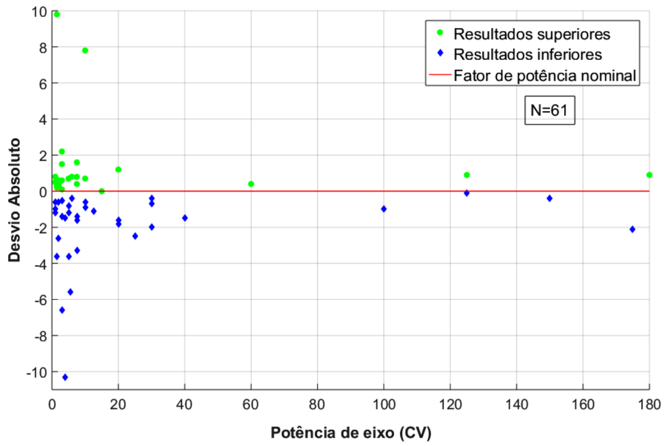

Fig. 4. Desvio absoluto dos valores de fator de potência para motores de 6 Polos.

A Tabela III apresenta o percentual de resultados igual ou acima do registrado nos informativos técnicos dos fabricantes, totalizando 40,98% dos motores com rendimento acima e 59,02% dos MITRGE com rendimento medido abaixo do valor apresentado pelos fabricantes. Os desvios máximos positivos e negativos apresentaram resultados iguais a 9,8% e -10,3%, respectivamente.

TABELA III
ANÁLISE ESTATÍSTICA DO FATOR DE POTÊNCIA PARA MOTORES DE 6 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
40,98%	59,02%	9,8%	-10,3%	-0,61%	2,7%

A Fig. 5 apresenta o desvio absoluto do fator de potência para 18 motores de 8 polos. A referida análise apresenta escala de potência de eixo com motores até 40 CV.

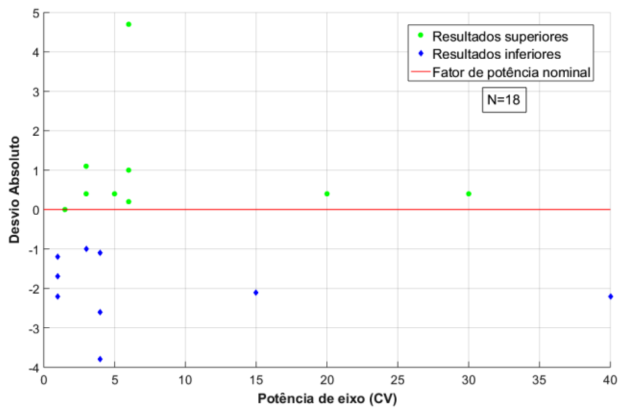

Fig. 5. Desvio absoluto dos valores de fator de potência para motores de 8 Polos.

Conforme a Tabela IV, os motores elétricos ensaiados apresentaram resultados iguais no que se refere ao percentual acima e abaixo do nominal.

TABELA IV
ANÁLISE ESTATÍSTICA DO FATOR DE POTÊNCIA PARA MOTORES DE 8 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
50%	50%	4,7%	-3,8%	-0,52%	1,91%

Uma análise geral dos resultados da comparação entre valores de fator de potência medidos e os valores informados é apresentada na Tabela V, onde é possível observar que 55% dos motores ensaiados apresentaram fator de potência medido abaixo do valor informado pelo fabricante.

TABELA V
COMPARAÇÃO GERAL DO FATOR DE POTÊNCIA ENTRE OS VALORES MEDIDOS E VALORES INFORMADOS

	2 Polos	4 Polos	6 Polos	8 Polos	Total
Medições abaixo do nominal	56	138	36	9	55%
Medições iguais ou acima do nominal	73	89	25	9	45%

Como já exposto, o fator de potência dos motores é uma grandeza de elevada importância, pois a partir dele são tomadas providencias para evitar otimizar a instalação elétrica e evitar a cobrança de multas, podendo também reduzir perda nas linhas elétricas. A norma NBR 17094-1 [15] e a Portaria nº 488 do INMETRO [20], [21] estabelecem a tolerância para o fator de potência, calculada conforme Equação (1):

$$Tolerância = -\left({}^{1}/_{6}\right).(1 - \cos\emptyset) \qquad (1)$$

Onde: $\cos\emptyset$ é o fator de potência informado pelo fabricante em catálogo ou dados de placa. O valor encontrado na equação 1 deve ser subtraído do valor informado pelo fabricante (valor nominal), obtendo assim o valor mínimo que o motor sob teste deve apresentar para ser considerado em conformidade com a exigência normativa. Caso o resultado da equação 1 seja, em módulo, menor que -0,02, adota-se este valor como tolerância, caso o resultado seja, em módulo, maior que -0,07 adotar este valor como a máxima tolerância para o resultado. Não há limite a se considerar caso o fator de potência medido seja maior que o valor declarado.

Aplicando a Equação (1) ao total de 435 MITRGE analisados, 58 motores encontraram-se fora da tolerância calculada, sendo, portanto, considerados reprovados no referido quesito.

Dos motores reprovados, 15 são de 2 polos, 40 são de 4 polos e 3 são de 6 polos. Nenhum MITRGE de 8 polos foi reprovado. Todas as reprovações registradas foram por dados medidos estarem abaixo do valor informado pelos fabricantes fora da tolerância determinada pela Portaria nº 488 do INMETRO [21].

É conhecido que a diminuição da resistência elétrica num circuito tem como uma das consequências a diminuição do fator de potência desse circuito. Trazendo esta informação para o caso dos motores em estudo, denominados de motores de alto rendimento, a principal alteração em relação aos antigos modelos da linha *standard*, é o aumento da seção dos condutores utilizados na construção dos enrolamentos do estator que tem como consequência a redução da resistência dos enrolamentos, bem como, a redução da perda joule (I^2R) do estator.

Assim, a redução da resistência ôhmica dos enrolamentos do estator tem como objetivo a melhoria do rendimento, mas por outro lado diminui o fator de potência dos MITRGE operando com carga nominal.

A seguir é apresentada a análise comparativa entre o rendimento medido e o rendimento informado pelos fabricantes para os mesmos 435 MITRGE utilizados para a análise anterior.

B. *Dados de placa Versus Valores Medidos – uma Análise do Rendimento*

A Fig. 6 apresenta 129 MITRGE entre 1 a 200 CV, 2 polos, ensaiados entre 2015 e 2016. Os pontos em verde referem-se aos resultados de medição de rendimento, igual ou superior ao valor de rendimento nominal disponibilizado pelos fabricantes e representado na figura pela linha horizontal em vermelho. Os pontos azuis representam resultados de medições inferiores aos valores informados pelo fabricante. No eixo das ordenadas é apresentada a magnitude do desvio absoluto entre os valores medidos e informados e no eixo das abscissas a potência nominal de eixo dos motores.

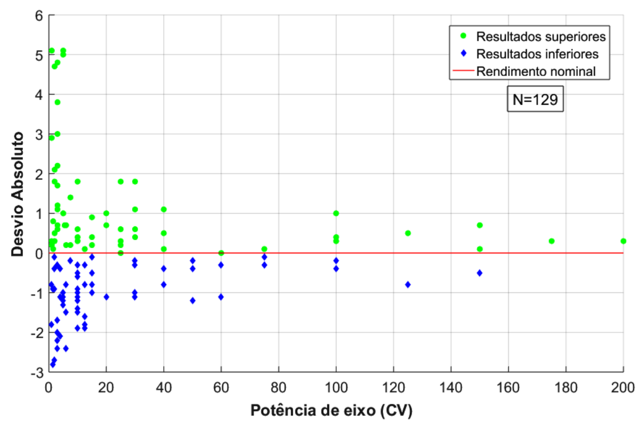

Fig. 6. Desvio absoluto dos valores de rendimento para motores de 2 Polos.

Conforme Tabela VI, os motores elétricos de 2 polos ensaiados apresentaram resultados próximos no que se refere ao Percentual acima do nominal e abaixo. Os valores de desvio máximo positivo e negativo foram iguais a 5,1% e -2,8%, respectivamente. O desvio médio resultou em 0,028%.

TABELA VI
ANÁLISE ESTATÍSTICA DO RENDIMENTO PARA MOTORES DE 2 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
48,06%	51,94%	5,1%	-2,8%	0,028%	1,52%

A Fig. 7 apresenta o desvio Absoluto do rendimento para 227 motores de 4 polos. A referida análise apresenta maior quantidade de motores elétricos, como, também, maior escala de potência de eixo, com potências até 250 CV.

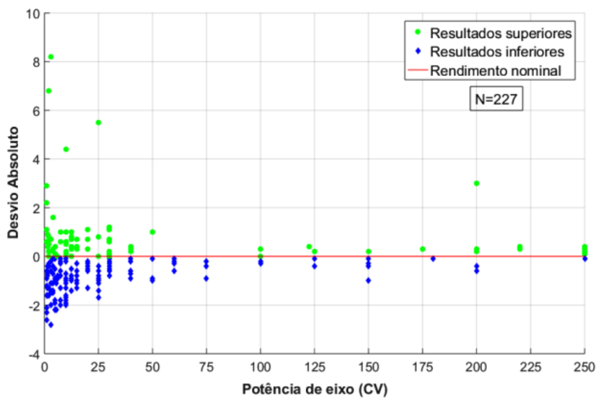

Fig. 7. Desvio absoluto dos valores de rendimento para motores de 4 Polos.

A Tabela VII apresenta percentual de resultados igual ou acima do registrado no informativo técnico do fabricante em 35,24%, do total de MITRGE de 4 polos. Em 64,76% dos MITRGE de 4 polos ensaiados, os resultados foram abaixo do valor apresentado pelo fabricante.

TABELA VII
ANÁLISE ESTATÍSTICA DO RENDIMENTO PARA MOTORES DE 4 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
35,24%	64,76%	8,2%	-2,8%	-0,26%	1,25%

A Fig. 7 apresenta o desvio absoluto do rendimento para 61 motores de 6 polos. A referida análise apresenta potência de eixo até 180 CV.

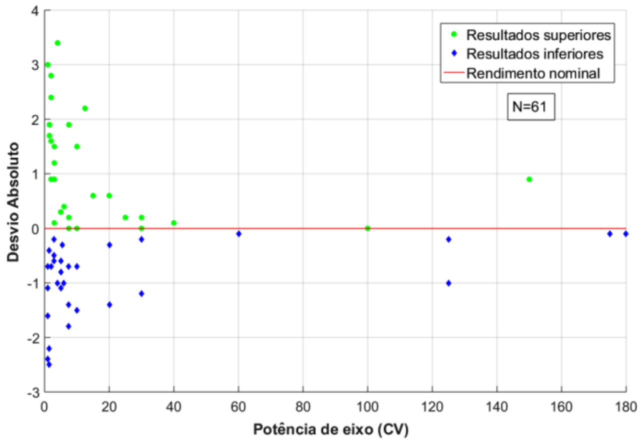

Fig. 8 . Desvio absoluto dos valores de rendimento para motores de 6 Polos.

Conforme Tabela VIII, os motores elétricos de 6 polos ensaiados apresentaram resultados próximos no que se refere ao percentual acima do nominal e abaixo. Houve baixa discrepância no valor do desvio máximo positivo em 3,4% e máximo negativo em -2,5%.

TABELA VIII
ANÁLISE ESTATÍSTICA DO RENDIMENTO PARA MOTORES DE 6 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
49,18%	50,52%	3,4%	-2,5%	0,044%	1,3%

A Fig. 9 apresenta o desvio absoluto do rendimento para 18 motores de 8 polos. A referida análise apresenta escala de potência de eixo com potências até 40 CV.

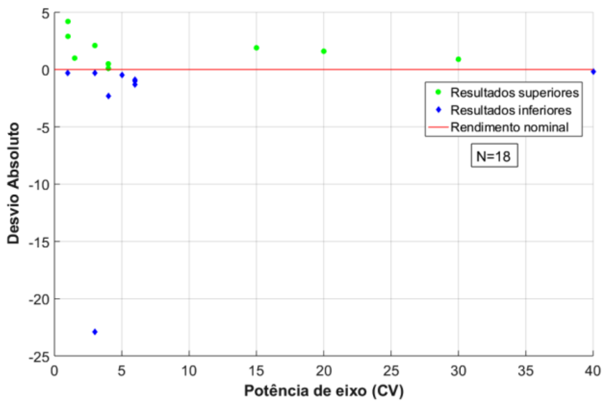

Fig. 9. Desvio absoluto dos valores de rendimento para motores de 8 Polos.

Conforme Tabela IX, os motores elétricos de 8 polos ensaiados apresentaram resultados iguais no que se refere ao percentual acima do nominal e abaixo. Houve significativa discrepância no valor do desvio máximo negativo, obtendo-se o valor 22,9% abaixo do valor informado pelo fabricante no informativo técnico.

TABELA IX
ANÁLISE ESTATÍSTICA DO RENDIMENTO PARA MOTORES DE 8 POLOS

Percentual acima do nominal	Percentual abaixo do nominal	Desvio máximo positivo	Desvio máximo negativo	Desvio médio	Desvio padrão
50%	50%	4,2%	-22,9%	-0,81%	5,74%

Uma análise geral dos resultados da comparação entre valores de rendimento medidos e informados é apresentada na Tabela X, onde é possível observar que 58% dos motores utilizados apresentam rendimento medido abaixo do valor informado pelo fabricante.

TABELA X
COMPARAÇÃO GERAL DO RENDIMENTO ENTRE OS VALORES MEDIDOS E VALORES INFORMADOS

	2 Polos	4 Polos	6 Polos	8 Polos	Total
Medições abaixo do nominal	67	147	31	9	58%
Medições iguais ou acima do nominal	62	80	30	9	42%

Diferentemente do que ocorre com o fator de potência, o rendimento tem um valor mínimo determinado em legislação. O informativo técnico do fabricante deve apresentar um valor igual ou superior ao da legislação mínima de desempenho de MITRGE de acordo com a Portaria nº 488 do Inmetro [21], vigente à época dos ensaios.

Para a determinação do rendimento do MITRGE no ensaio de desempenho, é estabelecida uma margem de tolerância para a aprovação ou não do referido motor elétrico sob ensaio. A determinação da tolerância também é estabelecida na Portaria nº 488 do Inmetro [21].

Para o rendimento (η), a tolerância é definida pelo Índice de Afastamento de Resultado (IAR). Este índice é calculado por duas diferentes equações que dependem do rendimento declarado pelo fabricante. O IAR é calculado conforme as Equações (2) e (3), conforme Portaria nº 488 do Inmetro [21]:

Se: $(\eta) \geq 0{,}851$

$$\text{IAR} = \left(\frac{(\text{valor declarado} - \text{valor obtido})}{0{,}20.(1 - \text{valor declarado})}\right).100 \qquad (2)$$

Se: $(\eta) < 0{,}851$

$$\text{IAR} = \left(\frac{(\text{valor declarado} - \text{valor obtido})}{0{,}15.(1 - \text{valor declarado})}\right).100 \qquad (3)$$

O valor obtido (pu) é o encontrado durante a realização do ensaio de rendimento e o valor declarado (pu) é o informado pelo fabricante/importador do motor.

O motor é considerado aprovado no ensaio de desempenho quando o IAR não ultrapassar +100% ou -100% (cem por cento), para cada MITRGE.

IAR é o número percentual (%) que informa o quanto as perdas do motor ensaiado estão divergentes do valor nominal declarado pelos fabricantes relativamente à tolerância padronizada, que segue a seguinte regra:

1) para motores com rendimento até 85,1% admite-se uma tolerância nas perdas de ± 15% do valor nominal declarado;
2) para motores com rendimento igual e acima de 85,1% admite-se uma tolerância nas perdas de ± 20% do valor nominal declarado.

Por exemplo:

i. para um motor que apresenta IAR igual a 25%, entende-se que as perdas do motor apresentam um valor que está 25% acima do valor declarado, dentro da faixa de tolerância;
ii. um motor que apresente IAR de 100% significa que este motor atingiu o limite (máximo) da tolerância das perdas em relação ao valor declarado. Assim como há limite superior para as perdas, também há limite inferior (perdas abaixo do valor declarado), encontrar motores com valores fora da tolerância padronizada pode ser indício de falta de controle da qualidade dos insumos ou do processo produtivo.

Desta forma, do total de 435 motores elétricos analisados, 22 se encontraram fora do espectro de tolerância, sendo 21 com rendimentos abaixo do permitido e 1 com rendimento acima do permitido, portanto, reprovados no quesito rendimento. Os motores com rendimento abaixo do permitido não poderiam ser comercializados. Entretanto, 58% do total de motores analisados, possuíam rendimento abaixo do valor de placa, totalizando 254 motores de 435.

Os baixos valores podem ser causados por uma série de elementos, entretanto, são destacadas as elevadas perdas joules, identificadas no ensaio em carga, sendo causadas principalmente pela economia de cobre na construção dos enrolamentos localizados no estator.

Como a maior parte dos motores apresentou rendimento abaixo do valor informado pelos fabricantes, mas acima do mínimo permitido pela legislação utilizando a tolerância, constata-se que muitos fabricantes trabalham com os projetos dos MITRGE próximo aos limites de tolerância admissíveis. Tal evidência ressalta a importância da legislação de despenho de MITRGE como política pública para promoção de eficiência energética no uso final de energia elétrica.

IV. CONCLUSÃO

Do total de motores ensaiados, 52% são motores de 4 polos, 30% são motores de 2 polos, 14% de 6 polos e 8% de 8 polos, não por acaso refletem a distribuição percentual relativa ao número de polos dos MITRGE em suas aplicações industriais. Os motores ensaiados foram enviados por 38 fabricantes distintos, apresentando assim uma ampla variedade de resultados, permitindo com que os resultados possam ser generalizados.

Verifica-se que após a publicação da Portaria Interministerial nº 553 de 08/12/2005 [22], que estabeleceu os níveis mínimos de rendimento a serem atendidos pelos MITRGE novos, comercializados no país, houve uma melhoria crescente nos índices de rendimento apresentados pelos motores quando confrontados com os resultados apresentados no estudo

"Avaliação histórica do Desempenho do Motores Elétricos de Indução comercializados no Brasil entre 1980 e 2016" [23].

Ainda que 58% dos motores ensaiados apresentam rendimento abaixo do valor mínimo para motores de alto rendimento, publicado na portaria interministerial 553 [22], apenas 5% deles estão efetivamente fora da tolerância e, portanto, em desacordo com a portaria interministerial 553 e portaria INMETRO 488/2010.

Com uma proporção semelhante, 55% dos MITRGE apresentaram fator de potência abaixo do seu valor nominal, sendo que o percentual de motores fora da tolerância foi de 13%. Ficou evidenciado que há um índice elevado de imprecisão na declaração do fator de potência, seja quando se analisa o desvio padrão que para motores de 4 polos foi de 3,9%, seja quando observando o índice de motores que estão fora da tolerância normalizada.

As perdas por atrito e ventilação foram as mais dispersas entre amostras semelhantes, seguida da perda nos enrolamentos do estator. Isso pode nos indicar que os fabricantes não investem em alterações no projeto de forma significativa. O ganho no aumento do rendimento está bastante relacionado com a alteração da qualidade dos insumos, como a qualidade do material empregado na construção dos rolamentos de melhor qualidade, a compactação dos enrolamentos do estator para utilizar fios com seção maior objetivando a redução das perdas joule (I^2R) do estator e o emprego de chapas magnéticas de melhor qualidade.

Conclui-se que o valor do rendimento declarado pelo fabricante na quase totalidade dos motores é igual ao rendimento mínimo indicado na Portaria Interministerial nº 553 [22], e por apresentarem rendimento abaixo do mínimo exigido, mas dentro da tolerância padronizada, são adequações dos projetos para rendimento da linha padrão (com produção proibida desde 2009).

Os resultados apresentados em rendimento e fator de potência reiteram a importância do controle de qualidade dos fabricantes, para garantir que os dados de placa dos equipamentos sejam efetivamente próximos aos valores reais, medidos por quaisquer que sejam as metodologias de ensaios dadas as tolerâncias e margem de erros aceitáveis.

Agradecimentos

Agradecimento ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) pela bolsa de estudos disponibilizada ao primeiro autor.

Agradecemos aos servidores Abraão, Antônio, Sabino, Buda e Fernando Gava da Divisão de Máquinas Elétricas do Instituto de Energia e Ambiente (IEE) da Universidade de São Paulo (USP) pela contribuição na realização dos ensaios padronizados.

Agradecemos aos revisores pelas profundas contribuições realizadas na revisão.

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APPENDIX C

DE SOUZA, Danilo Ferreira; SALOTTI, Francisco Antônio Marino; SAUER, Ildo Luís; TATIZAWA, Hédio; DE ALMEIDA, Aníbal Traça; KANASHIRO, Arnaldo Gakiya. An assessment of the impact of Brazilian energy efficiency policies for electric motors. **Energy Nexus**, v. 5, p. 100033, 2022. (DE SOUZA et al., 2021)

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

An assessment of the impact of Brazilian energy efficiency policies for electric motors

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ARTICLE INFO

Keywords:
Three-phase induction motors
Squirrel-cage rotors
Minimum nominal efficiency
Minimum energy performance standards
Policies for energy efficiency

ABSTRACT

The three-phase induction motor was the fundamental component for productivity and growth in the second industrial revolution in Europe and the United States in the late nineteenth century. Presently, it is the main charge in electrical systems on a global level. In Brazil, it reaches more than 65% of total electricity consumption. Policies were established on the minimum efficiency level of the three-phase induction motor to improve energy efficiency in the Brazilian electrical system. The Brazilian legislation for the performance of electric motors is recent because the first document was issued in 2002. Based on the policies on the performance improvement of motors, what were the changes that occurred in the three-phase induction motors with the squirrel-cage rotors marketed in Brazil? Therefore, this study evaluated the performance of 435 motors tested between 2015 and 2016, with powers between 1 HP and 250 HP for four normalized speeds based on three laws of electric motor performance: Presidential Decree No. 4,508/2002; Interministerial Ordinance No. 553/2005 and Interministerial Ordinance No. 1/2017. All data were collected via standardized laboratory tests accredited by the National Institute of Metrology, Standardization, and Industrial Quality (INMETRO) and the International Laboratory Accreditation Cooperation (ILAC). The results show that 97% of the tested motors have higher performances than Decree No. 4,508/2002. Relatedly. 64% have higher performances compared to what is stipulated by Ordinance 553/2005. Also, only 21% have higher performances compared to what is stipulated by Ordinance 1/2017.

1. Introduction

The industrial sector is responsible for a more significant percentage of electricity consumption in Brazil. About 40% [1] of the total electricity consumed in the country is traceable to this sector. However, electric motors are responsible for approximately 68% of this consumption [2].

Electric motors are responsible for about 70% of the electricity consumed worldwide in industry and 46% of the world's electricity. Pumping systems alone consume almost 22% of all electrical energy consumed in electric motors in the world [3]. The three-phase induction motors with squirrel-cage rotors or Squirrel Cage Induction Motor (SCIM) are responsible for more than 90% of total electricity consumption in electric motors [4].

A lower production cost is possible because of this machine's constructive simplicity compared to other technologies [5,6]. Furthermore, SCIM is also known to require very low maintenance rates and bearing lubrication and cleaning of the ventilation system basically [7].

Water and energy systems are interdependent. There are ways to improve the energy efficiency of water pumping systems powered by SCIM, including traditional optimization techniques [8] and system management or replacing less efficient equipment with more efficient equipment [9].

Almost every conceivable human activity and technology requires water, energy, food, or some combination of the three [10]. Agriculture accounts for 70% of total freshwater withdrawals globally, which makes it one of the sectors with the highest water consumption [11]. Irrigation is one of the sectors of agriculture which is increasing its energy consumption as a consequence of the modernization of water-distribution systems [12], the consumption in electric motors being the great consumer of energy in irrigation [13].

In the energy transition process, the change from internal combustion engine vehicles to those powered by electric motors represents one of the main gains for improving air quality, health, and transport

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https://doi.org/10.1016/j.nexus.2021.100033
Received 24 August 2021; Received in revised form 12 November 2021; Accepted 28 November 2021
Available online 8 December 2021

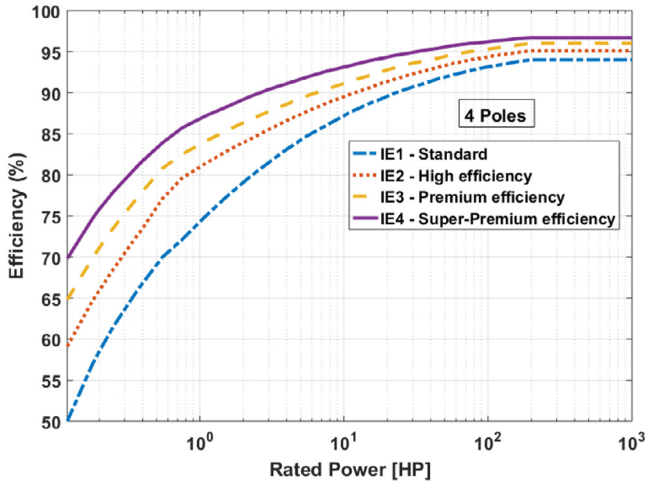

Fig. 1. Minimum efficiency values of 50 Hz defined in IEC 60,034–30–1 [21,22].

[14,15]. For this reason, the energy efficiency of electric motors is important for the overall efficiency of the systems.

Since the 1990s, some countries have initiated labelling programs to determine the minimum allowable efficiency for SCIM [16], Seeking to reduce the emission of effect gases, study in motor systems [17]. The visual identification involves putting efficiency labels on the electric motors to help customers choose high-performance motors. Labels must provide necessary information to enable users to decipher SCIM efficiencies and stimulate manufacturers to improve the energy efficiency performance of their products. In this way, the labels contribute to developing the market for high-performance engines and the conservation of electrical energy [18].

Before labelling, the motors are separated into classes according to their efficiency. This process has been adopted in different ways and various countries, resulting in different national standards. Meanwhile, the need for international efficiency equivalence emerged based on trade barriers resulting from the other efficiency classes. The International Electrotechnical Commission (IEC) proposal on developing a global efficiency rating, test standards, and labels for electric motors [19] becomes very significant in this context. The IEC rating distinguishes four efficiency levels – from Indice Efficiency – 1 “IE1" ″ nomenclature for standard efficiency motors to “IE4” for super-premium efficiency motors [20]. These classes are increasingly used in various countries that are concerned about the performance of energy-efficient end-use equipment.

The IEC regulation covers three-phase induction motors between 120 W and 375 kW. The efficiency classes are presented in Fig. 1 for motors built for 50 Hz operation with 4 poles. The IE4 class was introduced in that standard in 2014, and currently, few motors have this efficiency rating.

Many countries have existing regulations on the efficiency of electric motors or effective dates to implement them. The United States was the first country to regulate the use of electric motors. It was initially approved in 1992 as a voluntary regulation. After that, the legislation became mandatory in 1997, such that SCIM was commercialized. In this sense, motor manufacturers had five years to adapt themselves to new standards, optimize designs, and use better quality materials [23,24].

1.1. International standards for the SCIM efficiency

Aiming to advance the efficiency of electrical equipment, the minimum standard entitled the Minimum Energy Performance Standard (MEPS) and energy labels were defined, which is seen as one of the main ways to support energy efficiency directly at the product level. Using MEPS and energy product labels is a way to support rational consumer choice and overcome information barriers. These efforts are often mandatory, but they can also be voluntary [25], being updated over the years, according to improvements in construction materials and equipment designs, thus aiming to manufacture increasingly efficient equipment commercially.

The first legislation for SCIM efficiency became known as EPAct-92. It was an initiative of the United States government and approved by its Congress, which set the goals, creating mandates, and changing public service laws to increase clean energy use and improve global energy efficiency in the United States. The values of EPAct-92 to SCIM are equivalent to the IE2 definition of IEC [26,27]. In 2007 the IE3 equivalent legislation for the US and Canada was published. It became effective in 2010. Fig. 2 presents the general overview of the application dates of the SCIM minimum efficiency to some countries [28–31].

1.2. Minimum efficiency performance standards (MEPS) for SCIM efficiency

At the beginning of the 1980s, under the consequences of the world oil crisis, the Brazilian government was increasingly concerned about the end-use of electricity. In 1985 the National Electricity Conservation Program (PROCEL) was established. The first version of this program focused on a guide for domestic customers for rational use of electric energy to reduce energy waste [35].

In 1992, discussions about the labelling of electrical equipment were initiated. It was followed by the creation of the PROCEL seal a year after. The electric motor manufacturers could voluntarily be registered in the secretariat program directly linked to Centrais Elétricas Brasileiras S.A. (ELETROBRÁS) [36], which generates, transmits, and distributes electricity in Brazil. Moreover, the application of the stamps in SCIM was initiated in 1997 [37].

Brazil suffered an electricity supply crisis in 2001, obliging the government to adopt rationing measures for electric energy. Meanwhile, the discussions about the importance of the energy sector to reduce greenhouse gases advanced worldwide [38]. In this scenario, Law No. 10.295 – 17 October 2001 – was created and was called Energy Efficiency Law. The law establishes that specific minimum efficiency regulations should be created for end-use electric energy equipment to reduce energy consumption and preserve the environment [39,4].

Decree No. 4508 was published on 11 December 2002. It establishes the minimum levels of efficiency for SCIM that can be marketed in Brazil [40]. The decree was elaborated with more attention on the most commercialized electric motors in the Brazilian market, namely;

(a) three-phase induction motors;
(b) industrial frequency of 60 Hz or 50 Hz for 60 Hz operation;
(c) squirrel-cage rotors;
(d) power supply voltage up to 600 Vs;
(e) speeds corresponding to 2, 4, 6, or 8 poles;
(f) shaft power between 1 and 250 HP;
(g) motors produced for continuous operation.

Separated by efficiency level, two categories of motors were created by Decree No. 4508/2002: standard motors and high-performance motors. Standard motors are equivalent to category IE1, whereas high-performance motors are internationally equivalent to category IE2. Decree No. 4508/2002 covered more than 80% of the Brazilian market for electric motors [41]. It established a date – 30 December 2003 – as a limit for the commercialization of electric motors outside the minimum levels of efficiency.

On the 8th of December 2005, the Federal Government of Brazil published Ordinance No. 553, establishing a higher value as a minimum efficiency level (equivalent to IE2 classification of the IEC standard). Electric motors that did not comply with the high-performance level of Decree No. 4508/2002 could not be commercialized in Brazil from 2009 [42].

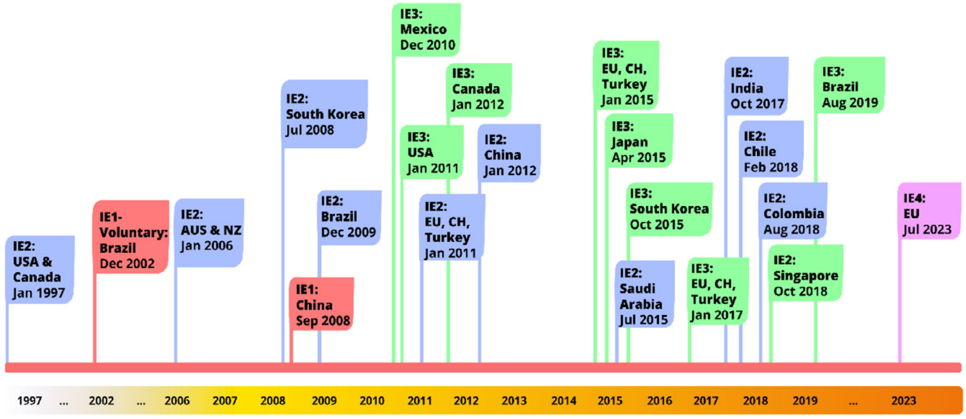

Fig. 2. Implementation of minimum efficiency legislation for electric motors [32,3,33,19,34].

In Brazil, the Federal Executive Power (Ministry of Mines and Energy; Science, Technology, Innovation and Communications; and Industry, Foreign Trade, and Services) establishes the MEPS for SCIM. The National Institute of Metrology, Quality, and Technology - INMETRO is responsible for publishing the regulatory measure for inspection, monitoring, and evaluation of compliance with the federal resolution, through inspection offices installed in all federative units in the country.

Published on the 4th of September 2009 by the National Institute of Metrology, Quality and Technology (INMETRO), Ordinance No. 243/2009 presented the mandatory requirements for the three-phase induction electric motors' conformity assessment standardizing the national assessment methodology of efficiency [43]. On the 8th of December 2010, INMETRO published Ordinance No. 488/2010, replacing Ordinance No. 243. From Ordinance No. 488/2010, the labelling of this sort of motor becomes mandatory [44].

From previous research, the last document that was published to establish new indexes of minimum nominal efficiency for SCIM was the Interministerial Ordinance No. 1/2017, published on the 8th of August 2017 [45]. In summary, the dates that the importation and commercialization of SCIM with lower efficiency (IE3) shall be prohibited as stated in this ordinance include:

(a) 30th of August 2019 (Manufacturing or Individual Importation),
(b) 2nd of March 2020 (Individual Marketing),
(c) 30th of August 2020 (Manufacturing or Importation of Equipment containing SCIM) and
(d) 1st of March 2021(Commercialization of Equipment containing SCIM).

Therefore, Interministerial Ordinance No. 1 establishes the minimum efficiency level for SCIM marketed for IE3, as presented in Table 1.

Ordinance No. 1/2017 expanded the power range of regulated motors, expanding to fractional motors from 0.16 HP up to 500 HP. The ordinance regulated only three-phase motors with a squirrel-cage rotor powered at low voltage for 60 Hz operation.

Thus, after publishing Interministerial Ordinance No. 1 of 2017, INMETRO issued Ordinance No. 200 [46], of June 3, 2020, with partial improvement of INMETRO Ordinance 488/2010, updating only the SCIM minimum income index table. In June 2021, a new INMETRO Ordinance No. 290/2021 [47] was published, unifying the provisions and requirements of Ordinances 488/2010 and 200/2020.

In the sequence, Fig. 3 organizes the Brazilian documents that contributed to the efficiency gains of the electric motors from 1985 to 2021.

Fig. 4 illustrates the evolution of the efficiency values between Decree No. 4508/2002, Ordinance No. 553/2005, and Ordinance No. 1/2017 for motors with a speed of 4 poles.

From Fig. 4, it is possible to observe the increasing values of the efficiency levels between the applied legislation. It also shows that a wide range of axis power is covered by Ordinance No. 1/2017. This Ordinance regulates motors with fractional powers (less than 1 HP) to large motors with powers of 500 HP that are not common in industrial plants. Therefore, at the moment, it is the most comprehensive legislation implemented in Brazil.

Table 1
Ordinance No. 1/2017 and the minimum percentage ffficiency for the SCIM IE3 category [45].

	2 Poles	4 Poles	6 Poles	8 Poles
HP	Nominal efficiency			
0,16	62	66	64	59,5
0,25	65,6	69,5	67,5	64
0,33	69,5	73,4	69	68
0,5	73,4	78,2	75,3	72
0,75	76,8	79	79,5	74
1	80,5	83,5	82,5	75,5
1,5	84	86,5	87,5	78,5
2	85,5	86,5	88,5	84
3	86,5	89,5	89,5	85,5
4	88,5	89,5	89,5	86,5
15	91	92,4	91,7	89,5
20	91	93	91,7	90,2
25	91,7	93,6	93	90,2
30	91,7	93,6	93	91,7
40	92,4	94,1	94,1	91,7
50	93	94,5	94,1	92,4
60	93,6	95	94,5	92,4
75	93,6	95,4	94,5	93,6
100	94,1	95,4	95	93,6
125	95	95,4	95	94,1
150	95	95,8	95,8	94,1
175	95,4	96,2	95,8	94,5
200	95,4	96,2	95,8	94,5
250	95,8	96,2	95,8	95
300	95,8	96,2	95,8	95
350	95,8	96,2	95,8	95
400	95,8	96,2	95,8	95
450	95,8	96,2	95,8	95
500	95,8	96,2	95,8	95

The migration of the industrial park to the SCIM with efficiencies compatible with IE3 is essential for saving electric energy and reducing the demand for new enterprises of generation and reinforcement in distribution networks [48].

Andrade and Thé Pontes (2017) simulated the replacement of IE2 motors for IE3 in the Brazilian case. They concluded that the energy efficiency measure could generate approximately 164 GWh/year savings if fully adopted from 2020. About 2600 GWh accumulated until 2030, reducing 0.64% of the total electricity consumption of the Brazilian industry until 2030, which represents 5.3% of the total electricity savings expected by the Brazilian government [49].

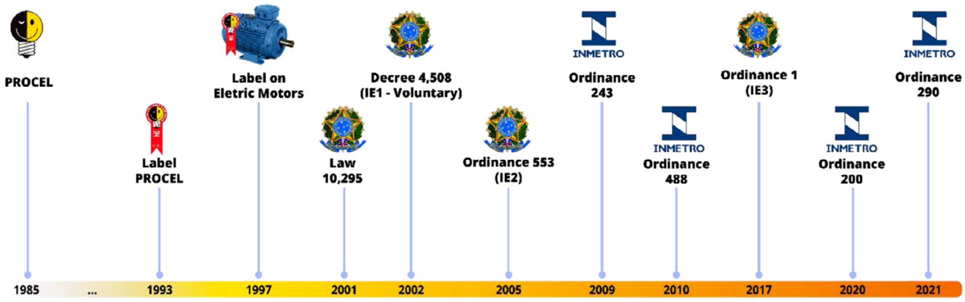

Fig. 3. Efficiency legislation of SCIM in Brazil [35,39,4,44,45,48].

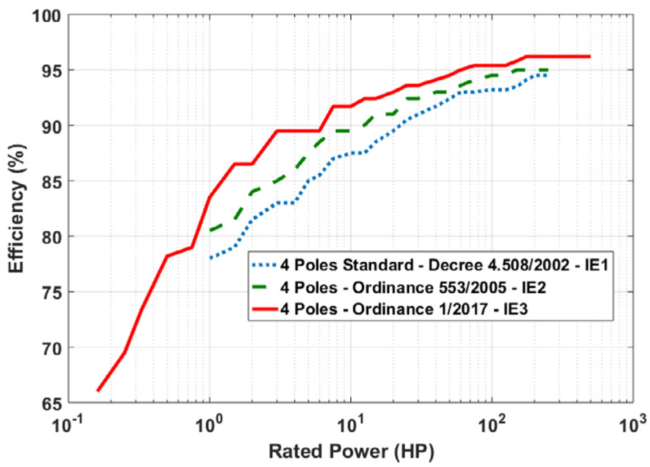

Fig. 4. The Evolution of national standard for SCIM of 4 poles [40,42,45].

Table 2
Comparison of efficiency levels of SCIM (2000–2012) with Decree No. 4508/2002 [41].

Decree No. 4508/2002	2 Poles	4 Poles	6 Poles	8 Poles	Total
Efficiency below nominal	98%	84%	94%	80%	89%
Efficiency abovnominal	2%	16%	6%	20%	11%

Bortoni et al. [18] estimated the amount of energy saved in SCIM due to Brazil's energy efficiency labelling program and its contribution to reducing peak demand, analysing the replacement of IE1 class motors by IE2 class motors. Bortoni et al. observed that efficiency increases in motors in the range of 1–10 HP are significant for the labelling program because, in absolute numbers, they represent 76% of induction motors installed in Brazil.

Improvements between IE1 and IE4 classes using SCIMs technology were promoted by using more copper in the stator windings, improvement in the quality of ferromagnetic materials, optimization of electrical designs, and the aerodynamics of the ventilation system [16,50–52].

1.3. The impact of legislation on SCIM marketed in Brazil

Sauer et al. (2015) analysed the efficiency of 276 SCIM tested at the Institute of Energy and Environment of the University of São Paulo (IEE/USP) between 2000 and 2012, with shaft powers between 1 HP and 350 HP, belonging to 29 manufacturers. Consequently, the efficiency tests for SCIM of 2, 4, 6, and 8 poles [41] were presented. From Table 2, it is possible to compare efficiency levels (2000–2012) concerning the standard level of Decree No. 4508/2002.

From Table 2, the 276 SCIM sent for testing by the manufacturers or buyers, 89% of the cases present efficiency levels below the minimum standard based on national marketing. However, according to the authors, most of them could still be marketed because they were within the accepted tolerance.

Therefore, Sauer et al. (2015) concluded that even many years after implementing Decree No. 4508/2002 and Ordinance No. 553/2005, SCIM marketed in Brazil were still with an efficiency significantly below the minimum allowed. Thus, one of is work's contributions is the evaluation of the motors tested in recent years, based on the current legislation, analysing the changes in efficiency and the impact of legislation [41].

2. Methodology

The data used in this work were collected at the Laboratory of Electrical Machines of the Institute of Energy and Environment of the University of São Paulo (IEE/USP). The Laboratory of Electrical Machines is accredited by the National Institute of Metrology, Standardization and Industrial Quality (INMETRO) according to the standard ABNT NBR ISO/IEC 17,025:2017 under number CRL-0011 [53]. INMETRO periodically carries out audits in the accredited laboratories, aiming to guarantee the quality resulting from the measurements. INMETRO is a signatory of the mutual recognition agreements of the International Laboratory Accreditation Cooperation (ILAC) and also signatory of the Interamerican Accreditation Cooperation (IAAC), following, in this sense, a worldwide standard of quality and reliability. Therefore, the Laboratory of Electrical Machines of IEE/USP has the Accreditation Certificate in the Brazilian Network of Test Laboratories (RBLE).

Test procedures obtained the results of efficiency tests based on the Brazilian standard ABNT NBR 17,094–3: 2018, method 2 [54], which is similar to the standard IEC/EN 60,034–2–1 [55]. Thus, 435 SCIM were analysed, and the results were compared with the Brazilian minimum efficiency legislation:

(1) Decree No. 4508/2002 – IE1.
(2) Ordinance No. 553/2005 – IE2.
(3) Ordinance No. 1/2017 – IE3.

The analysis was performed only for motors that are fed with low voltage at 60 Hz industrial frequency and 100% load on the shaft according to the electric induction motor test standards [21,56,57]. Concerning efficiency legislation, the evaluated motors were divided into four blocks according to their speeds as determined by the number of poles as follows;

(a) 129 of 2 poles,
(b) 227 of 4 poles,
(c) 61 of 6 poles and
(d) 18 of 8 poles.

Manufacturers or buyers shipped the tested motors after they were manufactured, and the tests were carried out in 2015 and 2016. Therefore, this evaluation was carried out using only new motors.

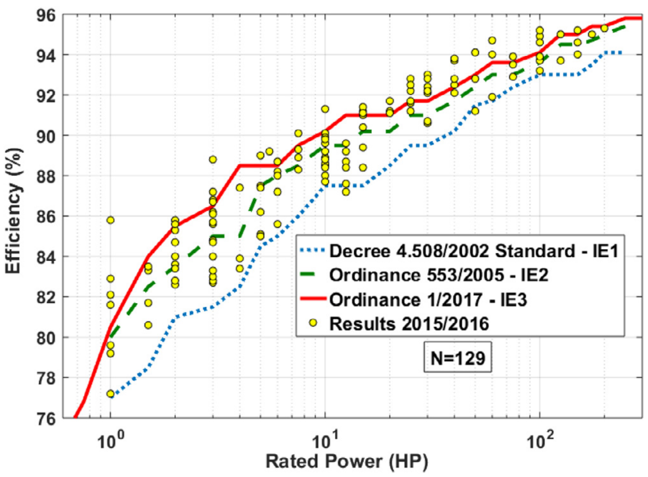

Fig. 5. Comparison of the MEPS with test results – 2 poles.

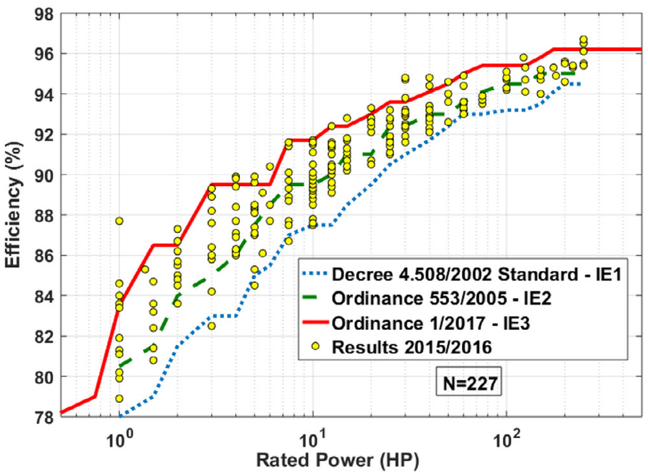

Fig. 6. Comparison of the MEPS with test results – 4 poles.

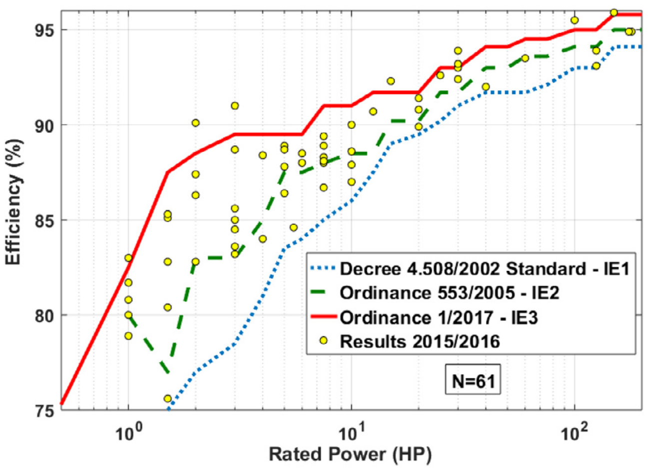

Fig. 7. Comparison of the MEPS with test results – 6 poles.

3. Results and discussions

Figs. 5–8 show the efficiency of the tested motors based on the three efficiency legislations and the four different regulated speeds. The red curve marks the highest efficiency quota and refers to Ordinance No.

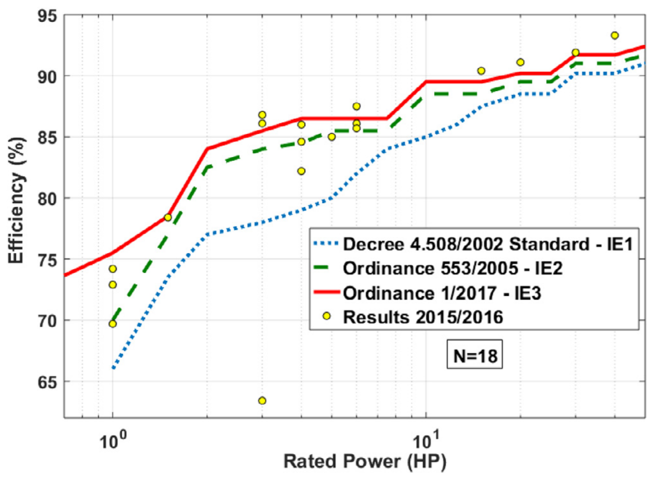

Fig. 8. Comparison of the MEPS with test results – 8 poles.

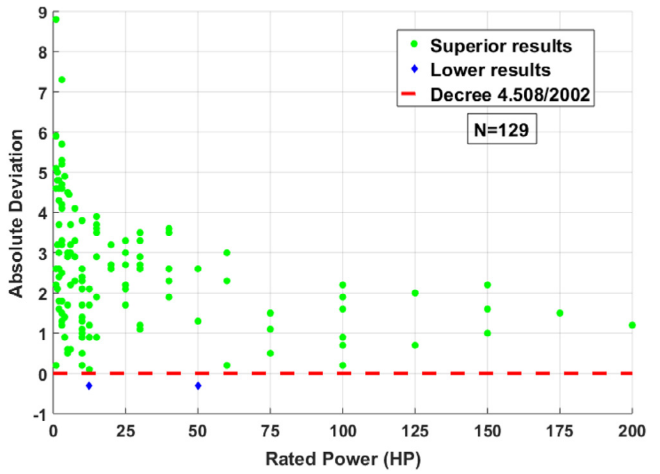

Fig. 9. Absolute deviation of the SCIM efficiency of 2 Poles with Decree No. 4508/2002.

1/2017 (equivalent to premium-efficiency). The intermediate line in green refers to Ordinance No. 553/2005 and the high-efficiency values of Decree No. 4508/2002, which are the same. The blue curve refers to the standard line of Decree No. 4508/2002.

Fig. 5 presents 129 test results for SCIM between 1 and 200 HP of 2 poles. Yellow circles represent test results for electric motors.

The results of the test on 227 4-pole motors positioned with the MEPS are presented in Fig. 6. This analysis shows a significant quantity of electric motors with powers up to 250 HP.

Fig. 7 shows the test result on 61 6-pole motors. The analysis presents an axis power scale with powers up to 180 HP.

Fig. 8 shows the result of the test on 18 8-pole motors. This analysis presents a shaft power scale with powers up to 40 HP.

From Figs. 9 to 20, the improved analyses of the results of the SCIM tested in the period are presented with the three legislations introduced previously.

3.1. Impact assessment

This aspect presents the assessment of the impact of the three selected legislation (Decree No. 4508/2002, Ordinance No. 553/2005, and Ordinance No. 1/2017).

Table 3
SCIM efficiency of 2 Poles with Decree No. 4508/2002.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
98,45%	1,55%	8,8%	−0,3%	2,53%	2,3%	1,55%

Table 4
SCIM efficiency of 4 Poles with Decree No. 4508/2002.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
96,48%	1,32%	9,7%	−0,5%	2,49%	2,2%	1,69%

3.1.1. Decree no. 4508/2002

The test results of 435 motors in their 4 different speeds are discussed concerning the first Brazilian efficiency legislation (Decree No. 4508/2002).

Fig. 9 shows the results of 2 pole SCIM tests with shaft power between 1 and 200 HP. The electric motors, whose results are represented by the green circles, present an efficiency equal to or higher than the value stipulated in Decree No. 4508/2002. The dashed line in red represents the minimum efficiency according to Decree No. 4508/2002 for the speed referring to 2 poles. The blue diamond's represent results of measurements lower than the value determined in the Decree. The axis (y) of the ordinates shows the magnitude of the absolute deviation between the measured values and the Decree. The axis (x) shows the nominal shaft power of the SCIM. It follows that a motor that has obtained a final clearance of + 2% means that its performance determined in the test was 2 percentage points higher than the normalized value.

Table 3 presents the result of the efficiency measurements of 129 test results concerning Decree No. 4508/2002. The percentage of results equal to or above the decree was 98.45%. In this sense, examining the findings, the great majority of motors had higher efficiency in the years following the document's publication.

The maximum positive and negative deviations, shown in Table 3, indicate punctual diversions considering the result of the tests and most of the manufacturer's nominal value. Relatedly, the maximum positive deviation of 8.8% and the maximum negative deviation of −0.3% show that almost all results are above what is established in Decree No. 4508/2002. As illustrated in Fig. 9, the results showing more significant absolute deviation have the lowest axis power. Such results are expected because the production processes of lower-power electric motors are cheap. Considering the total of the tested motors, as observed numerically in the industrial plants, it is evident from the data that the electric motors of lower power of power have a more significant percentage representation.

The mean deviation represented in Table 3 deals with the mean distance between the results of the tests and the arithmetic mean of the data. As more significant the dispersion of data, the more prominent will be the mean deviation. The observed mean deviation value (2.53%) is relatively low, indicating a sparse distribution.

In table 3, the median is the central value that separates the samples equally into two parts. One-half of the results presented in the test have efficiency values higher than that reported, and the other half of the samples present efficiency more minor than the reference value of the decree. In this case, the positive median value (2.3%) shows that the distribution of the electric motors is significantly above the values established in Decree No. 4508/2002.

The standard deviation illustrated in Table 3 is the magnitude of the dispersion of the efficiency values measured around the reference values of the legislation. As lower the standard deviation, the closer the measured values are to the values of the legislation. As higher the standard deviation, the opposite occurs.

Fig. 10 shows the absolute efficiency deviation for 227 4-pole motors. This analysis presents a more significant number of electric motors and a larger scale of shaft power with motors up to 225 HP.

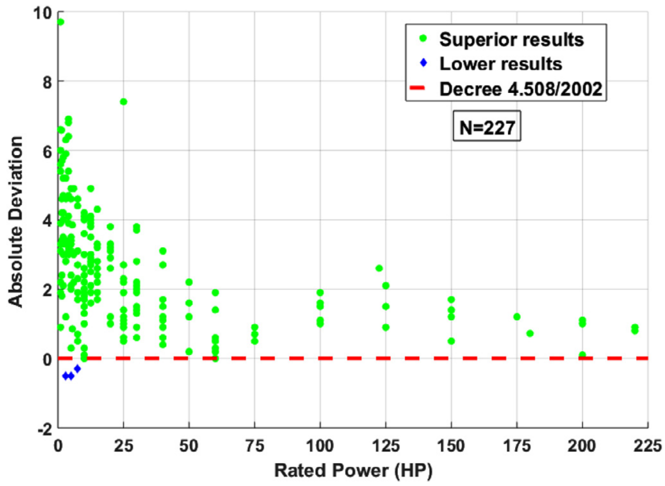

Fig. 10. Absolute deviation of the 4 poles SCIM efficiency with Decree No. 4508/2002.

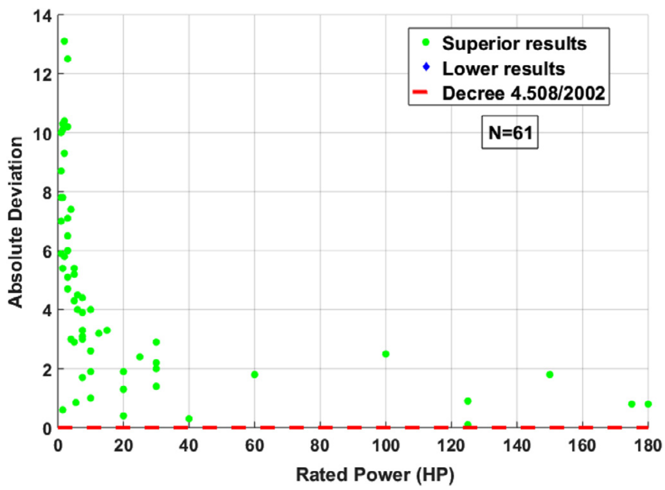

Fig. 11. Absolute deviation of the SCIM efficiency of 6 Poles with Decree No. 4508/2002.

The 2-pole and 4-pole motors presented similar results. Table 4 shows the comparison of 227 electric motors concerning Decree n° 4508/2002. The percentage of SCIM with measured efficiency above the minimum established in the decree was 96.48%, evidencing the electric motor market advances after the document's publication.

Figs. 11 and 12 and Tables 5 and 6, show the same results as before. It has been suggested that Decree No. 4508/2002 fully complies with national and international manufacturers of electric motors.

In the analysis of the efficiency test of 276 SCIM between 2000 and 2012, compared to the standard level of efficiency of Decree No.

Table 5
SCIM efficiency of 6 poles with Decree No. 4508/2002.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
100%	0,0%	13,1%	0,0%	4,5%	3,3%	3,36%

Table 6
SCIM efficiency of 8 poles with Decree No. 4508/2002.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
94,5%	5,6%	8,8%	−14,6%	3,9%	4,5%	5,1%

Table 7
SCIM percentage (2015–2016) with Decree No. 4508/2002.

	2 Poles	4 Poles	6 Poles	8 Poles	Total
Measurements below nominal	2	8	0	1	3%
Measurements equal to or above nominal	127	219	61	17	97%

Table 8
SCIM efficiency of 2 poles with Ordinance No. 553/2005.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
62,8%	37,2%	5,8%	−2,8%	−0,31%	0,4%	1,38%

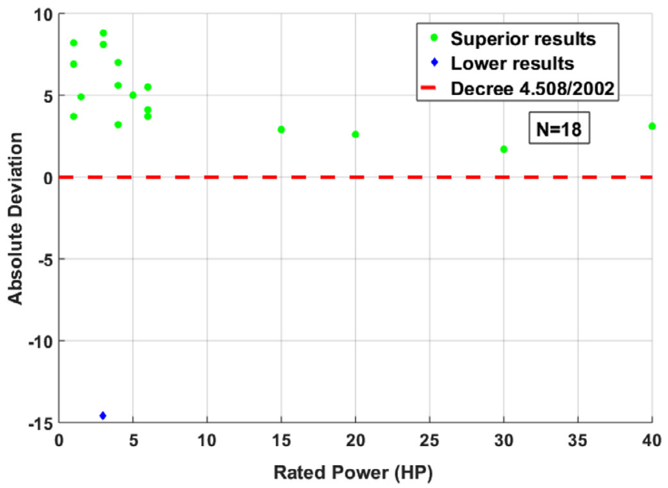

Fig. 12. Absolute deviation of the SCIM efficiency of 8 Poles with Decree No. 4508/2002.

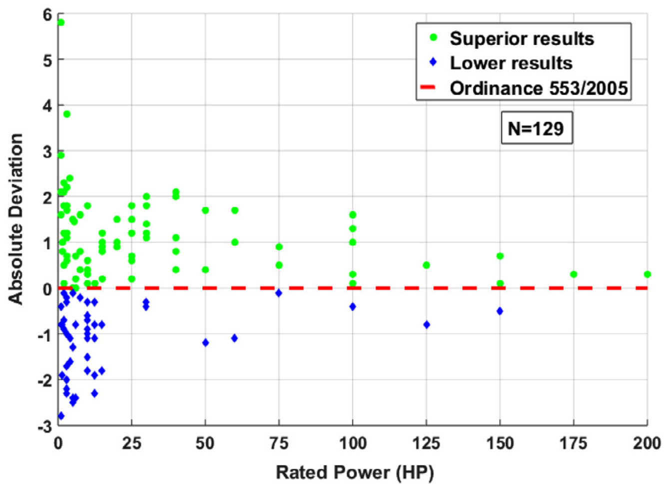

Fig. 13. Absolute deviation of SCIM efficiency of 2 Poles with Ordinance No. 553/2005.

4508/2002 as presented by Sauer et al. (2015) in Table 2, it is observable that 89% of the motors evaluated present efficiency values that are lower than the standard level. This article presents 435 motors tested between 2015 and 2016 (Table 7). The results are quite the opposite, as up to 97% of the tested motors present higher efficiency than the standard level of Decree No. 4508/2002.

It is evident from the analysis that SCIM marketed in Brazil in recent years has suffered a significant evolution of efficiency and the importance of Brazilian electric motors efficiency legislation Brazilian.

3.1.2. Ordinance no. 553/2005

The impact analysis of the MEPS is presented in Figs. 13–16. The same tests used in the previous study are now compared to the second MEPS (Ordinance No. 553/2005), which is currently in force. Tables 8–11 present the results of the tests following Ordinance No. 553/2005.

A general analysis of the results of the comparison between the measured efficiency values and the values related to Ordinance No. 553/2005 is presented in Table 12. It is observable that 64% of the motors used present measured efficiency values above the level allowed by the legislation.

Ordinance No. 553/2005 is the current legislation in Brazil. According to the information shown in Table 12, 36% of the tested motors do not comply with the legislation. The fact that the document was published in 2005 and the evaluations of the SCIM were carried out between 2015 and 2016 (about 10 years later), the value (36%) recorded for non-compliance is considerably high.

It is essential to determine the tolerance of the measured values considering Ordinance No. 553/2005. Therefore, the possibility (or otherwise) of the commercialization of SCIM was verified using the Result Clearance Index (RCI). RCI is the percentage number that shows the rate at which the tested motor differs from the nominal value declared by the manufacturers concerning the standard tolerance, which follows Ordinance No. 488 of INMETRO [44]:

(a) Loss tolerance of ± 15% of the declared nominal value is allowed for motors with performance up to 85.1%.

Table 9
SCIM efficiency of 4 poles with Ordinance No. 553/2005.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
61,7%	36,1%	7,2%	−3%	0,55%	0,3%	1,44%

Table 10
SCIM efficiency of 6 poles with Ordinance No. 553/2005.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
73,8%	26,2%	8,3%	−2,9%	1,44%	0,9%	2,41%

Table 11
SCIM efficiency of 8 poles with Ordinance No. 553/2005.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
77,8%	22,2%	4,2%	−20,6%	0,04%	1,45%	5,36%

Table 12
SCIM percentage (2015–2016) with Ordinance No. 553/2005.

	2 Poles	4 Poles	6 Poles	8 Poles	Total
Measurements below nominal	48	87	16	4	36%
Measurements equal or above nominal	81	140	45	14	64%

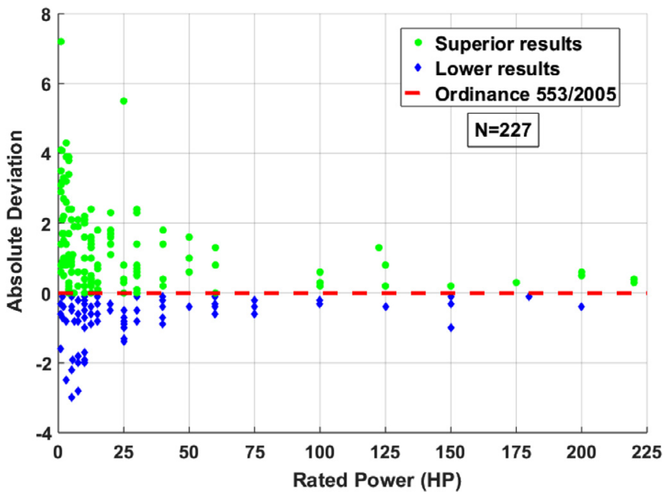

Fig. 14. Absolute deviation of SCIM efficiency of 4 Poles with Ordinance No. 553/2005.

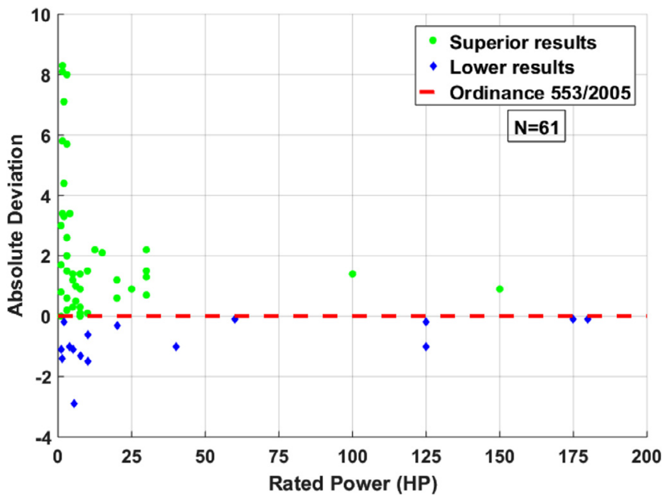

Fig. 15. Absolute deviation of SCIM efficiency of 6 Poles with Ordinance No. 553/2005.

(b) Loss tolerance of ± 20% of the declared nominal value is allowed for motors with displayed output above 85,1%.

Consequently, amongst the 435 SCIM analysed, twenty-two were outside the tolerance spectrum, twenty-one were with efficiencies below the permitted value, and one had efficiency above the allowed value. Considering this information, the efficiencies of these items may not be approved.

Analysing the exact data for IEC 60,034–2–1 [22], where the tolerance is 20% of losses, 19 SCIM are disapproved. In the same vein, using ANSI/NEMA MG 1–2016 [58] with 15% loss tolerance, 24 SCIM are disapproved.

In light of the evidence, 58% (254) of the total (435) motors analysed had efficiency values that are considerably below the plate value. A series of elements may cause these low values. However, the high joule losses identified in the test results are caused mainly by copper's economy in constructing the stator windings.

Most motors have efficiency values below the manufacturer's reported values but above the minimum values allowed by the law. This indicates that many manufacturers work with SCIM projects that are close to allowable tolerances. Such evidence underscores the importance of SCIM performance legislation as a public policy for promoting energy efficiency in the end-use of electricity.

3.1.3. Ordinance no. 1/2017

The results of the impact analysis of MEPS are presented in Figs. 17–20 and Tables 13–17. The same test results used in the two previous evaluations are now applied to Ordinance No. 1/2017.

A general analysis of the comparison results between the measured efficiency values and the values related to Ordinance No. 1/2017 is presented in Table 17. It shows that 79% of the motors used present measured efficiency values below the minimum level allowed by the legislation.

The results presented in Table 17 indicate that the electric motors that comply with Ordinance No. 1/2017 are already available in the Brazilian market. However, most results are below the value stipulated in Ordinance No. 1/2017.

Table 13
SCIM efficiency of 2 poles with Ordinance No. 1/2017.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
37,2%	62,8%	5,3%	−5,1%	−0,69%	−0,4%	1,57%

Table 14
SCIM efficiency of 4 poles with Ordinance No. 1/2017.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
11,0%	89,0%	4,3%	−7%	−1,48%	−1,4%	1,43%

Table 15
SCIM efficiency of 6 poles with Ordinance No. 1/2017.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
16,4%	83,6%	1,6%	−11,9%	−2,11%	−1,6%	2,35%

Table 16
SCIM efficiency of 8 poles with Ordinance No. 1/2017.

Percentage above nominal	Percentage below nominal	Maximum positive deviation	Maximum negative deviation	Mean deviation	Median	Standard deviation
38, 9%	61,1%	1,6%	−22,1%	−1,93%	−0,45%	5,4%

Table 17
SCIM percentage (2015–2016) with Ordinance No. 1/2017.

	2 Poles	4 Poles	6 Poles	8 Poles	Total
Measurements below nominal	81	202	51	11	79%
Measurements equal or above nominal	48	25	10	7	21%

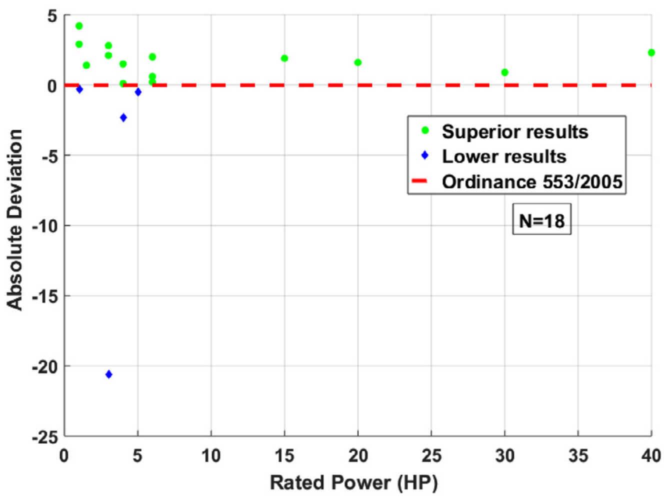

Fig. 16. Absolute deviation of SCIM efficiency of 8 Poles with Ordinance No. 553/2005.

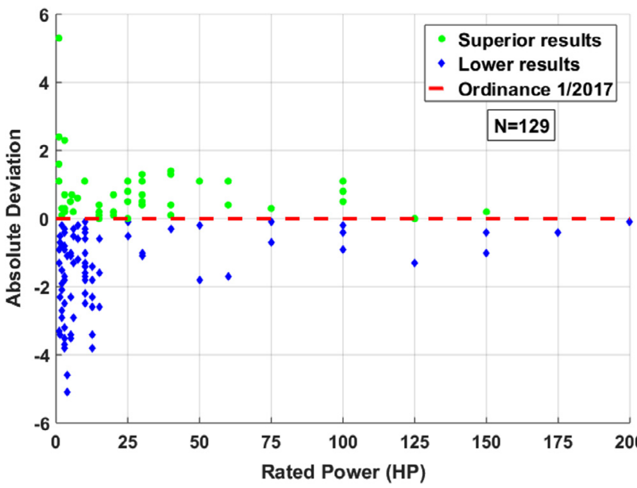

Fig. 17. Absolute deviation of SCIM efficiency of 2 Poles with Ordinance No. 1/2017.

The improvement in the energy efficiency of electric motors will cause significant gains in the entire food industry, which uses this equipment for movement and refrigeration throughout its entire chain. In water pumping systems, the efficiency gains of electric motors are essential to reduce service costs. In agriculture, irrigation of the plantation corresponds to significant expenses in production processes and with the improvement in energy efficiency, they can generate accumulated gains throughout the food chain.

In this way, the advance in MEPS and the inspection of the energy efficiency of electric motors will generate accumulated gains for producers, traders, and consumers of products.

4. Conclusions

From previous research, it has been suggested that the standardisation which establishes the minimum performance level for three-phase induction electric motors is relatively recent in Brazil. Considering the analysis based on the performance of electric motors before and after the proclaimed Decree No. 4508/2002 and Ordinance No. 553/2005, it is observable that, in general, the electric motor industry has adapted to the new requirements in a sense to dialogue in concordance with the MEPS even belatedly. However, the MEPS is still not comprehensive because it does not establish the minimum efficiency for single-phase motors. Besides, it is only in the last version of the decree that the three-phase fractional motors were included, which are very present in the

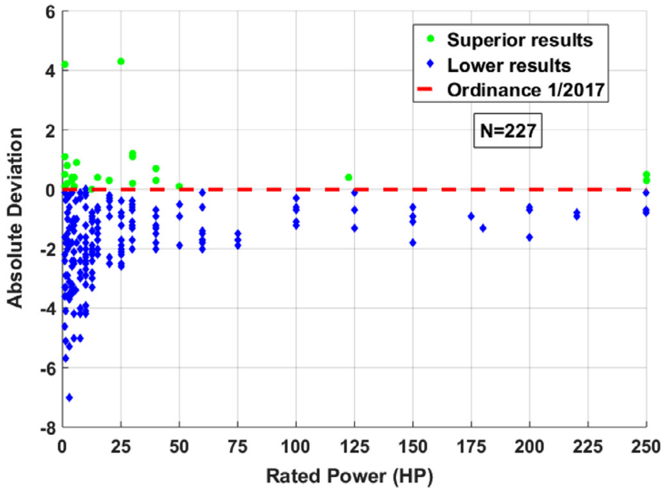

Fig. 18. Absolute deviation of SCIM efficiency of 4 Poles with Ordinance No. 1/2017.

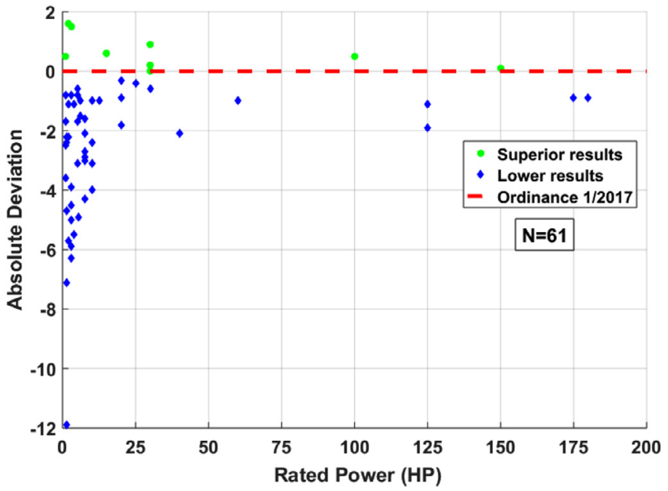

Fig. 19. Absolute deviation of SCIM efficiency of 6 Poles with Ordinance No. 1/2017.

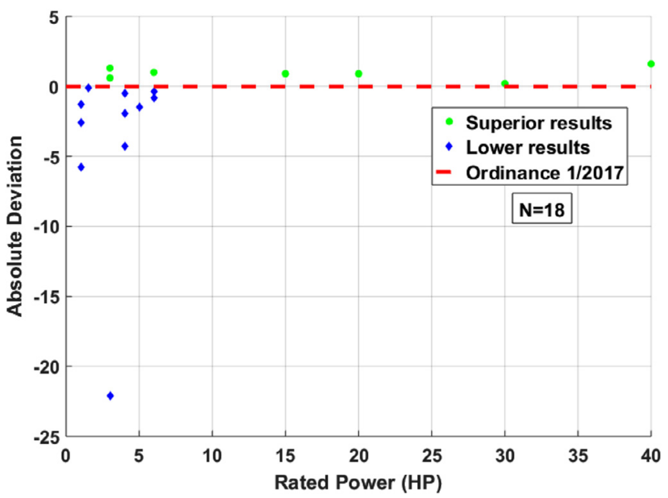

Fig. 20. Absolute deviation of SCIM efficiency of 8 Poles with Ordinance No. 1/2017.

end-use of electricity in the residential, commercial, and public sectors. Nowadays, these three sectors represent 50.8% of the total electricity consumption in Brazil.

Results analysed in 2015 and 2016 concerning Decree No. 4508/2002 indicate that almost all SCIM responded to the requirements, as shown in Table 7. These results are widely accepted because the standard level (level IE1) of Decree No. 4508/2002 is no longer in force. It is being replaced by Ordinance No. 553/2005 (IE2 level), where only the high-performance motors can be marketed. It is observable, based on Ordinance No. 553/2005, that a considerable quantity (36%) of SCIM is still outside the minimum allowed levels for importation and commercialisation, as shown in Table 12. The most recent publication by Ordinance No. 1/2017 raised the minimum required levels for the IE3 level. The minimum levels determined by Ordinance No. 1/2017 compared to the test results show that 21% answer to the new minimum performance standards. However, most (79%) of the tested motors are below the new minimum level.

The data presented in this work refer to the tested motors operating under nominal conditions, which is better in most cases. Generally, within industrial environments, motors operate below their nominal mechanical load. In this situation, the efficiency levels are lower than those obtained during laboratory tests.

Consequently, it is essential to emphasise that advances in MEPS within international standards are possible. Today, the current regulation is internationally equivalent to the IE3 level of the IEC standard (Ordinance No. 1/2017). However, like most electric motors, they have life cycles longer than 20 years. There is a significant part of IE1 electric motors in the Brazilian industrial park and even those manufactured before MEPS, known as IE0. Thus, there is an excellent possibility of achieving energy efficiency in power systems currently in Brazil.

It is also observed that it is possible to apply energy efficiency policies for single-phase motors and other equipment where motors are the predominant load (fractional motors).

INMETRO played an essential role in issuing an ordinance for standardising analysing the energy efficiency of electric motors. In the accreditation of laboratories to carry out standardised tests, INMETRO's role was essential for the levels of energy efficiency. It is now necessary to intensify inspection (Fig. 14,15,18,19, Tables 9, 10, 14–16).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

CRediT authorship contribution statement

Danilo Ferreira de Souza: Conceptualization, Formal analysis, Methodology, Writing – review & editing, Investigation. **Francisco Antônio Marino Salotti:** Methodology, Writing – original draft. **Hédio Tatizawa:** Visualization, Writing – review & editing. **Aníbal Traça de Almeida:** Visualization, Validation. **Arnaldo Gakiya Kanashiro:** Writing – original draft.

Acknowledgments

The authors thank the National Council for Scientific and Technological Development (CNPq) for the scholarship made available to the first author, through the project 870814/1999–0, process 142323/2020–9, so that he could dedicate himself to his Ph.D. research of and related fields. The authors are also grateful for the constructive criticism of the researchers: Rodolfo Quadros, Jakson Bonaldo, João Fong, Carlos Beuter, Luiz Fontenele and Richardson M Abraham-A. We also thank the reviewers of the journal for the crucial observations that helped to improve the work.

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APPENDIX D

DE SOUZA, Danilo Ferreira; DA GUARDA, Emeli Lalesca Aparecida; SAUER, Ildo Luis; TATIZAWA, Hédio. Energy Efficiency Indicators for Water Pumping Systems in Multifamily Buildings. **Energies**, v. 14, p. 7152, 2021. (SOUZA et al., 2021)

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Energy Efficiency Indicators for Water Pumping Systems in Multifamily Buildings

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Abstract: With the current concerns about sustainable development and energy consumption in buildings, water pumping systems have become essential for reducing energy consumption. This research aims to develop guidelines for the energy assessment of water pumping systems in multifamily buildings. The methodological procedures are: (i) definition of the efficiencies of electric motors; (ii) definition of pump efficiency levels; (iii) determination of energy consumption; and (iv) construction of the efficiency scale and guidelines for projects and assessments. The results obtained were that centrifugal pumps with 40% efficiency have higher energy consumption, regardless of the efficiency class of the electric motors, showing a 20% increase in electrical energy consumption. Lower efficiencies directly impact the energy efficiency rating of the water pumping system. Thus the 40% efficiency obtained energy efficiency rating "Very Low—VL" for all motor efficiency classes (between IE1 and IE5). At 60% efficiency, the energy efficiency level of the system was "Average—A", gradually increasing to "Very High—VH", as the energy consumption in the pumps decreased and the motors' energy efficiency classes increased. It is concluded that designers and professionals in the area must consider the efficiency of the pumps, as they play a fundamental role in the classification of the system's energy efficiency. It is also recommended to verify the energy efficiency of the water pumping system and implement design guidelines so that the pumping system achieves lower energy consumption, contributing to the building's energy efficiency and sustainability.

Keywords: motor efficiency level; pump efficiency; MEPS; guidelines

Citation: de Souza, D.F.; da Guarda, E.L.A.; Sauer, I.L.; Tatizawa, H. Energy Efficiency Indicators for Water Pumping Systems in Multifamily Buildings. *Energies* **2021**, *14*, 7152. https://doi.org/10.3390/en14217152

Academic Editors: Matthias Haase and Petter Wallentén

Received: 29 September 2021
Accepted: 25 October 2021
Published: 1 November 2021

1. Introduction

Access to water and energy is something necessary for the quality of life of a population and the economic growth of a region [1]. As a consequence, the energy demand has been increasing to allow this access. In the Brazilian context, commercial buildings, public agencies, and residences represented in 2019 approximately 52% of total electricity consumption [2].

In vertical buildings, one of the sources of energy consumption is water pumping systems. Urban water supply systems typically consume between 1% and 4% of a municipality's electricity and are typically the largest single consumer of electricity. From collection to final use by users in large cities, urban pumping systems can consume 3.3 kWh/m^3 [3]. In water distribution concessionaires, the expenditure on electricity in pumping systems contributes to about 90% of the electricity consumed in this sector [4].

Currently, 55% of the world population is concentrated in cities in urban areas, according to a report by the United Nations (UN) [5]. It is estimated that 2.5 billion people will be added to the urban population by 2050, leading to more than half an increase in the number of people living in urban areas today. Thus, it is observed that the expansion of water supply infrastructure should be expanded, as those related to water pumping will intensify. Currently, the internal demand for domestic water—excluding garden irrigation and other external uses—represents 30% to 70% of the total urban water demand in developed countries [6].

In this context, the trend of continuous urbanization will increase the number of megacities with more than 10 million inhabitants, which may also increase the number of vertical multifamily housing buildings, making this building an attractive option [7,8]. It is observed that the higher the building and the denser its occupation, the higher the energy demand will be, including the energy consumption of the water pumping systems.

Electric motors are responsible for about 70% of the electricity consumed worldwide in industry and 46% of the world's electricity. Pumping systems alone consume almost 22% of all electrical energy consumed in electric motors in the world [9]. Electric motors are considered highly efficient equipment. The energy efficiency of centrifugal pumps is not considered high when compared to the efficiency of electric motors. Overall, pumps with 50% or even fewer efficiencies are typical depending on design and horsepower, and efficiency decreases over the pump lifecycle [10].

Aiming to advance the efficiency of electrical equipment, the minimum standard entitled the Minimum Energy Performance Standard (MEPS) and energy labels were defined, which is seen as one of the main ways to support energy efficiency directly at the product level. Using MEPS and energy product labels is a way to support rational consumer choice and overcome information barriers. These efforts are often mandatory, but they can also be voluntary [11], being updated over the years, according to improvements in construction materials and equipment designs, thus aiming to manufacture increasingly efficient equipment commercially.

In electric motors, MEPS is based on efficiency classes, enabling different levels, which increase according to technological advances and market acceptance. Efficiency classes for motors internationally are harmonized with the IE code in IEC 60034-30-1 [12], widely accepted as the global standard, making efficiency classes comparable worldwide. The standard defines efficiency classes IE1 to IE4, where IE1 is the least efficient and IE4 is the motor efficiency class with the highest efficiency. Similarly, in the United States, the efficiency classes IE1 to IE4 are called Standard, High Efficiency, Premium Efficiency, Super-Premium Efficiency, according to NEMA [13]. The new IE5 class has not yet been defined in detail but is planned for potential products in a future edition of the standard. For IE5 electric motors called Ultra-Premium Efficiency, the goal is to reduce losses by about 20% compared to the IE4 class [14,15]. Some manufacturers already offer IE5 class electric motors.

Efficiency classes are specified by the shaft power of the electric motor and by the number of poles on which the motor is built, responsible for speed. Most motors are 4-pole, representing between 50 and 70% of total electric motors. In motors that drive centrifugal pumps, most are 2-pole, which are the fastest alternating current electric motors, representing between 15 and 35% of the total number of motors [16].

A pumping system has several types of equipment besides the electric motor and the centrifugal pump that form the motor unit. Figure 1 shows the equipment/components presented for a typical system.

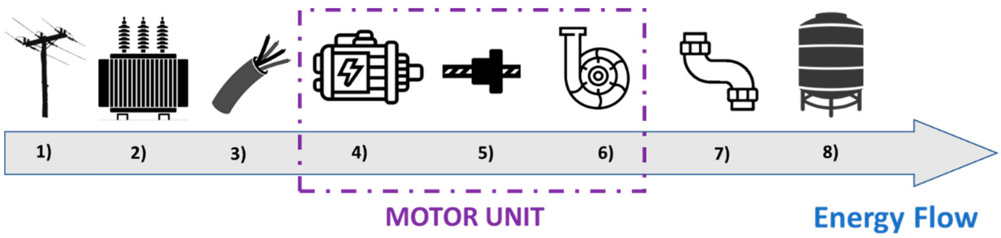

Figure 1. Equipment/components of a building pumping system.

The equipment/components with the most significant possibility of intervention in order to reduce energy losses are the electric motor and the centrifugal pump [17], as they are the equipment that presents the highest losses in a pumping system. Table 1 presents the description of the components in Figure 1 and the approximate typical efficiency of each one of them.

Table 1. Losses in the building's water pumping system.

#	Component in Pumping System	Efficiency Level (%)	Comments	Authors
1	Electric power distribution system	-	There are losses in the electricity distribution system. However, this analysis is restricted to the pumping system.	-
2	Electrical transformer	~98	There is no direct energy conversion. The input and output are electrical energy, and the transformer is naturally high-efficiency equipment.	Krishnamoorthy and Jayabal [18]; Kazakbaev et al. [19]
3	Electric cables	~98	For short distances, electrical cable losses are low.	Krishnamoorthy and Jayabal [18]; Kazakbaev et al. [20]
4	Electric motor	>80	The electric motor converts electrical energy to mechanical energy. It presents electrical losses, magnetic losses, and mechanical losses.	Almeida et al. [14]
5	Coupling	~99	It performs the coupling between the electric motor and the centrifugal pump.	Kalaiselvan et al. [17]
6	Centrifugal pump	35–70	Centrifugal pumps have mechanical and hydraulic losses. They are dependent on the flow and pressure of the piping system.	Mitrovic et al. [21]
7	Piping system	~73	High pressures in the piping system cause vibrations and wear. However, they are difficult to measure.	WSU Energy Program [22]
8	Upper reservoir	-	Losses in the upper reservoir occur due to water evaporation. If not, effectively energy loss.	-

Labels and MEPS for these devices tend to be stabilized by the theoretical limits of the dominant technologies so that the following improvements will come through new technologies in the case of electric motors [14,19], replacing the traditional three-phase Induction Motors with Squirrel Cage Rotor (SCIMs), by Permanent Magnet Synchronous Motors (PMSM), and by Motors Synchronous Reluctance (SynRM), to achieve the highest levels of IE4 and the future IE5 [20,21].

Improvements between IE1 and IE4 classes using SCIMs technology were promoted by using more copper in the stator windings, improvement in the quality of ferromagnetic materials, optimization of electrical designs, and the aerodynamics of the ventilation system [23–25]. However, it is easier to increase the efficiency of the motor system with the application of other technologies, such as PMSM and SynRM, where joule losses in the motor rotor do not exist, as they operate synchronously, thus increasing efficiency [14].

Several works in the literature analyze the impact of IE classes on the electrical system, discussing the economic and environmental impacts.

Andrade and Thé Pontes [26] simulated the replacement of IE2 motors for IE3 in the Brazilian case. They concluded that the energy efficiency measure could generate approximately 164 GWh/year savings if fully adopted from 2020. About 2600 GWh accumulated until 2030, reducing 0.64% of the total electricity consumption of the Brazilian industry until 2030, which represents 5.3% of the total electricity savings expected by the Brazilian government.

Mahlia and Yanti [27] simulated the advancement of MEPS in Malaysia for electric motors, demonstrating the reduction of the country's electricity consumption, the indirect reduction of emissions, and the reduction in electricity bills. The study proved the remarkable benefit to consumers, manufacturers, government, and the environment by implementing energy efficiency standards for electric motors. Mahlia and Yanti [27] also noted that improving the efficiency of electric motors in the industrial sector is a valuable strategy for reducing the impacts of electricity generation in Malaysia. Energy efficiency standards benefit the consumer, national economy, natural environment, and local manufacturing.

Bortoni et al. [28] estimated the amount of energy saved in SCIM due to Brazil's energy efficiency labeling program and its contribution to reducing peak demand, analyzing the replacement of IE1 class motors by IE2 class motors. Bortoni et al. [28] observed that efficiency increases in motors in the range of 1–10 HP are significant for the labeling program because, in absolute numbers, they represent 76% of induction motors installed in Brazil.

Safin et al. [29] compared the energy consumption in a water pumping system using SCIM class IE2 starting directly from the electrical network with a SynRM class IE5 starting with Electronic Speed Variator (VSD) with a power of 0.75 kW. They achieved savings of 13.9% using the IE5 class electric motor compared to the IE2 class.

Goman et al. [30] analyzed the energy consumption of 8 electric motors from different manufacturers, with a shaft power of 2.2 kW, with 3 SCIM class IE3, 2 SCIM class IE4, and 3 PMSM class IE4 being in the electrical drive of a pumping unit with variable speed for a water supply system. Goman et al. [30] simulated the energy consumption by a pump unit in four typical work cycles, considering 25%, 50%, 75%, and 100% electric motor loading, and concluded that for the IE4 standard, the PMSM do not provide significant advantages over peer SCIM.

Kazakbaev et al. [20] compared SCIMs class IE2 and IE3 fed directly from the network with PMSM and SynRM class IE4, fed through an Electronic Speed Variator (VSD), evaluating the energy savings over the life cycle of the motor-pump set and the payback period when replacing an IE2 class SCIM motor with an IE4 class motor. Kazakbaev et al. [18] concluded that the IE4 electric motor, in addition to saving more energy due to its higher efficiency class, with the higher power factor, losses in the cable and the transformer were also reduced, recording a payback time of less than one year.

The efficiency of the centrifugal pump is a determining element in the efficiency of the pumping system. Thus, another way to improve energy efficiency is in the optimal sizing of the installation, seeking to operate the centrifugal pump in the region where efficiency is maximum, also known as the Best Efficiency Point (BEP) [31].

According to Wong et al. [32], from studies carried out in Hong Kong, approximately half of energy losses in the water supply is reserved for pumping systems, as well as aging systems and misuse. In many cases, the centrifugal pump is used at low or medium loads, despite having higher efficiency values at loads close to the nominal. Glover and Lukaszczyk [33] estimated that 75% of centrifugal pumps are oversized by more than 20% and that 80% of electric motors driving centrifugal pumps are operating outside the region of maximum efficiency.

In the Brazilian case, there are still no standards or regulations to establish the minimum efficiency of centrifugal pumps. In the European case, positive experiences such as the Minimum Efficiency Index (MEI) that limits circulation pumps and centrifugal pumps with lower efficiency in the market have already shown good results [32,33].

Buildings are known to account for more than 30% of global energy demand and global greenhouse gas emissions [34,35] and improving energy efficiency in building pumping systems is a strategy to reduce Greenhouse Gases (GHG) [36,37]. Therefore, the adoption of design strategies to promote energy efficiency is fundamental.

Low efficiency in building water pumping systems is common, as it is generally not visible to residents, and most often, the pumping systems are installed by builders, who are not users of the building, nor do they pay the bills for the low system efficiency. With this, the barriers to the energy efficiency of these systems are higher [11,38].

In the context of energy consumption in multi-family buildings, attention to energy efficiency is normally directed towards systems that consume the most energy, such as heat pumps, lighting, refrigeration, and cooking. Thus, environmental certifications for sustainable buildings usually focus credits on these energy consumptions.

The energy efficiency of the building's water pumping system is usually not assessed by environmental certifications for sustainable buildings. For this reason, means of advancing energy efficiency in these systems for multifamily buildings is a research potential. As building water pumping systems are essential for multifamily buildings, considering the growing energy consumption of buildings, the improvement in the energy efficiency of these systems is essential in the context of building certifications and on the path to sustainable buildings.

Thus, research aims to develop project guidelines for evaluating water pumping systems in multifamily buildings.

2. Materials and Methods

The focus of this research is to develop design guidelines for water pumping systems to serve vertical multifamily buildings. Thus, the methodological process consists of five steps, namely: (i) definition of the object of study; (ii) definition of the efficiencies of two-pole electric motors; (iii) definition of pump efficiency levels; (iv) determination of energy consumption; and (v) construction of the efficiency scale and design guidelines, as shown in Figure 2.

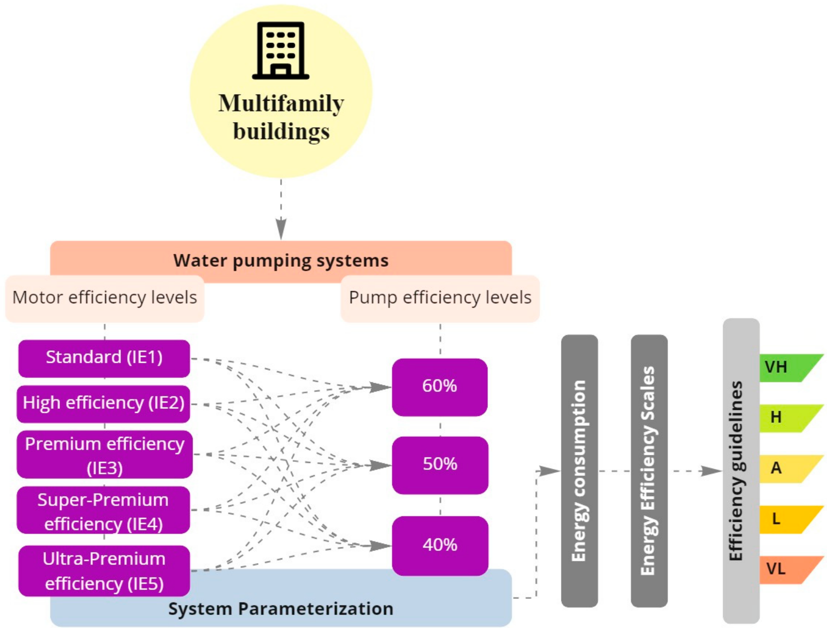

Figure 2. Methodological process flowchart.

2.1. Study Object

The object of study was a vertical multifamily building (Figure 3) for the design of the water pumping system. The building has 16 floors, distributed into a ground floor and 15 intermediate floors, featuring four housing units per floor, elevators, emergency exits, and entrance halls, totaling 60 m in height. In the housing units, an occupation of four people was considered, totaling 240 people in the building.

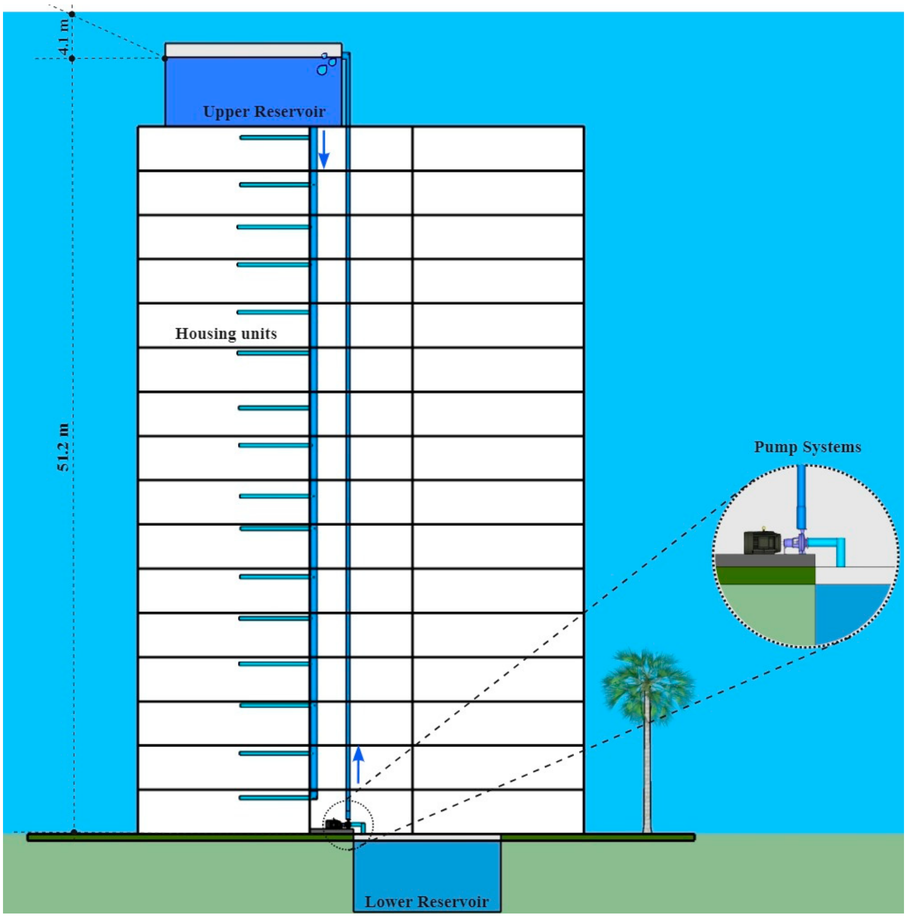

Figure 3. Representation of the building object of study.

On the building's roof, there is an upper water reservoir, which distributes to the housing units, and on the ground floor, there is a lower reservoir that receives and stores the water from the municipal sanitation concessionaire. Thus, in this study, a water consumption of 200 L per person per day was considered, totaling 48 m^3 per day in the building. Thus, the capacities considered in the reservoirs are less than 2/3 of the daily volume (32 m^3) and greater than 1/3 of the daily volume (16 m^3).

In this context, the sizing of head losses [39] was given by the difference in level between the lower and upper reservoir of 51.2 m and head losses due to pipes, bends, special hydraulic parts, and others in 4.1 m, the losses of total loads being considered in 55.3 m. Suction and discharge hydraulic piping materials are in accordance with Brazilian standards [40].

In view of the daily consumption and the losses of distributed loads, the sizing of the centrifugal pump is obtained, given by the power of the equipment (kW), according to Equation (1). The operation of the pump system was considered for four hours a day, the flow of 12 m^3/h, and three different efficiencies, being 40%, 50%, and 60%. The power increase was not considered.

$$P_{pump} = \left(\frac{\gamma \times Q \times H_{total}}{270 \times n_{pump}} \right) * 0.736 \quad (1)$$

where:

P_{pump} = pump power (kW);
γ = specific water weight (1 kg/L);
Q = flow (m^3/h);
H_{total} = total height including head losses (m);

n_{pump} = Pump efficiency (%).

In addition to the pumps, it is necessary to dimension the electric motors, which are responsible for the mechanical drive of the centrifugal pump to lift water. For this, the power of the motors was considered to be the same as that of the pumps, determined by Equation (1), as well as only two-pole motors, as they are the most used in pumping systems. As the operating power of the electric motor is very close to the nominal power of the motor, polynomial interpolation will not be necessary to find a new efficiency value for the electric motor, considering the nominal efficiency for the analysis.

Thus, to identify the efficiency of two-pole electric motors for each calculated power, the Brazilian Decree number 4508 of 2002 [41] was considered for classes IE1 and IE2; the Interministerial Ordinance number 1 of 2017 [42] for class IE3. Standard IEC 60034-30-1 [12] was applied for class IE4. For class IE5 motors called Ultra-Premium Efficiency, a 20% reduction in losses was considered in relation to class IE4 [14].

2.2. Estimation of Energy Consumption and Energy Efficiency Scales

Energy consumption was defined based on the power of the motor-pump set, defined in Equation (1), by the efficiency of the electric motor at full load and by the hours and days of use, according to Equation (2). In addition, 0.736 was used to convert the power of electric motors in kW.

$$E = \left(\frac{P_{motor} \times 0.736}{n_{motor}}\right) \times \left(h \times N_{days}\right) \tag{2}$$

where:

E = electricity consumption (kWh);
P_{motor} = motor power (kW);
n_{motor} = engine efficiency (%);
h = daily hours of use;
N_{days} = number of days of use.

The energy consumption and energy efficiency scale was elaborated based on the efficiency classes of the motors and on the efficiency range of the pumps of 40%, 50%, and 60% considered in this study. This scale was created with the objective of classifying building water pumping systems, mainly for vertical multifamily buildings, classifying as Very High (VH), High (H), Average (A), Low (L), or Very Low (VL).

The definition of the intermediate classes results in the division of the difference between the highest and lowest energy consumption with the scale efficiency intervals, in five parts, according to Equation (3), with the value of the consumption difference and the coefficient "E", the scale according to Table 2.

$$E = \frac{(H_E - L_E)}{5} \tag{3}$$

where:

E = coefficient representing the intervals between classifications;
H_E = highest energy consumption obtained (kWh/year);
L_E = lowest energy consumption obtained (kWh/year).

Table 2. Range limits of energy efficiency ratings for the water pump system.

Efficiency Class	VH	H	A	L	VL
	$< H_E - (5 \times E)$	$< H_E - (4 \times E)$	$< H_E - (3 \times E)$	$< H_E - (2 \times E)$	$> H_E$

Finally, with the help of a scale, guidelines for projects for water pumping systems for vertical multifamily buildings of up to 16 floors were elaborated in order to help designers and researchers achieve energy efficiency in these systems.

3. Results and Discussion

3.1. Analysis of Energy Consumption of the Water Pump System

Through pump efficiency of 40%, 50%, and 60%, the respective powers were obtained, resulting in 3.01 kW, 4.91 kW, and 6.14 kW. In this way, the powers of the electric motors were defined by means of the powers of the pumps, being 3.0 kW, 3.7 kW, and 5.5 kW, respectively, for each pump efficiency. Thus, using the procedure described in item 3.1, the efficiency classes of electric motors were obtained (Table 3).

Table 3. The efficiency of two-pole electric motors for different classes.

Pump Efficiency	60%	50%	40%
Pump power	3.01 kW	4.91 kW	6.14 kW
Rated power of electric motors (2 poles)	3.0 kW	3.7 kW	4.5 kW
IE1	82.5%	84.5%	85.0%
IE2	85.0%	87.5%	88.0%
IE3	88.5%	88.5%	88.5%
IE4	89.1%	90.0%	90.9%
IE5	92.1%	92.0%	92.7%

From these results, the energy consumption of the pumping system was obtained. It is noteworthy that the energy consumption of the building was not considered, with only the consumption of pumps and motors with different efficiencies being considered. Thus, the highest energy consumptions were from the pump with 40% efficiency of pumps and from the efficiency classes of motors IE1 to IE4, which obtained values above 7000 kWh/year. In this scenario, IE5 presented lower values, with a difference of 626 kWh/year in relation to IE1 (Figure 4). It is noteworthy that using the 40% efficiency pump, it is possible to obtain energy efficiency in the system of up to 4% with IE2 and IE3, up to 7% with IE4, and up to 5% with IE5 in relation to IE1.

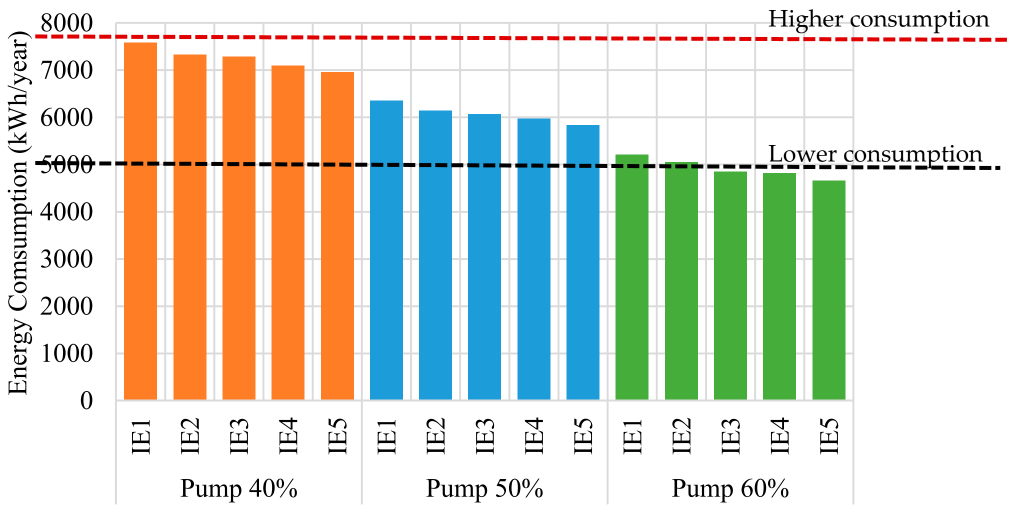

Figure 4. Energy consumption by pump efficiency range and electric motor classes.

It was observed that in the scenario of 50% pump efficiency, it presented median energy consumption values ranging from 6959 kWh to 5970 kWh from IE1 to IE5. The level of efficiency increased gradually according to the class of electric motors, obtaining a difference of 4% with IE2, 5% with IE3, 7% with IE4, and 9% with IE5 (Figure 4). However, comparing the efficiency of 50% (IE5) with 40% (IE5), I obtained smaller reductions in energy consumption, 518 kWh/year, compared to IE1 and difference between the scenarios of up to 108 kWh/year.

The scenario using a pump operating at 60% efficiency presented lower energy consumption with the same reduction profile as the other scenarios, gradually increasing according to the classes of electric motors. In this way, better energy efficiency levels were obtained up to 3% with IE2, up to 7% with IE3, up to 8% with IE4, and up to 12% with IE5. Thus, this scenario presented better efficiency levels from IE4 on compared to other scenarios. Thus, the difference in energy consumption between IE5 and IE1 was 543 kWh (Figure 4).

It was observed that the 40% scenario obtained greater energy consumption reductions with efficiency class IE5, followed by the 60% scenario and the 50% scenario. However, the highest energy consumptions were obtained in the 40% scenario; that is, the lower the pump efficiency, the greater the energy consumption of the system, so that the efficiency classes of electric motors had little influence on consumption when compared to savings with different pump efficiencies. Thus, in multifamily buildings that use pumps with an efficiency of approximately 40%, it is recommended to use class IE4 to IE5 motors so that the average consumption of the pumping system is around 7000 kWh/year.

3.2. Classification of the Energy Efficiency of the Water Pumping System of the Object of Study

The classification of energy efficiency of the water pumping system in the three pump efficiency scenarios was performed based on energy consumption. Thus, the intermediate classes were defined through the difference between the highest and lowest energy consumption, being 7585 kWh/year and 4667 kWh/year, respectively, and the coefficient "E"—Equation (3) and Table 2. Table 4 presents the 5 resulting energy efficiency classes.

Table 4. Energy efficiency ratings for the water pumping system of the object of study.

Energy Efficiency Rating	VH	H	A	L	VL
	≤4.667 kWh/year	4.667 < 5.251	5.251 < 5.834	5.834 < 6.418	≥7.585

Thus, the energy efficiency rating "VL" was obtained for all efficiency classes of electric motors using the pump with 40% efficiency. Thus, water pumping systems that present these scenarios may present less energy efficiency, contributing to the increase in the energy demand of the building under analysis (Figure 5).

Energy Efficiency Rating	IE1	IE2	IE3	IE4	IE5
Pump 40%	7.585kWh/year	7.327 kWh/year	7.285 kWh/year	7.093 kWh/year	6.959 kWh/year
	VL	VL	VL	VL	VL
Pump 50%	6.358 kWh/year	6.140 kWh/year	6.071 kWh/year	5.970 kWh/year	5.840 kWh/year
	VL	L	L	L	L
Pump 60%	5.210 kWh/year	5.057 kWh/year	4.857 kWh/year	4.824 kWh/year	4.667 kWh/year
	A	H	H	H	VH

Figure 5. Energy efficiency rating of the analyzed water pumping system.

In the 50% scenario, the electric motor class IE1 presented an efficiency rating of "VL", changing to "L" in the other classes (IE2 to IE5) (Figure 5). However, it is noteworthy that the lowest consumption was observed in the scenario 50% (IE5) and 50% (IE4). Thus, to achieve better levels of energy efficiency, it is recommended to use these scenarios. It was also observed that the difference in the efficiency levels of these scenarios was only 136 kWh/year to become "A" efficiency level; that is, reducing energy consumption, consequently increasing the energy efficiency of the system as a whole including the building under analysis.

In the 60% scenario, the energy efficiency level of the system was "A", gradually increasing to "VH", according to the reduction in energy consumption and increase in the energy efficiency classes of electric motors (Figure 5). It is noteworthy that this scenario is the most optimistic in terms of energy efficiency, which presented the best levels achieved through water pumping systems in multifamily buildings.

Thus, it was observed that the efficiency of pumps played a preponderant role in a pumping system, regardless of the efficiency classes of electric motors. Thus, comparing the efficiency of the pumps, considering the 40% pump and the IE1 class motor, 15.6%, and 35.0% were obtained in relation to the use of 50% and 60% efficiency pumps. These differences show a similar behavior if we consider the other efficiency classes of electric motors.

In this context, in order to assist designers in building water pumping systems for vertical multifamily buildings, project guidelines are presented. Thus, through the ratings obtained, it was observed that with the efficiency of pumps above 60% from the IE3 efficiency class, it is possible to obtain the energy efficiency rating "VH". As for pumps with efficiency between 60% and 50% for all classes of electric motors, it is possible to obtain an energy efficiency rating of "H" and a lower increase in energy consumption of the water pumping systems in the building (Figure 6).

	Guidelines				
Pump Efficiency	≤60%	60% < 50%	50% < 40%	<40%	≥40%
Motor Efficiency	<IE3	IE5 < IE1	IE5 < IE1	IE4 < IE2	≥IE2

Figure 6. Guidelines for designing water pumping systems for multi-family buildings.

In the pump efficiency range between 40% and 50% for all motor energy efficiency classes, it is possible to obtain energy efficiency level "A". Thus, it is observed that without major difficulties, it is possible to reach average levels of energy efficiency, which can help in total energy efficiency when considering the complete building, especially in cases of retrofit. Finally, centrifugal water pumps with efficiency greater than 40%, considering efficiency classes IE2, IE3, and IE4 of electric motors, it is possible to obtain efficiency level "L". For pump efficiency and motor efficiency class less than 40% and IE2, respectively, it is only possible to obtain a "VL" efficiency level, being the worst energy efficiency rating.

Thus, it is observed that to have better levels of energy efficiency in pumping systems, it is necessary to apply higher pump efficiencies, while with classes above IE3, it is possible to achieve high levels of efficiency. Thus, it is recommended that designers and professionals in the area use pumps with greater efficiency and ensure that they are operating in the region where they have the best performance, as well as verifying the energy efficiency of the system as a whole, so that it achieves better levels of efficiency and reduces the energy consumption of the system, helping both in environmental sustainability and in the energy classification of the building under construction.

4. Conclusions

Given the results presented, it is concluded that the efficiency of pumps is preponderant in the efficiency of the pumping system. The highest energy efficiency classes of electric motors IE4 and IE5 showed significant gains compared to the lower classes IE1 and IE2. However, the efficiency of the pumps played a fundamental role in the energy consumption of the system.

Pumps with efficiency of 50% and 60% presented better levels of energy efficiency in the system, depending on the efficiency class of the motors used. Thus, for the 50% scenario (IE1), it presented an efficiency class "VL", changing to "L" in the other classes (IE2 to IE5). In the 60% scenario, the energy efficiency level of the system was "A", gradually increasing to "VH", according to the reduction in energy consumption and increase in the energy efficiency classes of electric motors. Thus, it is observed that to have better levels of energy efficiency in the systems, it is necessary to apply higher pump efficiencies. In the efficiency range between 40% and 50% for all motor energy efficiency classes, it is possible to obtain an average energy efficiency level "A".

It is concluded that the designers and professionals in the area must consider the efficiency of the pumps, as they play a fundamental role in the classification of the system's energy efficiency. In addition, in old buildings, the energy efficiency of pumping systems can be improved without changing the envelope or other equipment, thus reducing energy consumption.

In addition, it is recommended to verify the energy efficiency of the water pumping system and implement design guidelines to achieve lower energy consumption, contributing to the building's energy efficiency and sustainability. For future research, it is recommended to investigate other efficiency levels of pumps and motors and use other case studies of vertical multifamily buildings.

Usually, energy efficiency in water pumping systems in buildings is not evaluated by sustainable certifiers. Therefore, the proposed efficiency assessment guideline presents an initial and original contribution to increasing the energy efficiency of buildings.

Author Contributions: Conceptualization, D.F.d.S. and E.L.A.d.G.; methodology, D.F.d.S. and E.L.A.d.G.; formal analysis, E.L.A.d.G.; investigation, D.F.d.S. and E.L.A.d.G.; writing—original draft preparation, D.F.d.S. and E.L.A.d.G.; writing—review and editing, D.F.d.S. and E.L.A.d.G.; visualization, H.T. and I.L.S.; funding acquisition, H.T. and I.L.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the support received from the Institute of Energy and Environment of the University of Sao Paulo (IEE-USP) and Enel Electric Power Distribution of Sao Paulo in partnership with the National Electric Energy Agency (ANEEL), through the Priority Project for Energy Efficiency and Strategic R&D—Call 001/2016, "Energy Efficiency and Mini generation in Public Institutions of Higher Education". Project number 00390-1086/2018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the National Council for Scientific and Technological Development (CNPq) for the scholarship made available to the first author, through the project 870814/1999-0, process 142323/2020-9, so that he could dedicate himself to his PhD research of and related fields.

Conflicts of Interest: The authors declare no conflict of interest.

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APPENDIX E

DE SOUZA, Danilo Ferreira; DA GUARDA, Emeli Lalesca Aparecida; DA SILVA, Welitom Ttatom Pereira; SAUER, Ildo Luis; TATIZAWA, Hédio. Perspectives on the Advancement of Industry 4.0 Technologies Applied to Water Pumping Systems: Trends in Building Pumps. **Energies**, v. 15, p. 3319, 2022. (FERREIRA DE SOUZA et al., 2022)

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Perspectives on the Advancement of Industry 4.0 Technologies Applied to Water Pumping Systems: Trends in Building Pumps

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Citation: de Souza, D.F.; da Guarda, E.L.A.; da Silva, W.T.P.; Sauer, I.L.; Tatizawa, H. Perspectives on the Advancement of Industry 4.0 Technologies Applied to Water Pumping Systems: Trends in Building Pumps. *Energies* **2022**, *15*, 3319. https://doi.org/10.3390/en15093319

Academic Editor: Nikolaos P. Theodossiou

Received: 30 March 2022
Accepted: 29 April 2022
Published: 2 May 2022

Abstract: The rational use of energy systems is one of the main discussions in sustainability in the 21st century. Water pumping systems are one of the most significant consumers of electricity in urban systems, whether for urban water supply, sewage, or use in vertical buildings. Thus, this work aims to present Industry 4.0 (I4.0) technologies applied in buildings' water pumping systems, focusing on energy efficiency, supervision, and control of the pumping system. The work involves four steps: (i) identifying the existing I4.0 technologies and (ii) mapping the possibilities of applying Industry 4.0 technologies in building pumping systems. The study includes the analysis of (16) articles published in journals between 2018 and June 2021 to identify I4.0 technologies cited in the publications. It identified and grouped eighteen (18) technologies based on twenty-two (22) terms observed in the papers. The study classified the identified technologies into three possible applications in a building water pumping system. The applications include: (i) directly applicable, (ii) partially applicable, and (iii) application not yet identified. Therefore, the study presents the advantages of I4.0 technologies developed primarily for the industry sector, also applicable in residential building water pumping systems. These technologies' benefits include energy efficiency, user control, a reduction from periods of failure of the pumping system (maintenance), water quality, and moving towards Intelligent Pumping or Pumping 4.0.

Keywords: Intelligent Pumping; buildings; Internet of Things; sustainability

1. Introduction

In ancient times, access to water was a limiting factor in human development and quality of life. The development of water pumps allowed humans to overcome this challenge [1]. From hunter-gatherers to early farmer-herders, energy sources for pumping power included human labour (manual pumping), animal labour, and forces of nature (wind and water, i.e., gravity). Thus, since ancient times, the quest for efficiency in water and energy use has been important for human development [2].

According to the United Nations (2019), 55% of the world's population concentration is in cities [3]. It is estimated that 2.5 billion people will be added to the urban population by 2050, leading to a greater than 50% increase in people living in urban areas. In this sense, society's need/energy demand will increase.

The building construction sectors combined are responsible for almost one-third of total global final energy consumption and nearly 15% of direct CO_2 emissions, and energy demand from buildings and building construction continues to rise [4]. Given this, it is observed that the need for infrastructure, such as water pumping in buildings, can intensify. For example, in vertical buildings, one of the sources of energy consumption is water pumping systems. Urban water supply systems consume between 1 and 4% of a municipality's electricity; they are usually the most significant single electricity consumer, and from capture to final use in homes, urban pumping systems can consume 3.3 kWh/m^3 [5].

In this context, continuous urban growth will lead to an increase in megacities with more than 10 million inhabitants and the number of vertical multifamily housing buildings, making this type of building an attractive option [6,7]. Therefore, high energy demand becomes one of the answers to the verticalization of buildings, as there is a direct relationship between the height of the building versus population density versus the pumping system. Thus, these systems must be efficient and have low amounts and frequencies of failures, to fit into essential equipment for residential buildings.

There are two indicators to advance pumping system energy efficiency—the minimum standard called the Minimum Energy Performance Standard (MEPS) and the equipment efficiency labels, which inform consumers about the equipment's energy efficiency level [8].

MEPS and labels are updated over the years according to improvements in materials and equipment designs, making it possible to manufacture on a commercial scale with increasing efficiency. Electric motors and hydraulic pumps are the equipment with the most significant reductions in energy losses in pumping systems [9]. However, the efficiency indicators of this equipment tend to stabilize due to the theoretical limits of the technologies [10,11]. Thus, in the short term, there is no prospect that new technologies for electric motors and pumps will present for a significant increase in efficiency [11].

In this way, the following performance gains are in the optimal dimensioning of the installation and the search for the pumping system operation in the best performance region [12]. Thus, the subsequent advances will be in process management and pre-identification of problems that cause a pumping system to stop.

Since 2011, the management of an industrial process has changed significantly from the technologies of Industry 4.0 (I4.0), with a strong tendency towards computerization of the manufacture and manufacture of products, concepts of safety, efficiency, and sustainability [13], in addition, to be in line with the need to improve efficiency in water pumping systems. I4.0 advances and trends point to cities and buildings becoming intelligent, efficient, and sustainable [14–17], with pumping systems becoming important.

The central question of this research is to answer the following question: What are the technologies to be implemented in building water pumping systems so that they are considered Intelligent Pumping? From this perspective, this work aims to map the application possibilities of I4.0 technologies, which can be applied to water pumping systems in buildings, and to propose a flexible architecture for the application.

2. Methodology

The proposed methodology includes: (i) identification of the leading technologies of I4.0 and (ii) mapping of application possibilities of the I4.0 technologies, as shown in Figure 1.

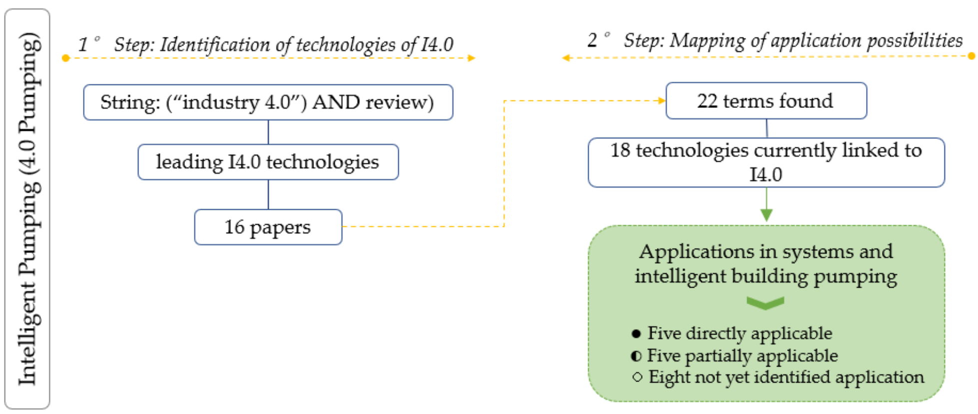

Figure 1. Flowchart of the methodological steps of the study.

A typical pumping arrangement in a building system is composed of an upper and lower reservoir, pump motor set, suction, and discharge pipes. The water originates from the public supply system and is then conducted to the reservoir units, and later flows by gravity to the housing units of the building. To see more details of the typical building pumping system considered in this study, consult the model available in [18].

Traditional pumping systems are activated based on two conditions: (i) the presence of water in the lower reservoir unit and (ii) a low level of water in the upper reservoir unit. With these conditions, a float switch in each reservoir interconnected in a series turns the pumping system on and off by an electromagnetic switch (contactor), as shown Figure 2. The system can be energized during the day and activated only by the two conditions.

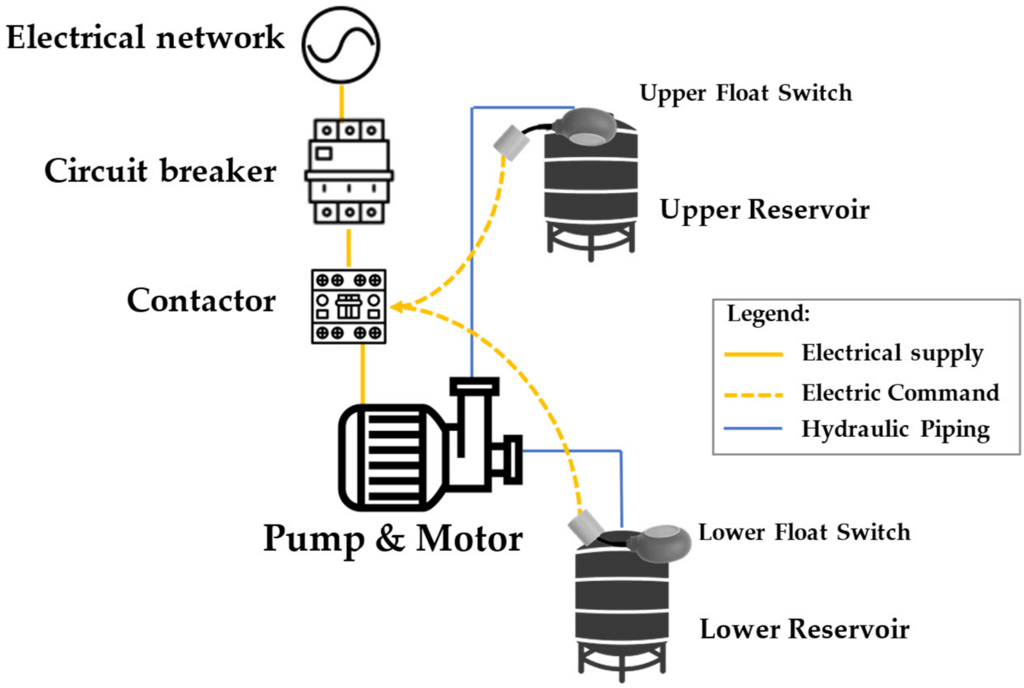

Figure 2. A traditional electrical schematic of the pumping system.

2.1. Identification of the Main Technologies of I4.0

Identifying the leading I4.0 technologies depended on a review of the literature and considered publications from 2018 to June 2021. The Scopus scientific base was used, applying the keyword, and review and industry 4.0 was restricted to English-language titles.

The concept of I4.0 comprises a variety of technologies that often cannot be distinguished clearly. There are several solidly defined methods to apply I4.0 technologies in manufacturing processes in small, medium, and large companies. Then, sixteen (16) papers were selected, as presented in Table 1.

Through the identification of the leading I4.0 technologies, six most common grouped terms were obtained, namely: Intelligent Sensors, Big Data & Data Mining, Cloud & Edge Computing, Machine Learning & Artificial Intelligence, Internet of Things (IoT), Human Machine Interface (HMI), Systems Integration & Network Operation, and Cyber Security, which were mapped in selected papers and their application possibilities discussed in relation to building pumping systems.

Table 1. I4.0 review papers published between 2018 and 2021.

#	Title	Journal	Year	Reference
1	From technological development to social advance: A review of Industry 4.0 through machine learning	Technological Forecasting and Social Change	2021	Lee and Lim [19]
2	Industry 4.0 as a data-driven paradigm: a systematic literature review on technologies	Journal of Manufacturing Technology Management	2021	Klingenberg et al. [20]
3	Industry 4.0: A technological-oriented definition based on bibliometric analysis and literature review	Journal of Open Innovation: Technology, Market, and Complexity	2021	Rupp et al. [21]
4	Evolutions and revolutions in manufacturers' implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework	Production Planning & Control	2021	Calabrese et al. [22]
5	Industry 4.0 triggered by Lean Thinking: insights from a systematic literature review	International Journal of Production Research	2020	Bittencourt et al. [23]
6	Maintenance transformation through Industry 4.0 technologies: A systematic literature review	Computers in Industry	2020	Silvestri et al. [24]
7	Industry 4.0 in the port and maritime industry: A literature review	Journal of Industrial Information Integration	2020	De la Peña Zarzuelo et al. [25]
8	Industry 4.0 and its impact in plastics industry: A literature review	Journal of Industrial Information Integration	2020	Echchakoui and Barka [26]
9	Information and digital technologies of Industry 4.0 and Lean supply chain management: a systematic literature review	International Journal of Production Research	2020	Núñez-Merino et al. [27]
10	The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review	Advances in Mechanical Engineering	2020	Sartal et al. [28]
11	The role of crowdsourcing in industry 4.0: a systematic literature review	International Journal of Computer Integrated Manufacturing	2020	Vianna et al. [29]
12	The smart factory as a key construct of industry 4.0: A systematic literature review	International Journal of Production Economics	2020	Osterrieder et al. [30]
13	Industry 4.0: A bibliometric review of its managerial intellectual structure and potential evolution in the service industries	Technological Forecasting and Social Change	2019	Mariani and Borghi [31]
14	Industry 4.0 in management studies: A systematic literature review	Sustainability	2018	Piccarozzi et al. [32]
15	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	Process Safety and Environmental Protection	2018	Kamble et al. [13]
16	Industry 4.0 framework for management and operations: a review	Journal of Ambient Intelligence e Humanized Computing	2018	Saucedo-Martínez et al. [33]

2.2. Mapping of Application Possibilities of I4.0 Technologies in Building Pumping Systems

The discussion of possibilities and the presentation of possible gains were developed by explaining the positive and negative points derived from applying appropriate I4.0 technologies to the case. Subsequently, the discussion of the implementation of the leading I4.0 technologies is presented in the research so that the pumping system can be considered Intelligent Pumping (4.0 Pumping) in a building system. The objective is to verify the possibilities of classifying the I4.0 technology, aiming at the gain in the useful life of the water pumping system, the connectivity with the user, and the increase in the energy efficiency of the building pumping system.

After surveying the leading I4.0 technologies (Table 1), 18 technologies are currently linked to I4.0 (Table 2), as the study identified and grouped according to the 22 terms found.

Table 2. Overview of I4.0 pillar concepts found in literature review papers.

Item	Technologies Linked to I4.0	Application in Building Water Pumping Systems	References Analyzed
1	Smart Sensors	●	[17,34–38]
2	Big Data & Data Mining	●	[17,39]
3	Cloud & Edge Computing	●	[39,40]
4	Machine Learning & Artificial Intelligence (AI)	●	[39–45]
5	Internet of Things (IoT)	●	[35,40]
6	Human Machine Interface (HMI)	◐	[46]
7	Systems Integration & Network Operation	◐	[47,48]
8	Cyber Security	◐	[49]
9	Autonomous Robotics	○	-
10	Automatic identification and digital product memory	○	-
11	3D printing	○	-
12	Augmented Reality or Virtual Reality	○	-
13	Simulations	◐	[6,50]
14	Additive and Intelligent Manufacturing	○	-
15	Machine-to-Machine (M2M) Communication	○	-
16	Knowledge-Based Systems (KBS) & Semantic Web	◐	[51]
17	Automated guided vehicles (AGV)	○	-
18	Cyberphysical Systems	○	-

● Directly applicable. ◐ Partially applicable. ○ Not yet identified application.

The technologies linked to I4.0 were classified into three possibilities based on the reading of the analyzed references: directly applicable, partially applicable, and still unidentified application. In Table 2, the 18 technologies linked to I4.0 are classified according to the current possibilities (2022) of application in building water pumping systems to implement Pumping 4.0 or Intelligent Pumping.

3. Industry 4.0: Applications in Systems and Intelligent Building Pumping

This section discusses I4.0 technologies that can be considered viable applications for building pumping systems, that is, technologies linked to I4.0 aimed at building the concept of Intelligent Pumping.

The identification of the possibilities of application of I4.0 technologies in pumping building systems took place through the analysis of compatibility, comparison, and feasibility of I4.0 technology versus pumping building systems. Also presented are successful applications of I4.0 technologies used in pumping systems in industry and sanitation.

3.1. Mapping and Identification of I4.0 Technologies Applicable in Building Pumping Systems

3.1.1. Smart Sensors

The use of sensors is essential for inserting a process in I4.0. The sensors can also monitor the system's energy efficiency and production of indicators that allow monitoring parameters and preventive maintenance programming to avoid downtime due to failure. The equipment (e.g., electric motor and centrifugal pump) can emit signs indicating acceleration of degradation. Therefore, evaluating the degradation throughout the life span of the equipment is essential. This way, machines and equipment's operating condition and integrity are monitored. Figure 3 is a typical degradation pattern of electrical and mechanical equipment.

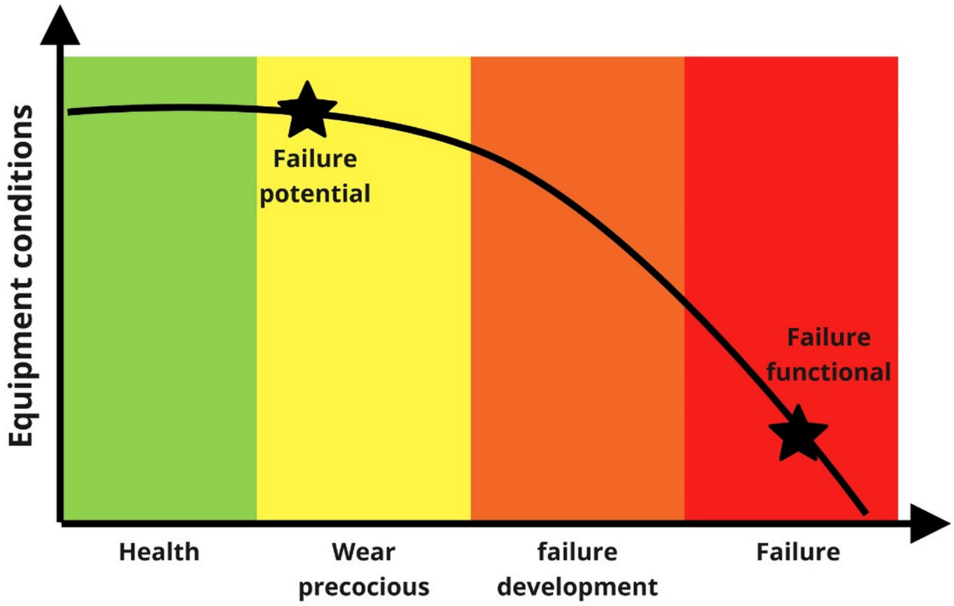

Figure 3. PF curve represents the condition of a component until functional failure. Source: Adapted from [52].

The point of functional failure is when the equipment fails to provide its intended function. Condition-based maintenance aims to detect the potential failure before the actual failure occurs. In this case, maintenance actions can be planned before the functional failure, with advantages such as reducing downtime, eliminating unexpected production stops, maintaining downtime, eliminating unexpected production stops, maintaining optimization, and reducing spare parts inventory.

Sensors for Hydraulic Measurements and Water Quality

A smart water network would integrate sensors, controls, and analytical components to ensure quality and efficient water supply. Smart meters and end-use detection devices can aid in leak detection. For example, continuous data from a smart residential meter can reveal a leak, showing a positive water flow when all accessories are off [17].

A theoretical smart water network starts at water harvesting, where smart meters, smart valves, pumps, and smart sensors are installed, with continuous monitoring along the water path, through the water treatment steps with more meters, valves, and smart pumps.

Within the city's water distribution system, water contaminant sensors are applied. End-use sensing devices, smart irrigation controllers, contaminant sensors, and smart meters can be used at end-user sites. Finally, the water goes through the sewage system to treat effluents, and the same technologies used at the beginning of the system are also used [34].

The quality of the water consumed by users can be affected by several factors, such as various contaminants, materials from corrosion of the pipe, distribution, accidents, and even terrorism. Contaminant sensors in a smart water network can alert consumers to potential problems before consumption [34].

The persistent storage of measured data allows for monitoring possible changes in water quality parameters (physical, chemical, and biological parameters). It can even prevent a series of diseases transmitted by water via analyzing data from measures of domestic water. (Potential of hydrogen; Turbidity; Temperature; Reduction of oxidation potential; Electrical conductivity), providing a preliminary laboratory analysis if necessary. The data collected can indicate deviations in standards and anomalies and predict future water quality trends using machine learning techniques. If the water is not within acceptable standards, the pumping system is not activated [35].

Sensors for Measuring Mechanical Quantities

Analyzing mechanical vibration data from electric motors is universally accepted as an excellent technique for detecting mechanical failures, especially among the most common failures, such as alignment defects, bearing failure, mechanical load breakdown, and ventilation [36].

Using smart sensors for vibration, acoustic, and flow measurements makes it possible to identify pump parameters variations. The set of sensors makes it possible to predict cavitation problems, one of the leading causes of pump downtime. Sensing can guarantee the optimal functioning of the centrifugal pump at different operating points [37].

Vibration sensors (accelerometers), in addition to being low cost, are reliable for early detection of failures of both the electric motor and the centrifugal pump, enabling optimization and maintenance planning and reducing the probability of failure [38].

Sensors for Measuring Electrical Quantities

Changes in the form of the electric current wave, also known as the electrical signatures of electric motor currents, are an essential way of applying methodologies to detect rotor problems, stator asymmetries, defects in the cooling system, and faults in the bearings or the coupling system. These failures reduce the efficiency of the electric motor before bringing the equipment to a complete stop [53].

Electronic current waveforms are collected by current sensors installed in the electrical panels or as part of the electric motor's Variable Speed Drives (VSDs). Figure 4 illustrates the topology with the primary sensors highlighted in the discussion in Section 3.1.1.

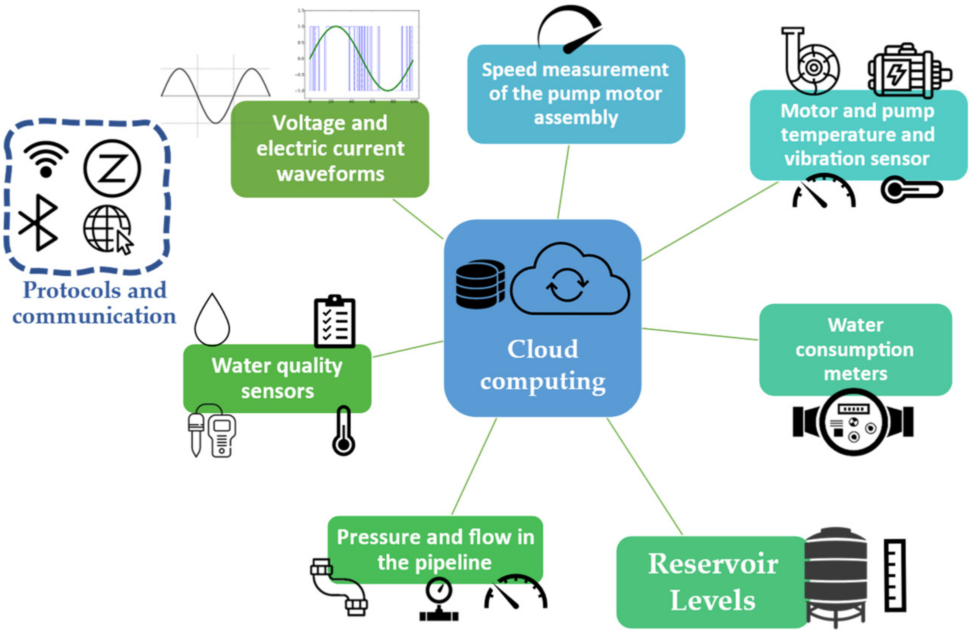

Figure 4. Key Smart Sensor Measurements for Smart Pumping.

The temperature sensors in the electric motor and the centrifugal pump are essential for evaluating the operating condition of this equipment. Upper and lower reservoir level sensors must assess pumping system turn-on moments. The speed transducer (tachometer) to measure the speed of the motor-pump assembly assists in determining the loading of the electric motor and the operating of the pump point. Figure 4 presents items related to cloud computing, big data, and Systems Integration that will be discussed in subsequent topics.

3.1.2. Big Data & Data Mining

The implementation of new sensor monitoring and control technologies, combined with the availability of high computational power, changed the traditional approach to designing and managing water systems and enabled the development of new data-based techniques powered by Big Data [17]. Big Data is already a reality for water supply companies in large cities, but it can also become a reality for water pumping building systems. When smart metering becomes more present in systems, a large amount of data will be collected, stored, and processed to make decisions aimed at improving supply [39].

With the use of smart meters in each consumer unit, it is possible to perform the automatic collection of consumption, self-diagnosis of the system, and monitor the status of the quantity and quality of water, enabling remote management and saving decisions by the user. With this technology applied on a large scale, it will be possible to provide meter readings instantly, generate domestic leak reports for each user, and even send smartphone alerts [39]. In addition to this term, others such as Cloud & Edge Computing, Machine Learning & Artificial Intelligence, Internet of Things IoT, Human Machine Interface (HMI), Systems Integration & Networking, and Cyber Security, are linked to the monitoring and previous solutions of possible system failures and problems.

3.1.3. Cloud & Edge Computing

In pumping systems, cloud computing allows data from sensors and meters installed in the electrical and hydraulic network to be readily available to various stakeholders responsible for asset maintenance or even users. The mass of measurement data is uploaded to the cloud computing facility for continuous analysis [39].

3.1.4. Machine Learning and Artificial Intelligence

The optimization of the water pumping system, aiming at the lowest consumption of electricity, and meeting the need for water supply, can be carried out using Variable Speed Drives (VSDs). Combining machine learning and Artificial Intelligence (AI) to make decisions based on data from pressure and flow sensors in pipes and electricity consumption enables the system to perform at the best efficiency point [41].

Artificial intelligence through machine learning makes it possible to generate algorithms to identify long-term trends that analyse historical data collected from sensors. Long-term trends can inform the maintenance period and enable action before failure occurs. For example, the vibrations of the motor-pump set are one of the leading failure indicators of both the electric motor and the pump [43].

The manufacturer's performance curve of a hydraulic pump shows the region with the best operational efficiency. Pump performance simulations can be carried out using machine learning techniques, thus making it possible to operate at the points or in the best efficiency region, reduce electrical energy consumption, avoid vibrations and excessive wear, improve maintenance, and timely maintenance downtime [44].

In a sanitary sewage pumping system, the flow decreases with the increase in the size of the contamination particle or sludge, for example. With the pressure and flow reading and using a machine learning algorithm, through the knowledge of the system's operating patterns, it is possible to identify the high effort of the system for significant impurity, and to act by turning off the pumping system [45].

3.1.5. Internet of Things (IoT)

In the more general framework of Industry 4.0, the recent development of IoT technologies applied to smart grids has opened up new opportunities in the management of water network systems [17]. Monitoring water quality is critical to consumer health. In this perspective, recently developed systems based on smart sensor technology combined with recent advances in the IoT can contribute to drinking water quality management. It will also inform building users, in real-time, of access to the leading quality indicators of water [35], according to the topology in Figure 4.

Figure 5 presents a simplified schematic of the IoT process for water quality monitoring.

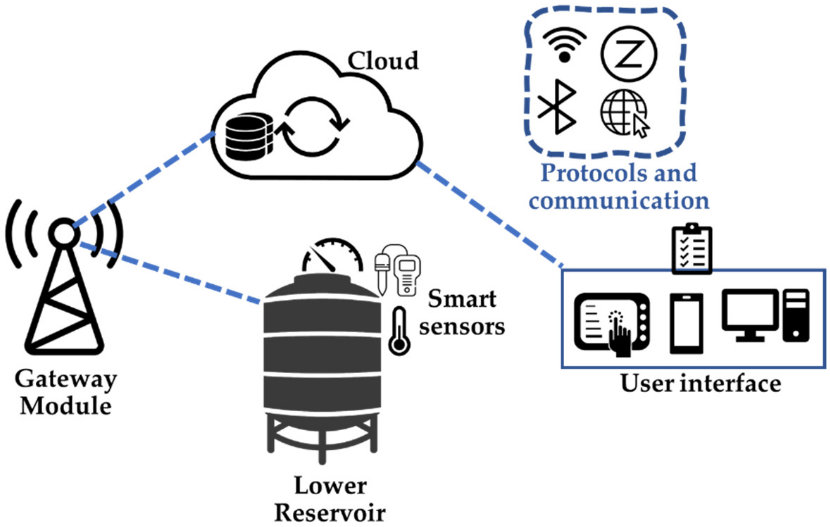

Figure 5. Simplified schematic of the IoT process for water quality monitoring.

The same topology presented in Figure 5 can be applied to several other sensors presented in Section 3.1.1. For example, the application of vibration sensors can be applied in centrifugal pumps for diagnostics of the pump's operating state and in avoiding failures. With data being stored in the cloud, patterns of behaviour are processed and analyzed by Machine Learning and expressed by IoT [40].

3.1.6. Human Machine Interface (HMI)

From the perspective of I4.0, the HMI is a device that mediates the interaction between an operator/user and a pumping system, where the user can give operating commands and visualize the process. Viewing on computers, smartphones, and even displays is entirely possible in this concept. The pumping system visualization process is commonly visualized through a SCADA system (Supervisory Control and Data Acquisition), providing users with an interactive layout of the system.

3.1.7. Systems Integration & Network Operation

The rapid growth of large urban residential areas necessitates the expansion and modernization of existing water pumping facilities. The process automation system based on the use of integration via network operation through industrial protocols, Programmable Logic Controllers (PLC), and Supervisory Control and Data Acquisition (SCADA), represents the best way to improve the technological process of distribution of water [47].

The automation of the pumping system using systems integrated with a network with the support of PLCs that may even be available in VSDs being visualized by SCADA can provide several gains. Such benefits include: general supervision and remote control of all equipment, reliability of measurement data by monitoring, continuity of water distribution and protection of water quality, reduction of water resource losses, detection of water leaks made by monitoring online consumption or pressure drop, real-time alarms triggered by any equipment failure in the pumping system, optimization of exploration and maintenance costs, and preparation of an automated database [48].

3.1.8. Cyber Security

From abstraction to end-use management, evolution in water supply systems through computing hosts, smart sensors, IoT layers, edge computing, wireless networks, and artificial intelligence has increased and will increase the possibilities of cyber-attacks because they operate in a network. Tuptuk et al. (2021) [49] highlighted the importance of protecting water infrastructure from malicious entities that may carry out industrial espionage and sabotage against these systems.

3.2. Implementation of I4.0 Technologies in Building Pumping Systems

Based on the characterization of the technologies linked to I4.0, its implementation is directly related to electronic and computational resources. Thus, one of the main elements of this application is using VSDs to drive and control the pump motor set, enabling the drive and control of the system electronically. VSDs are typically used in applications that need to control the flow of the pumping fluid, and this system has also become advantageous in applications that do not require speed control.

With the implementation of new electric motor technology, VSDs have become even more present in motor systems, as they are mandatory for the operation of motors, such as Permanent Magnet Synchronous Motors (PMSM) and Synchronous Motors. Reluctance Motors (SynRM) should assume a more significant role in the coming years, as they reach higher efficiency levels than the traditional Squirrel Cage Rotor Induction Electric Motors (SCIM) traditionally used in pumping systems [54].

According to Huse et al. 2020 [55], the significant productivity gains with the application of VSDs in electric motors that drive hydraulic pumps to pump water are mainly:

1. Pump speed control maintaining a pressure requested by the system.
2. Applying VSDs reduces motor wear due to reduced speed, vibration, and torque.
3. Soft start of the motor and gradual accelerations to reduce large electrical transients where high-starting currents can cause voltage drops in the electrical network.
4. Soft start of the motor and gradual accelerations, reducing the mechanical stress of the shaft, as well as the thermal stresses in the windings and mechanical stresses in the couplings and belts.
5. Reduction of sudden changes in water speed (transients), which may result in water hammer, cavitation, and vibration of the pump motor assembly [42].
6. A small reduction in speed or flow can significantly reduce energy usage.
7. Reduction in the maintenance fee of the motor-pump set.
8. A total of 20 to 40% energy consumption, a typical 38% water leakage reduction, 53% reduced breakdowns, and extended motor pump life.

A pumping system using VSD is shown in Figure 6.

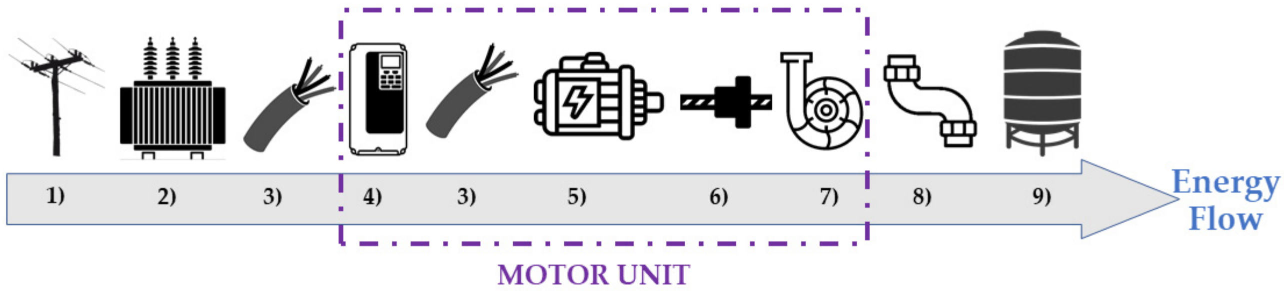

Figure 6. Pumping system using VSD. Source: Adapted from [18].

As one of the pillars of I4.0 is network operation, the role of VSDs in this context is not that of a simple electronic trigger. In addition to being power processors, VSDs have become elements of the information chain, increasingly used as sensors or intelligent controllers. For the application of technologies linked to I4.0, VSDs play a fundamental role, characterized by intelligent action through various resources aimed at continuous connectivity with the various devices, and performing electrical data acquisition and electric motor control [56].

The electrical energy savings achieved are remarkable when controlling the speed of the pumping system using the VSDs. Opportunities to improve the energy efficiency of the water pumping system fall into three distinct categories: (i) component selection, (ii) dimensioning of the pumping system, and (iii) variable speed control of the pumps.

In the context of I4.0, for the formation of Intelligent Pumping, the various elements of the system, such as motors, drives, sensors, and controls, are interconnected and connected to the cloud—where data is stored, processed, and analyzed, and decisions are made as discussed in Section 3.1. After the decision is made, the intelligent equipment that acts as the operation of the Intelligent Pumping System is the VSDs. For this reason, it is the central equipment for the conception of this new concept, as shown in Figure 7.

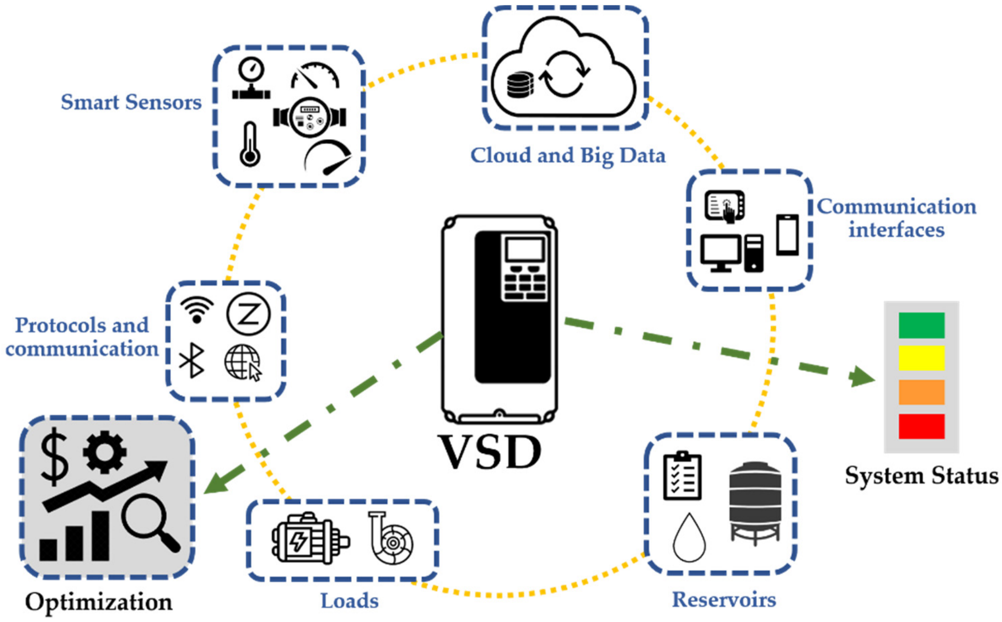

Figure 7. VSD is a core element of Smart Pumping.

3.2.1. Operation at the Point of the Best Performance

To achieve the maximum performance of the motor pump set during its operation (i.e., the different demands from pressure and flow throughout the day), VSDs are commonly used in industrial pumping systems and the sanitation sector. However, the application is still not widespread in pumping systems installed in residential or commercial buildings.

In a building water pumping system, the motor-pump set is designed to meet a specific value of rotations, with this value reaching pressure and flow, providing a specific performance. This is considered the operating point of the system.

The motor-pump set is desired to work with pressure and flow values to meet the variable demand typical of user requests. For this, the VSD controls the speed of the set, seeking operational optimization so that the system operates in the region known as the Best Efficiency Point (BEP). This is when the ratio between the system flow (m^3/h) and the electrical energy consumed (kWh) is the maximum possible.

The location of the operating point is mandatory to optimize the energy efficiency of the pumping system. A VSD-powered pumping application is achieved using an algorithm already available in most current VSDs. Modern VSDs are equipped with conventional flow vs. head (QH) and (QP) to determine pump flow [57].

3.2.2. Demand Side Management (DSM) Using VSD

The DSM is a set of forecasting techniques and demand services based on the balance between supply and demand. Its application has significant success records for industrial pumping stations and the sanitation sector. There are expectations of applicability and success also for the cases of water pumping building systems.

Figure 8 shows operating ranges when the VSD is present. The operating ranges are delimited by the pump curves with nominal speed (N1) and minimum viable speed (N3), and can be explored to reach the best performance point (BEP) of the motor-pump set.

In the building pumping system, the flow demanded by the piping system is modified according to the population's immediate needs (Figure 8; points A, B, and C).

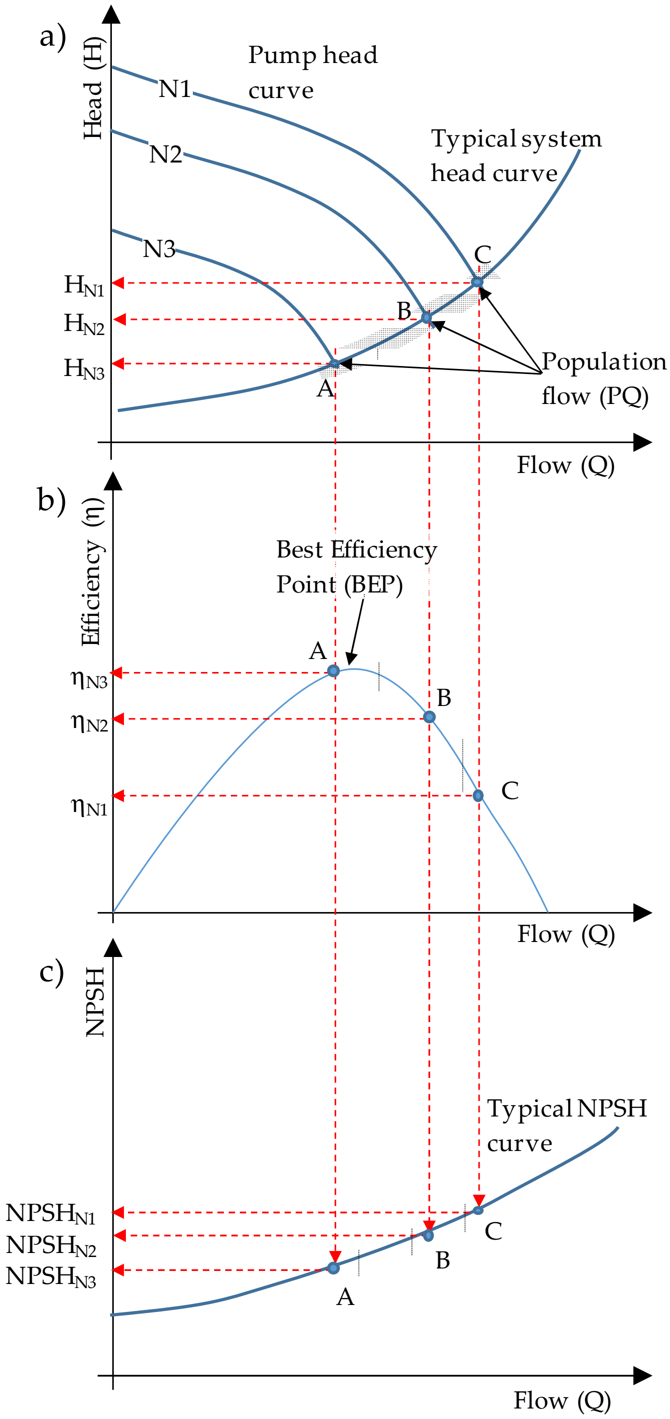

Figure 8. Operating range of centrifugal pump with VSD: (**a**) evolution of Head and Flow with the variable speed; (**b**) evolution of Efficiency and Flow with the variable speed; (**c**) evolution of NPSH and Flow with the variable speed.

The without of VSD means that the head (H), the flow (Q), the yield (η), and the cavitation indicator (NPSH) are kept constant (Figure 8a; point C), disregarding the immediate need of the population. For example, the population's immediate need is at point A, but the motor-pump assembly operates only at point C; or, the population's immediate need is at point B, but the motor-pump assembly operates at point C.

In these cases, the population's immediate needs are served by numerous starts/stops of the motor-pump set (Figure 8a; N1) with short operating times. This reduces the life of the equipment due to the excessive number of starts/stops and the operation with low efficiency, as can be seen in Figure 8b. On the other hand, the presence of the VSD associated with I4.0 and DSM techniques allows the effective use of the operating range (Figure 8a; points A, B, C with curves N1, N2, N3; yields h1, h2, h3, as per Figure 8b; NPSH1, NPSH2, NPSH3, as per Figure 8c). Therefore, increasing equipment life span and reducing operating/maintenance costs (better yields, fewer starts/stops, and operation without cavitation) is important. Essential gains in equipment life span and energy efficiency are obtainable with the right combination of VSD, I4.0, and DSM.

Already, several optimization methods are widely known in the industry and are in use in water pumping building systems, such as Multiobjective optimization [58], Genetic algorithm [20], Mixed-integer nonlinear programming [6], multi-criteria analysis [51], Multi-Objective Mixed Integer Linear Programming [58], and Mixed-Integer Nonlinear Programming [59]. Table 3 shows some optimization methods applied in building water pumping systems.

Table 3. Traditional optimization methods that can be applied in the building water pumping system.

Item	Method	Paper	Journal	Year	Reference
1	Multi-objective optimization	An Updated Survey of GA-Based Multiobjective Optimization Techniques	ACM Computing Surveys	2020	Coello [60]
2	Genetic Algorithm	Decision support for sustainable option selection in integrated urban water management	Environmental Modelling & Software	2008	Klingenberg et al. [20]
3	Mixed-integer nonlinear programming	Optimization and validation of pumping system design and operation for water supply in high-rise buildings	Optimization and Engineering	2021	Müller et al. [6]
4	Multi-criteria analysis	An Analysis on Optimization of Living and Fire Water Supply Systems of Small High-Rise Residential Blocks	Earth and Environmental Science	2017	Yuan [51]
5	Multi-objective mixed integer linear programming	Integrating energy and water optimization in buildings using multi-objective mixed-integer linear programming	Sustainable Cities and Society	2020	Emami Javanmard et al. [58]
6	Mixed-integer nonlinear programming	Optimization of Pumping Systems for Buildings: Experimental Validationof Different Degrees of Model Detail on a Modular Test Rig	Operations Research Proceedings 2019	2019	Müller et al. [59]

3.3. Research Limitations

- The research was limited to evaluating the possibilities of application of I4.0 technologies in a building water pumping system, but these technologies could be applied in other types of drives such as: compression, elevation, ventilation, etc.
- The research did not delve into the discussion of communication protocols between the various systems.
- We recommend continuing the research with the construction of an IoT architecture for application in a pumping system using I4.0 technologies, enabling the experimental validation of the proposal.

4. Conclusions

The building water pumping system is an integral and fundamental part of the services for the proper functioning of the buildings. With the new paradigms of I4.0, buildings also point to integrated and increasingly autonomous intelligence systems.

This research presented some of the technologies of I4.0 that can already be used in water pumping systems for buildings. With the application of the concepts, the improvements are structured into four pillars: (i) increase in the energy efficiency of the system, (ii) increase in the useful life of the system, reducing failures, (iii) improvement in the control and predictability of the system, and (iv) possibility of monitoring.

Most of the research activities on pumping systems focus on water supply systems, heat pumps and irrigation systems in agriculture. There are few concerns in the literature about building water pumping systems, which calls for the need to continue researching the subject.

The application of I4.0 technologies seeking to form intelligent pumping systems will reduce water loss, waste, quality of water consumed, user control, and improvements in energy efficiency and service continuity, moving towards an intelligent and flexible pumping system.

Intelligent sanitation is a fundamental component of the formation of Smart Cities. However, it is necessary to move toward intelligent building systems, promoting the incorporation of Intelligent Sensors, Big Data, IoT, etc. This wave of data brings new possibilities in building water design and management and economic prospects.

For advances in research, more coordination between academia, industry, and government is needed to guide the deployment of smart building systems in the real world. The publications date of the references used in this research demonstrates the current concept of I4.0 and the broad field of application of technologies for the construction of a connected society.

Author Contributions: Conceptualization, D.F.d.S. and E.L.A.d.G.; methodology, D.F.d.S. and E.L.A.d.G.; validation, D.F.d.S., E.L.A.d.G., H.T., I.L.S. and W.T.P.d.S.; investigation, D.F.d.S., E.L.A.d.G. and W.T.P.d.S.; resources, H.T. and I.L.S.; writing—original draft preparation, D.F.d.S., E.L.A.d.G., I.L.S., H.T. and W.T.P.d.S.; writing—review and editing, D.F.d.S., E.L.A.d.G., H.T., I.L.S. and W.T.P.d.S.; supervision, H.T. and I.L.S.; funding acquisition, I.L.S. and H.T. All authors have read and agreed to the published version of the manuscript.

Funding: National Electric Energy Agency (ANEEL): Project number 00390-1086/2018 (ENEL)—Integrated assessment of distributed generation, demand management, monitoring, quality, performance of the network, aimed at optimizing investments and tariff regulation in the underground network, and Project number 00061-0054/2016 (CESP)—Analysis of the efficiency of complementary energy storage with hydroelectric plants, using electrochemical and hydrogen storage technologies; National Council for Scientific and Technological Development (CNPq): Project 870814/1999-0, Process 142323/2020-9.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the National Council for Scientific and Technological Development (CNPq) for the scholarship made available to the first author through the project 870814/1999-0, process 142323/2020-9, so that he could dedicate himself to his PhD research in this and related fields. The authors thank Richardson M Abraham-A for improving the translated manuscript. The authors thank Rodolfo Quadros and João Lopes for reading and contributing to the research. The authors would like to thank the professors of PEA5733-1/4—Automation and Society, responsible for introducing the discussion of Industry 4.0 at the Polytechnic School of Engineering of the University of Sao Paulo. The authors are grateful for the reviewers' criticisms, which contributed to improving this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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APPENDIX F

DE SOUZA, Danilo Ferreira; DA SILVA, Pedro Paulo Fernandes; DE ALMEIDA, Aníbal Traça; SAUER, Ildo Luis; TATIZAWA, Hédio. Life Cycle Assessment of Electric Motors-A Systematic Literature Review. **Journal of Cleaner Production**, p. 142366, 2024. (DE SOUZA et al., 2024)

Journal of Cleaner Production 456 (2024) 142366

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Life cycle assessment of electric motors - A systematic literature review

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ARTICLE INFO

Handling Editor: Xin Tong

Keywords:
Permanent magnet motors
Synchronous reluctance motors
Industry energy efficiency
Ecodesign
Electric motors

ABSTRACT

Electric motors account for over 53% of global electricity consumption, making their energy efficiency relevant for climate change mitigation and for a more competitive industry. However, more efficient motors often require more materials. Despite this, research primarily focuses on motors' energy efficiency during usage, neglecting other life cycle phase like manufacturing and disposal. This study conducted a Systematic Literature Review, identifying 1112 publications on the topic, with only 20 deemed relevant. Squirrel Cage Induction Motors (SCIM) were dominant due to their cost, reliability, and efficiency. However, over the past 30 years, efficiency has improved largely due to altered material use. This impacts production and disposal phases but lessens the use phase impact. Alternatives like Switched Reluctance Motors (SRM) provide better energy efficiency with fewer materials compared to SCIM. Permanent Magnet Synchronous Electric Motors (PMSM) emerge as the most energy efficient but with high environmental impacts in production and disposal. Synchronous Reluctance Motors (SynRM) are competitive SCIM alternatives, boasting less vol/wt, higher efficiency, and reduced impacts. The analyzed Life Cycle Assessments (LCAs) showed variations in included life cycle phases, materials accounted for, and impact categorization. Thus, a tiered framework for electric motor LCAs is recommended. The use phase has the most significant impact, accounting for over 90% of life cycle impacts. Efficient motors generally have reduced environmental effects over their lifespan, even if their production and disposal impacts are higher. Notably, all analyzed LCA publications are European, so findings might vary in other regions. The study concludes by highlighting seven research gaps to further reduce electric motors' environmental impacts.

1. Introduction

Today, issues related to energy transition, efficiency and mitigating climate change are major items on the global agenda for sustainable development (Von Stechow et al., 2016)– (Serôa da Motta, 2019). According to a European Environment Agency (EEA) report, the energy sector was a prominent contributor to greenhouse gas emissions in 2019, substantially making up 77% of the total emissions (European Environment Agency, 2019a). The energy sector's emissions can be divided into three major segments: power generation, fuel, and transportation, each accounting for approximately one-third of the overall greenhouse gas emissions (European Environment Agency, 2019b).

The industrial sector's dependency on electrical energy encompasses a diverse array of applications, including motor drive power for fluid motion, materials processing and handling, as well as operations of air compressors, refrigeration systems, and boilers, not to mention heating, lighting, and miscellaneous uses (Dyer et al., 2008)– (Choi et al., 2018). Electric motor systems accounted for approximately 70% of the industrial sector's electrical consumption in 2021 (International Energy Agency, 2021), highlighting the critical need for enhanced energy efficiency within these systems. Such improvements serve as a strategic approach to optimize the existing electrical grid capacity, presenting a preferable alternative to the introduction of new, costly, and time-intensive infrastructure developments (Saidur, 2010)– (Bortoni et al., 2020).

Recognizing energy efficiency as a vital tool for reducing greenhouse

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https://doi.org/10.1016/j.jclepro.2024.142366
Received 11 December 2023; Received in revised form 20 April 2024; Accepted 26 April 2024
Available online 29 April 2024
0959-6526/

gas emissions (Cordroch et al., 2022, Fong et al., 2020, Méjean et al., 2019, Talaei et al., 2019, Prada et al., 2020), the International Energy Agency (IEA) projects that energy conservation could contribute to 40% of the greenhouse gas emissions reductions required by 2040, in alignment with the climate goals established by the Paris Agreement (International Energy Agency, 2018). The IEA's Energy Outlook for 2021 further asserts the necessity of adopting only the most efficient electric motors by 2035 to fulfill the decarbonization objectives (International Energy Agency, 2021).

Historically, the shift towards energy-efficient electric motors, supplanting their less efficient counterparts, has been extensively investigated and reported in the literature since the 1990s. This period marked the initiation of Minimum Energy Performance Standards (MEPS) (Hiatt, 1990, Bonnett, 1995, McNaught, 1992, Bonnett, 1994, 1996, Cole and Thome, 1995a, Cole and Thome, 1995b, Desai, 1996, De Oliveira and De Almeida, 1996, Baker, 1996, De Almeida, 1994, de Almeida and Fonseca, 1998). Progressing into the 2000s, numerous studies have focused on the role of electric motor upgrade and duty cycle optimization in mitigating the effects of global warming (Shires and Campbell, 2006, Aro, 2009, Gallaher et al., 2009, Blok, 2005, Damrongsak et al., 2020).

Determining the environmental impact of electrical motors has generally been limited to usage and not complete life cycle analysis, and this is illustrated by the scarce publications on the extraction and use of raw materials in producing electrical motors (Gross, 2006, Hu et al., 2015, Tong, 2017, Turowski and Turowski, 2017). Thus, it is essential to apply techniques for assessing and quantifying possible environmental impacts associated with electric motors, analyzing the following phases: *i*) extraction of raw materials, *ii*) processing of raw materials, *iii*) production of the equipment, *iv*) transportation, *v*) distribution *vi)* specific source and use of electricity, and lastly vii) the final disposal, also contemplating recycling, reuse, and disposal (Klöpffer, 1997, Jacquemin et al., 2012, Dicks and Hent, 2015, Guinée et al., 2011). Life Cycle Analysis or Life Cycle Assessment (LCA) was first used for electrical equipment in 1968 (Stokes and Stehle, 1968).

Electric motors are fundamental to industrial production processes and society. Compared to other electrical components destined for consumers, manufacturing these motors requires a large amount of energy-intensive raw materials. Electric motors are the most energy-consuming electrical equipment in the world; thus, the following questions beg to be answered.

RQ1. Are there existing Life Cycle Analyses (LCA) on industrial electric motors?
RQ2. What are the methods engaged in the analysis?
RQ3. What kind of electric motor technologies have been analyzed?
RQ4. What were the environmental impact analysis categories?
RQ5. What energy mix was chosen for the analysis?
RQ6. What were the main results found?
RQ7. What are the restrictions of the research and the main challenges in the field?

A Systematic Literature Review (SLR) has been utilized to answer these questions (RQ1-RQ7) (Ramey and Rao, 2011, Okoli and Schabram, 2010, Mulrow, 1994, Tranfield et al., 2003, Lame, 2019, Graham, 2011, Xiao and Watson, 2017).

Consequently, this study aims to answer seven proposed research questions through a Systematic Literature Review (SLR) in order to identify the environmental impacts of electric motors, which are the world's leading consumers of electricity, from their production (cradle) to their disposal or recycling (end of life or grave), thus encompassing their entire life cycle. Traditional Squirrel Cage Induction Motors (SCIMs), which account for over 95% of all drive applications in the industrial sector, are already nearing the limits of energy efficiency. Technologies such as Synchronous Reluctance Motors (SynRM) and Permanent Magnet Synchronous Motors (PMSM) have emerged as viable alternatives to achieve higher levels of efficiency. However, PMSMs require materials different from those previously produced motors, necessitating an assessment of the impacts of new electric motor technologies' production and disposal phases.

Therefore, this study is significant in systematizing knowledge on the environmental impacts of the primary technologies of electric motors, aiding decision-makers concerning the purchase of electric motors. This goes beyond just focusing on efficiency, which is linked to the economic costs over the life cycle of the equipment, but also includes the environmental costs of the technology to be chosen.

The first step consists of the introduction (Section 1.0), contextualizing the problem and the questions that motivated this study. The next step is the methodology (Section 2.0), where the study search strategies are presented, and the criteria for including or discarding publications. Some fundamental concepts regarding LCA in Electric Motors are explained in the overview section (Section 3.0). The fourth step is the results and discussion (Section 4.0) based on the seven questions. Furthermore, based on the results, the study identified research gaps related to environmental impacts (Section 5.0). Finally, the last step includes the research conclusions (Section 6.0).

2. Methodology

Choosing a tool that would provide access to relevant publications through created keywords was required. Among the several tools available, Scopus was chosen as it offers excellent access to curated abstracts and citation databases linked to a wide range of academic literature (Falagas et al., 2008, Adriaanse and Rensleigh, 2013, Bakkalbasi et al., 2006, Harzing and Alakangas, 2016, Martín-Martí et al., 2021, Martín-Martí et al., 2018). Applying the best combinations of keywords to retrieve publications directly linked to the subject of interest (Mergel et al., 2015) is one of the essential stages in the Systematic Literature Review (SLR). Thus, the study applied the iterative methodology proposed by Marcos-Pablos and Garcia-Penalvo (Marcos-Pablos and García-Peñalvo, 2018).

The keyword "*i) Electric Motor*" was used because it is the central element of the analysis. The keyword "*ii) Life Cycle*" was also used because it is generic and can incorporate the four significant derivations: "*1 - Life Cycle Analysis*", "*2 - Life Cycle Assessment*", "*3 - Life Cycle Impact*", and "*4 - Life Cycle Costing*". Also, in the case of electrical equipment, "*ii) Ecodesign*" was widely used as a specific and simplified LCA methodology and, for this reason, was incorporated into the search string as an alternative to "*Life Cycle.*" Thereby ensuring a broad and general search, making it possible to find the most significant number of linked publications. Consequently, the study engages the following search string:

(TITLE-ABS-KEY(electric AND motors) AND TITLE-ABS-KEY (ecodesign) OR TITLE-ABS-KEY(life AND cycle)).

The search string considers published articles dated up to December 2022; therefore, the study did not involve related literature released after this date. Characteristically, in SLR, the research should report the methods and results in sufficient detail to allow users to assess the reliability and applicability of the research findings, from choosing keywords to applying criteria for the exclusion of publications to the process of systematization.

Several methods and checklists are available to perform a systematic search for publications (Page et al., 2021a). Among those available, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) stands out due to the high number of SLR research publications performed using this methodology and the constant process of improvement performed by systematic review methodologists and editors of SLR journals (Page et al., 2021a).

The PRISMA Statement offers a complete guide to performing an SLR. It was initially developed focusing on systematic reviews and meta-analyses in health care. However, its detailed criteria have been applied in various other areas (Sarkis-Onofre et al., 2021). The PRISMA

Statement consists of a 27-item checklist for conducting an SLR and a flowchart outlining the flow of information through the different stages of a systematic review. The PRISMA checklist suggests qualitative or quantitative synthesis procedures for the publications included.

The flowchart maps out the number of publications identified, included, and excluded and the reasons for exclusions. Thus, the PRISMA Statement aims to establish mechanisms for the SLR to be robust and reproducible, seeking to minimize bias (Page et al., 2021b), (Rethlefsen et al., 2021). Due to the arguments above, PRISMA was the preferred methodology for this study. Fig. 1 shows the six stages of this study, where the first five stages explain the method, and the sixth stage is the results and discussions.

1. The first stage (Fig. 1) defines the keywords to create the search string.
2. In the second stage, the search string was applied to the Scopus database.
3. The third stage involved implementing the protocol to identify and screen publications based on the applied search string, resulting in the publications included in this study.
4. In stage four, the research involves the collection of references and citations (up to December 2022 on Google Scholar) from publications identified in stage three for further analysis in stage five.
5. In the fifth stage, the protocol used in stage three was reapplied to the results from stage four. (Stages 4 and 5 collectively constitute a technique known as "Snowballing in SLR," as described by C. Wohlin et al. (Wohlin, 2014), (Wohlin et al., 2022))
6. The sixth stage of this study consisted of an exhaustive analysis of the publications included in the third and fifth stages to answer the questions (RQ1-RQ7).

Fig. 2 is a detailed visualization of the protocol used in stages 3 and 5 to select the included publications.

Some observations can be derived from the application of the protocol as expressed in Fig. 2.

i. Early publications on the Life Cycle Assessment (LCA) of electric motors focused solely on the economic costs associated with electrical energy consumption during the operational phase (use phase only) and did not consider the complete life cycle (from production to disposal or recycling) of electric motors involving environmental impacts. For this reason, they were excluded from this study (Ganapathy, 1983, Andrade and Pontes, 2017, Canova et al., 2001, Johnson, 1979, Hamer, 1997);
ii. Electric motors for special applications have not been included in this SLR, as the objective of the research is to assess the LCA for general-purpose electric motor technologies applied in the drive of industrial loads (Ma and Kim, 2016, Cicconi et al., 2014, Debusschere et al., 2009, Debusschere et al., 2010);
iii. Many publications related to electric motor vehicles (electric mobility) were found during data collection. The available literature on LCA is extensive, enabling the construction of literature review publications to synthesize the findings (Tintelecan et al., 2020-, Del Pero et al., 2020, Schillingmann et al., 2021, Xia and Li, 2022). However, an SLR focusing on the LCA of electric motors for industrial applications (stationary motive force) was not found, demonstrating its novelty.
iv. Some publications identified contain all the keywords included in the search; however, they do not constitute complete LCAs. They only analyze parts of an LCA, such as the production of the electric motor, or disposal. For this reason, they were excluded from this study (de Almeida et al., 2017, Autsou et al., 2018, Boughamni et al., 2013 Ayyappan et al., 2019 Falkner, 1999, Kallaste et al., 2014 Laitinen et al., 2013, Vaimann et al., 2013, Vaimann et al., 2015, Mueller and Besant, 1999, Nguyen et al., 2017, Rassõlkin et al., 2018).

Table 1 shows the 20 publications included in this study.

3. Overview – LCA in electric motors

3.1. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) methodology, guided by the International Standards ISO 14040 and ISO 14044 (ISO - International Organization for Standardization, 2006), (ISO - International Organization for Standardization), adopts a multi-criteria, iterative approach comprising objective and scope definition, inventory analysis, impact assessment, and interpretation, to evaluate environmental impacts across a product's lifespan, including production, transportation, and usage phases (Fig. 3). This method can be adapted to assess specific lifecycle segments, such as cradle-to-grave, to focus on particular phase excluding the disposal phase or solely on the usage phase, respectively.

There are also ISO 14040-based programs specialized in performing LCA of specific equipment. The EROD platform, for example, consists of integrated software tools to support electric motor designers throughout the design process. It is composed of several interconnected systems and devices that generate different functionalities: i) Knowledge-Based

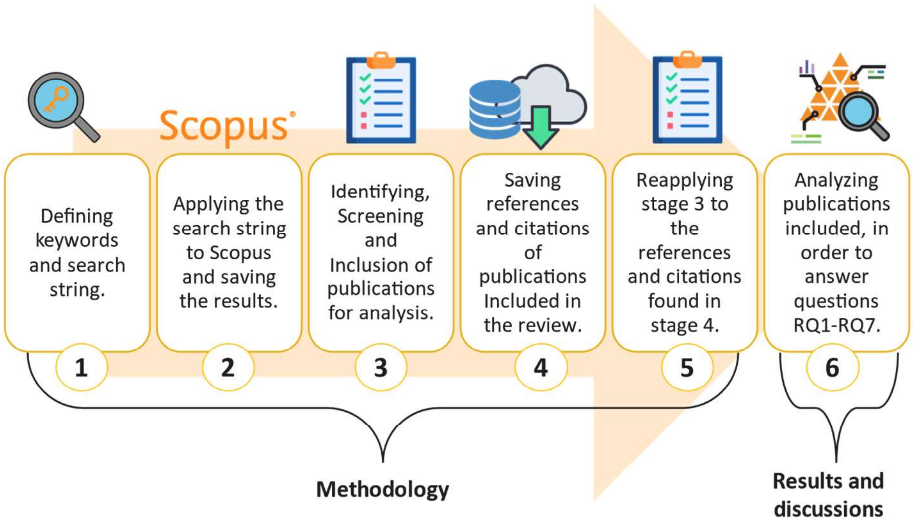

Fig. 1. Systematic Literature Review (SLR) stages.

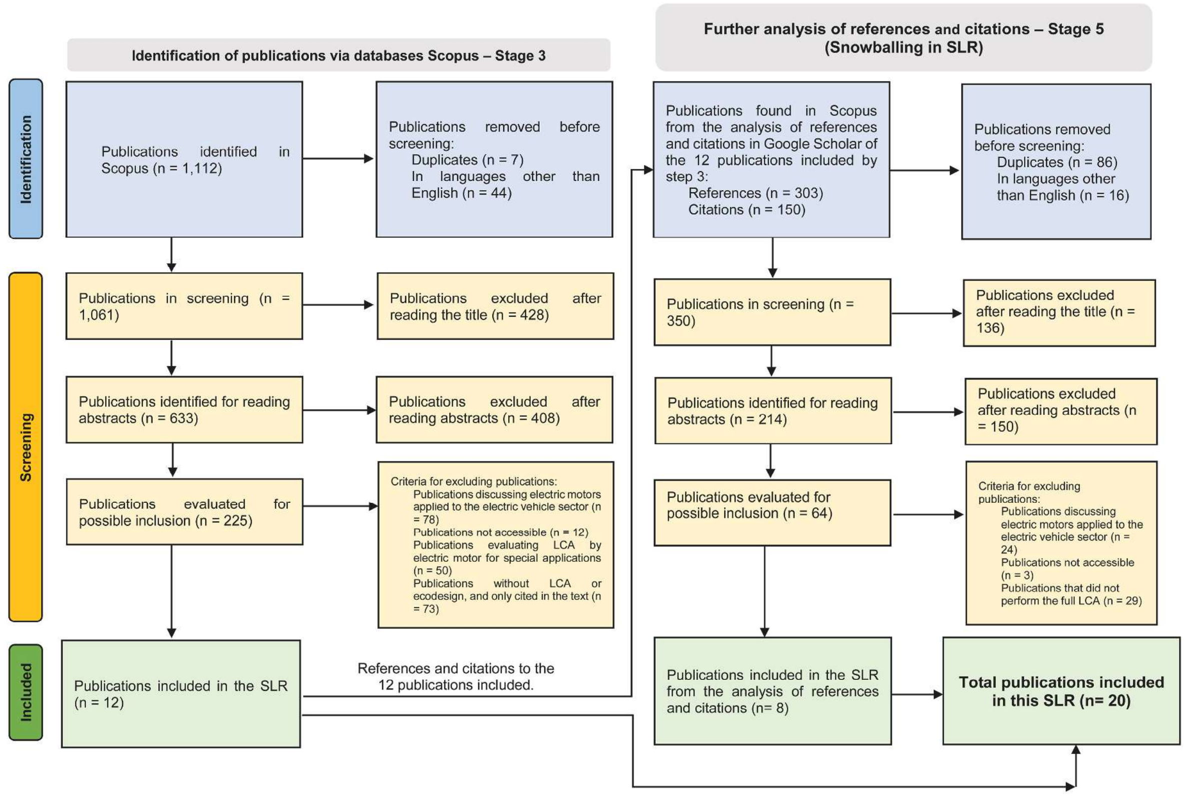

Fig. 2. Flowchart with the protocol applied for the selection of included publications.

System (KB); ii) Design For Energy Efficiency (DFEE) Module; iii) Life Cycle Assessment (LCA) Module; iv) Cost Estimation Module. Co-Design Module (Favi et al., 2012).

The impact assessment within the LCA module follows the methodology described by the ISO 14040 series. The EROD platform accesses a European Commission-certified open-source database (ELCD DB) and an impact calculator that performs the environmental impact assessment.

Another way of analyzing the life cycle, which is specific to products that consume electrical energy, is the Ecodesign Methodology for Energy Using Products (MEEUp). The base methodology stands on the use of a particular LCA spreadsheet that, applied to a set of data, comprises the amount of each material used in the manufacture of the electric motor and the electrical energy that the electric motor consumes during the lifetime phase (according to its power and efficiency). The MEEUp methodology comprises eight application steps, as shown in Fig. 4. MEEUp emerged due to the Energy Using Products (EuP) Directive 2005/32/EC of the European Parliament and the Council (Nissen et al., 2007).

Both ISO and MEEUp methodologies measure environmental impacts according to selected impact categories. The quantitive comparison between different environmental impact types is the primary goal of any LCA. Table 2 shows some of the typical LCA categories. It is worth mentioning that the list of impacts is not exhausted in Table 2, as there are process-specific indicators (Guinée, 2002); therefore, depending on the processing steps and materials used, they generate unique environmental damages.

3.2. Electric motor life cycle

The “birth” of an electric motor involves manufacturing, where energy transforms essential raw materials like copper, aluminum, and iron into the final product based on predetermined assembly conditions. Disposal at the end of its life includes recycling, burial, or incineration, with the potential for limited reuse of components such as copper and aluminum while considering the environmental impacts of waste disposal (Antonacci et al., 2023). The equipment’s Life Cycle Assessment (LCA) must account for the impacts of using materials and emissions during production, evaluating effects across selected environmental categories. Electric motors, which convert electrical into mechanical energy, significantly impact electricity consumption’s environmental footprint, depending on the primary energy sources used for electricity production. The use phase is typically the most impactful, with the impact level varying by the energy matrix’s renewability (Varun et al., 2009).

Fig. 5 summarizes the electric motor’s LCA, highlighting the production (“Cradle”), use, and end-of-life (“Grave”) phases, including material transportation impacts. The production phase impacts stem from both the material production and the manufacturing processes, while the end-of-life phase addresses the disposal of non-reused parts.

4. Results and discussion

Based on the knowledge of the primary LCA methodologies and their phases, the study tries to answer the proposed research questions (RQ1-RQ7) in the following sections in the light of the found bibliography.

4.1. RQ1. Are there existing Life Cycle Analyses (LCA) on industrial electric motors?

By identifying twenty publications within Table 1, LCA publications have already been carried out for electric motors in the industry. However, compared to other sectors, the number of publications found is low regarding electric motors being the primary electricity consumers. This finding demonstrates a lack of research in this area of knowledge.

The authors of the twenty researched publications are from fourteen European countries, as shown in Fig. 6. One of the reasons Europe concentrates on publications is that the Methodology MEEUp emerged as a consequence of the Energy-Using Products Directive (EuP) 2005/

Table 1
Publications included in the study[b].

References	Title of the publication	Date of publication	Number of references cited	Number of citations received until December 2022
(Deprez et al. (2006))	*Ecodesign toolbox for electrical equipment*	2006 (Jun)	17	2
(de Almeida AT et al. (2008))	*EuP Lot 11 Motors*[a]	2008 (Feb)	38	88
(De Almeida et al. (2008))	*Electric motor standards, ecodesign and global market transformation*	2008 (Aug)	12	36
(Martínez et al. (2008))	*Environmental and life cycle cost analysis of a switched reluctance motor*[a]	2009 (Mar)	5	29
(Andrada et al. (2009))	*Comparison of Environmental and Life Cycle Impact of a Switched Reluctance Motor Drive and Inverter-Fed Induction Motor Drives*[a]	2009 (Apr)	8	3
(Ferreira et al. (2011))	*Ecoanalysis of Variable-Speed Drives for Flow Regulation in Pumping Systems*[a]	2011 (Jun)	20	96
(Torrent et al. (2012a))	*Life cycle analysis on the design of induction motors*	2011 (Sep)	18	18
(Boughanmi et al. (2011))	*Comparative environmental assessment of the electrical machines winding using the Life cycle assessment*[a]	2011 (Nov)	2	1
(Boughanmi et al. (2012a))	*Life cycle assessment of a three-phase electrical machine in continuous operation*	2012 (May)	27	18
(Andrada et al. (2012))	*Environmental and life cycle cost analysis of one switched reluctance motor drive and two inverter-fed induction motor drives*	2012 (Aug)	14	23
(Torrent et al. (2012b))	*Assessing the environmental impact of induction motors using manufacturer's data and life cycle analysis*	2012 (Sep)	15	6
(Boughanmi et al. (2012b))	*Contribution of LCA approach to the choice of rotating electrical machines for environmental impact minimization*	2012 (Nov)	17	4
(Favi et al. (2012))	*Innovative software platform for eco-design of efficient electric motors*	2012 (Dez)	34	21
(de Almeida et al. (2014))	*EuP Lot 30: Electric Motors and Drives*[a]	2014 (Jun)	38	13
(Orlova et al. (2016))	*Lifecycle Analysis of Different Motors from the Standpoint of Environmental Impact*[a]	2016 (Dec)	10	20
(Rassolkin et al. (2016))	*Environmental and life cycle cost analysis of a synchronous reluctance machine*[a]	2016 (Dec)	12	6
(Auer and Meincke (2018))	*Comparative life cycle assessment of electric motors with different efficiency classes: a deep dive into the trade-offs between the life cycle stages in ecodesign context*	2017 (Aug)	49	3
(Cassoret et al. (2019))	*Comparative life cycle assessment of induction machines made with copper-cage or aluminum-cage rotors*	2019 (Feb)	23	3
(Jocanovic et al. (2019))	*LCA/LCC Model for Evaluation of Pump Units in Water Distribution Systems*	2019 (Sep)	26	4
(Rassõlkin et al. (2020))	*Life cycle analysis of electrical motor-drive system based on electrical machine type*	2020 (Jan)	51	12

[a] Publication included in the study from stage 5. Stage 5 was performed by analyzing the 303 references and 150 citations of the 12 publications in stage 3.
[b] The 150 citations for the 12 included publications were identified through Google Scholar.

32/EC of the European Parliament. Therefore, the greater interest of the European Union countries is evident in applying the methodology.

Given the global interest in the life cycle impacts of electric motors, attributed to the modern society's reliance on these devices, it would be reasonable to anticipate the existence of publications conducted on continents beyond Europe. Countries such as China and the United States, for instance, rank among the top producers of electric motors (Golini et al., 2016).

As mentioned in the previous section, the first time a LCA was conducted for electrical appliances was in 1968. However, in the case of electric motors, the first publications dated 2006, 38 years later, as shown in Fig. 7.

Fig. 7 presents all the twenty chosen publications based on the publication year. It can be observed that 2012 was the year with the highest number of publications in the literature. The number of publications increased in 2012 because, in January 2011, IE2 efficiency electric motors became compulsory within the European Union, China, and Turkey (Energy Agency et al., 2011), (de Souza et al., 2021). So, most of the publications in 2012 used LCA to compare IE1 induction motors with IE2 induction motors, both with the same pole number and power.

Discussion on the efficiency classes was present in all evaluated publications. Electric motors are internationally classified with the code

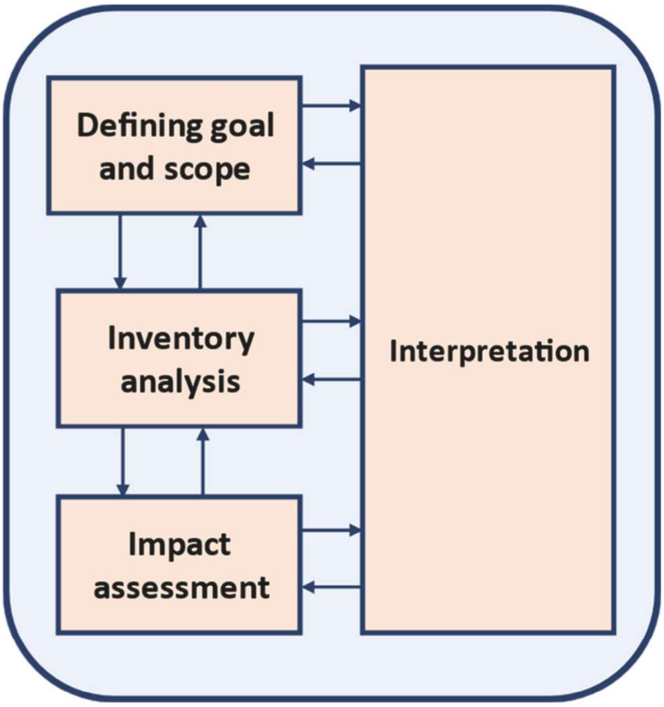

Fig. 3. LCA's structure according to ISO 14040. Source: (ISO - International Organization for Standardization, 2006), (ISO - International Organization for Standardization).

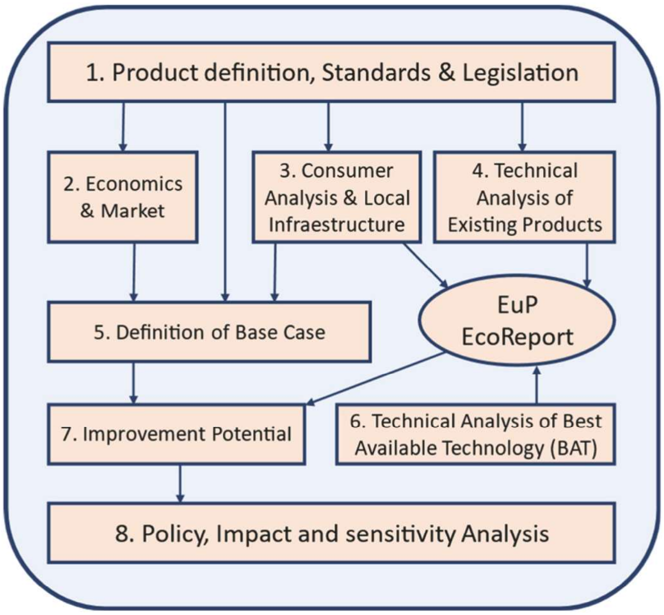

Fig. 4. Methodology for ecodesign of energy-using products (EuP). Source: (René and Elburg, 2006).

Table 2
Main impact categories/indicators considered in a typical LCA. Source: (Guinée, 2002).

Impact category	Unit[1]	Description
Depletion of abiotic resources	kg	"Abiotic resources" are natural resources (including energy resources) such as: • Mineral and metals • Fossil fuel. • Water.
Land competition	m^2.yr (land use)	Loss of land as a resource, in the sense of being temporarily unavailable.
Climate change	kg (carbon dioxide eq)	Atmosphere warming due to heat radiation absorption, is known as the "greenhouse effect".
Stratospheric Ozone Depletion	kg (CFC-11 eq)	Thinning of the stratospheric ozone layer as a result of anthropogenic emissions
Human toxicity	kg (1,4-dichlorobenzene eq)	Impacts on human health of toxic substances present in the environment
Ecotoxicity	kg (1,4-dichlorobenzene eq)	Class of impacts of toxic substances on one or more of the following ecosystems: • Freshwater aquatic • Marine aquatic • Terrestrial • Freshwater sediment • Marine sediment
Photo-oxidant formation/ Emission of Volatile Organic Compounds (VOC)	kg (ethylene eq)	Reactive chemical compounds such as ozone (below the stratosphere) are formed by the action of sunlight on certain primary air pollutants.
Acidification	kg (SO_2 eq)	Formation of acidifying pollutants.
Eutrophication	kg (PO_4 eq)	Impacts of excessively high environmental levels of macronutrients, such as nitrogen (N) and phosphorus (P).
Waste heat	MJ (heat)	Increase temperatures on a local scale.
Odor	m^3 (air/water)	An increase in a given concentration of odorous substances is experienced as unpleasant. It encompasses two categories: • Malodorous air • Malodorous water
Noise	Pa^2.s (sound)	Human and ecosystem health impacts due to exposure of sound.
Impacts of ionizing radiation	yr	Damage to human health and ecosystems linked to the emissions of radionuclides.
Depletion of abiotic resources – minerals and metals	kg substance-eq	Substance-specific, indicator of the depletion of natural non-fossil resources.
Depletion of abiotic resources – fossil fuels	MJ (heat)	Indicator of the depletion of natural fossil fuel resources.

IE according to the International Electrotechnical Commission (IEC) 60,034-30-1 standard (IEC 60034-31, 2021). This classification has a wide acceptance as a global pattern, making efficiency classes comparable all around the World. The norm defines the efficiency class from EI1 to IE4, wherein IE1 is the less efficient, and IE4 is the most efficient.

Similarly, the USA establishes the IE1 to IE4 as performance classes, which are Standard, High efficiency, Premium efficiency, and Super-Premium efficiency, according to a NEMA (National Electrical Manufacturers Association) standard (Association, 2016). No norm has yet defined the new class IE5 (Ultra-Premium efficiency). However, it is expected that a new norm will define it in the future, as there are already some motors with such high efficiency available in the market. The target for IE5 electric motors is to reduce energy loss by about 20% when operated at the rated power, compared to IE4 class (De Almeida et al., 2019).

In this context, LCA publications gain relevance because in the case of the most widely used motor technology in the market (3-phase Squirrel Cage Induction Motor – SCIM), each energy efficiency increment since 2020 represented an increase in the material mass used in the motor (de Souza et al., 2022). So, LCA publications made it possible to

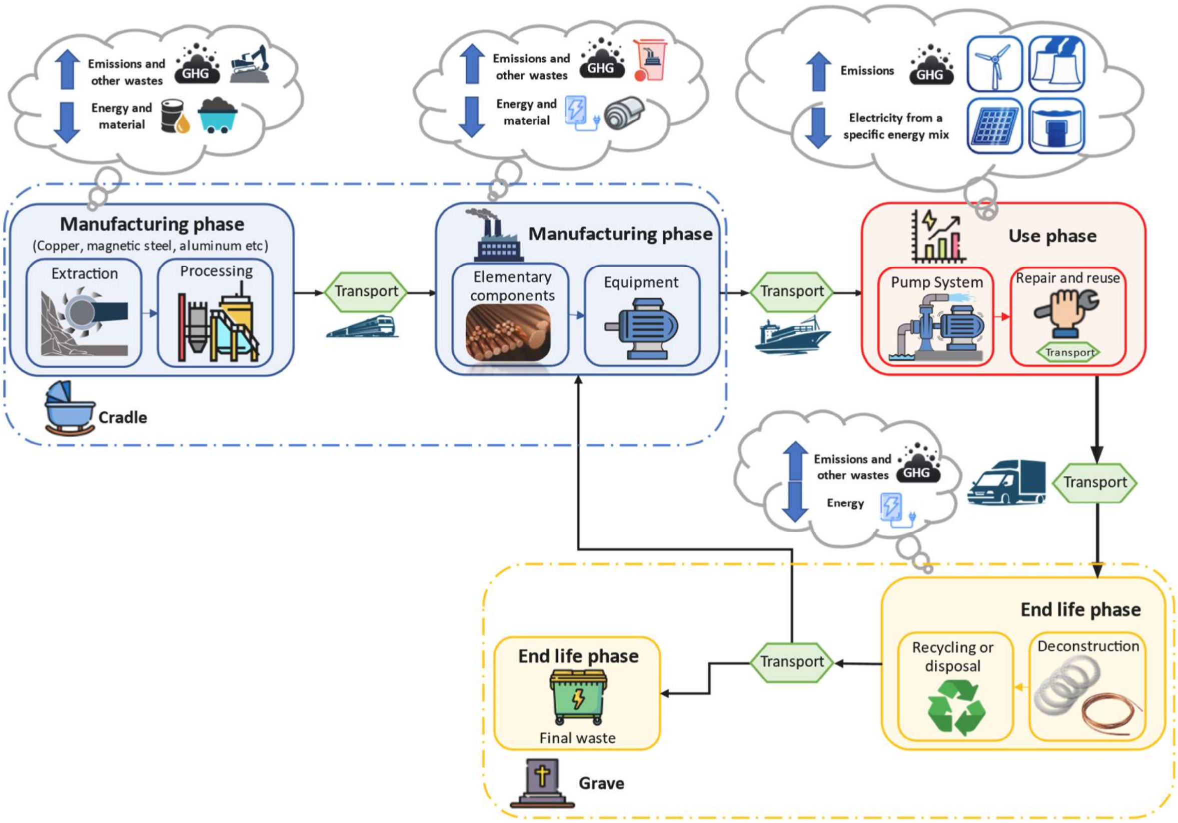

Fig. 5. Life Cycle phase of a typical electric motor.

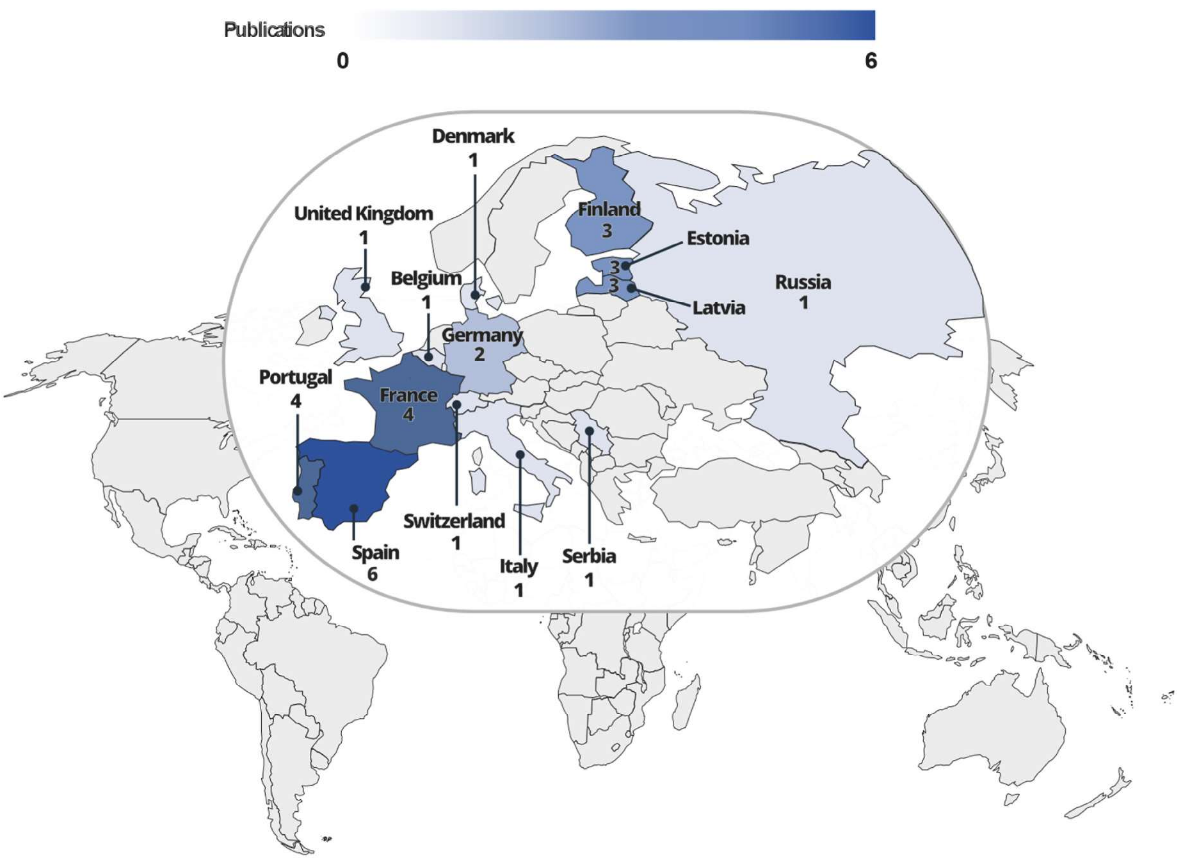

Fig. 6. Origin of electric motors LCA publications around the World.

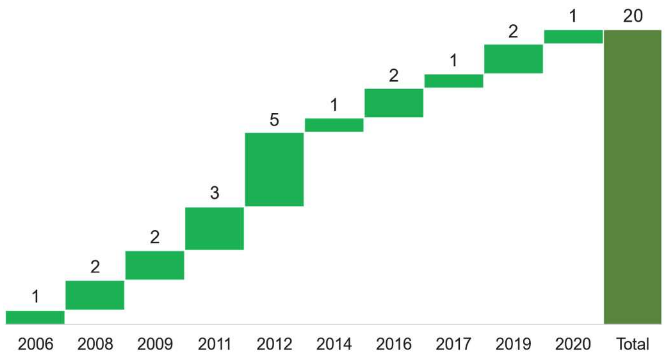

Fig. 7. Number of electric motors LCA publications per year and the accumulated.

measure environmental impacts due to the rise in raw materials that constituted the most efficient motor drive.

4.2. RQ2. What are the methods engaged in the analysis?

Different methods exist for carrying out an LCA, the most well-known, as stated before, being; *i)* LCA based on the International Standards ISO 14040 and ISO 14044 and *ii)* Ecodesign Methodology for Energy Using Products (MEEUp). Knowing the methodology, the software, and the materials and emissions inventory database used is essential to understand the research reliability and limitations. Table 3 highlights the different tools used in each of the twenty publications.

Regarding the methodology, publications can be divided into two groups. Eight (40%) publications used LCA tools based on ISO 14040 and ISO 14044, and the remaining twelve (60%) publications applied the Ecodesign Methodology for Energy Using Products (MEEUp). Among publications based on ISO methodology, SimaPro is the most popular, utilized in five publications. GaBi is the second most used, appearing twice, followed by EROD, which was used once.

From the study of these publications, some differences were observed between the LCA methods via ISO 14040 and ISO 14044, with the Ecodesign of Energy-Using Products Methodology (MEEUp). MEEUp is a methodology focused on electrical equipment that was developed to determine whether and to what extent a product meets the criteria stipulated in the Directive on the Ecodesign of Energy-Using Products (EuP 2005/32/EC). For this reason, simplified inputs and outputs are featured, making it easy to apply. MEEUp does not require a specialized

Table 3
Identification of LCA tools used.

References	MEEUp	GaBi	SimaPro	EROD
(Deprez et al. (2006))		X		
(de Almeida AT et al. (2008))	X			
(De Almeida et al. (2008))	X			
(Martínez et al. (2008))	X			
(Andrada et al. (2009))	X			
(Ferreira et al. (2011))	X			
(Torrent et al. (2012a))	X			
(Boughanmi et al. (2011))			X	
(Boughanmi et al. (2012a))			X	
(Andrada et al. (2012))	X			
(Torrent et al. (2012b))			X	
(Boughanmi et al. (2012b))				X
(Favi et al. (2012))	X			
(de Almeida et al. (2014))	X			
(Orlova et al. (2016))	X			
(Rassolkin et al. (2016))		X		
(Auer and Meincke (2018))			X	
(Cassoret et al. (2019))			X	
(Jocanovic et al. (2019))	X			
(Rassõlkin et al. (2020))	X			
Percentage	**60%**	**10%**	**25%**	**5%**

practitioner, which facilitates the dissemination and application of this LCA methodology.

As for ISO-based publications, instead of a fixed “black box” tool within which researchers input their data, LCA requires the definition of prior parameters that will modify the outputs of the adopted tools. These parameters include analysis boundary, impact categories, and functional unit. Therefore, ISO-based publications need professionals with more practice in life cycle analysis. On the contrary, the high degree of customization could make ISO-based tools less adopted by professionals with less experience in the field.

4.3. RQ3. What kind of electric motor technologies have been analyzed?

It is necessary to provide data on equipment and its use to carry out the LCA on electric motors. Among these, the following stand out.

1) **Technology:** The type of technology will define the type of material used and is essential for the decision maker in the evaluation phase of the LCA result to choose the least impacting technology.
2) **Rated power:** The magnitude of the power is fundamental to know the size of the electric motor under evaluation. The evaluation of small electric motors cannot be generalized to large equipment, as the percentage of each material used does not increase linearly.
3) **Efficiency:** The overall efficiency of the electric motor under analysis is fundamental, especially in the usage phase.
4) **Loading:** Electric motors only a few times operate at 100% of their nominal load. Since different loading values correspond to other efficiencies, knowing the load at which motors operate is crucial for accurately measuring the impacts during motor usage.
5) **Annual use:** Knowing the number of hours that motor systems operate in a year affects their energy consumption, ultimately influencing their environmental impacts. Additionally, motor drives that operate longer hours in a year tend to depreciate faster over time.
6) **Lifetime:** Electric motors have an estimated service life. This lifetime usually depends on the power and must be informed in the LCA processing.
7) **Poles number:** The number of poles of an electric motor determines its speed. The number of poles also directly influences the electric motors’ material.

Based on the twenty publications under study, Table 4 identifies the type of motor technologies and the above seven parameters. An NA is adopted when some information is unavailable in the publication analyses.

Table 4 suggests the extension of the study universe concerning LCA in electric motors. A considerable diversity of analysis, technologies, and scenarios is noticed. Some publications focus on comparing different loads to which motors are exposed. Other publications focus on the different efficiency between motors of the same technology and the differences between different technologies.

Most of the LCA considered the traditional Squirrel Cage Induction Motors (SCIM), especially comparing levels IE1 to IE3. Some publications have also compared Synchronous Reluctance Motors (SynRM), Permanent Magnet Synchronous Reluctance Motors (PMSynRM), and Switched Reluctance Motors (SRM) technologies with efficiency levels compatible with IE4. Three publications no longer focused exclusively on motors but include control devices such as inverters and soft starters.

Most publications have focused on the electric motor, not the motor drive. With the massive use of speed control technologies for SCIMs via VSD and drivers for SynRM, PMSynRM, and SRM drives, the next LCA should include the entire drive in the bill of materials to analyze environmental impacts.

Table 4 reveals that several analyses did not inform essential characteristics of any life cycle assessment, such as the useful life of the equipment under investigation, the number of poles, the annual hours of

Table 4
Identification of motor technology, type, and operational parameters.

References	Motor technology, rated power, and efficiency	Loading	Annual use (h)	Lifetime (years)	Poles Number
(Deprez et al. (2006))	Three 3-phase Squirrel Cage Induction Motors (SCIM): • SCIM – 1.5 kW; Efficiency – 77.4% • SCIM – 1.5 kW; Efficiency – 80.7% • SCIM – 1.5 kW; Efficiency – 83.8%	33%	3000	10	NA
(de Almeida AT et al. (2008))	Six 3-phase SCIM with three different rated powers: • SCIM IE1 – 1.1 kW; Efficiency – 75.1% • SCIM IE1 – 11 kW; Efficiency – 87.6% • SCIM IE1 – 110 kW, Efficiency – 93.3% • SCIM IE2 – 1.1 kW; Efficiency – 81.4% • SCIM IE2 – 11 kW; Efficiency – 89.8% • SCIM IE2 – 110 kW; Efficiency – 94.5% • SCIM IE3 – 1.1 kW; Efficiency – 84.1% • SCIM IE3 – 11 kW; Efficiency – 91.4% • SCIM IE3 – 110 kW; Efficiency – 95.4%	60%; 100%;	1st Analyze: 2250 h (1.1 kW); 3000 h (11 kW); 6000 h (110 kW). 2nd Analyze (same for all rated power): 2000; 4000; 6000; 8000 h.	12 (1,1 kW); 15 (11 kW); 20 (110 kW)	4
	Permanent Magnet Synchronous Motors (PMSM): 1.1 kW; Efficiency – 88.75%	NA	2000; 4000; 6000; 8000.	12	4
	The same six electric motors from the first analysis, including VSDs for speed control	50%: 25% of the time; 75%: 50% of time; 100%: 25% of time.	3000	10	NA
(De Almeida et al. (2008))	Six 3-phase Squirrel Cage Induction Motors (SCIM): • SCIM IE1 – 1.1 kW; Efficiency – 82.7% (100% load) • SCIM IE1 – 11 kW; Efficiency – 90.2% (100% load) • SCIM IE1 – 110 kW; Efficiency – 94.5% (100% load) • SCIM IE2 – 1.1 kW; Efficiency – 85.3% (100% load) • SCIM IE2 – 11 kW; Efficiency – 91.7% (100% load) • SCIM IE2 – 110 kW; Efficiency – 95.4% (100% load) • SCIM IE3 – 1.1 kW; Efficiency – 82.7% (100% load) • SCIM IE3 – 11 kW; Efficiency – 90.2% (100% load) • SCIM IE3 – 110 kW; Efficiency – 94.5% (100% load)	60 %	4000	12 (1,1 kW); 15 (11 kW); 20 (110 kW)	NA
(Martínez et al. (2008))	One Switched Reluctance Motor (SRM): SRM – 1.5 kW; Efficiency – 82.6%;	NA	NA	12	NA, Speed equivalent to 4 poles.
(Andrada et al. (2009))	Three motors from two different technologies (SRM - Switched Reluctance Motor and SCIM): • SRM – 1.5 kW; Efficiency – 83.6% (global) • SCIM IE1 – 1.5 kW; Efficiency – 75.1% (global) • SCIM IE2 – 1.5 kW; Efficiency – 77.5% (global)	60%	4000	12	4
(Ferreira et al. (2011))	Three 3-phase Squirrel Cage Induction Motors (SCIM) in two scenarios: *i)* constant speed, e *ii)* variable speed using VSD: • SCIM IE1 – 1.1 kW; Efficiency – 75% • SCIM IE1 – 11 kW; Efficiency – 87.6% • SCIM IE1 – 110 kW; Efficiency – 93.3%	Three load profiles for the pumping system: 50%, 75%, and 100%;	500; 1000; 2000; 4000 (base case); 6000; 8000.	12 (1.1 kW); 15 (11 kW); 20 (110 kW)	4
(Torrent et al. (2012a))	Three 3-phase Squirrel Cage Induction Motors (SCIM): • SCIM IE1 – 1.5 kW; Efficiency – 78.1% • SCIM IE2 – 1.5 kW; Efficiency – 82.0%	100%	4000	12	4
(Boughanmi et al. (2011))	One 3-phase SCIM – 10 kW, Efficiency – NA	NA	NA	NA	NA
(Boughanmi et al. (2012a))	One 3-phase SCIM – 10 kW, Efficiency – NA	NA	2000	10	4
(Andrada et al. (2012))	Three motors from two different technologies (SRM - Switched Reluctance Motor and SCIM - Squirrel Cage Induction Motor): • SRM – 1.5 kW; Efficiency – 83.8% • SCIM IE1 – 1.5 kW; Efficiency – 82.0% • SCIM IE2 – 1.5 kW; Efficiency – 82.8%	50%; 75%; 100%;	1000; 2000; 4000	12	4
(Torrent et al. (2012b))	Six 3-phase SCIM: • SCIM IE1 – 22 kW; Efficiency - According to load. • SCIM IE1 – 30 kW; Efficiency - According to load. • SCIM IE1 – 37 kW; Efficiency - According to load. • SCIM IE2 – 22 kW; Efficiency - According to load. • SCIM IE2 – 30 kW; Efficiency – According to load. • SCIM IE2 – 37 kW; Efficiency – According to load.	1st Analyze: 22% 2nd Analyze: Loading correspondent to multiple mechanical power ranging from 0.75 to 370 kW	4000	12	4
(Boughanmi et al. (2012b))	Three 3-phase SCIM: • SCIM IE1 – 9 kW; Efficiency – 86% (Loading: 125%). • SCIM IE1 – 11 kW, Efficiency – 87.7% (Loading: 100%). • SCIM IE1 – 15 kW, Efficiency – 89.3% (Loading: 75%).	NA	2.000	10	4
(Favi et al. (2012))	Five motors from five different technologies: • One-phase SCIM. • Three-phase SCIM. • Shaded poles.	NA	NA	NA	NA

(*continued on next page*)

Table 4 (*continued*)

References	Motor technology, rated power, and efficiency	Loading	Annual use (h)	Lifetime (years)	Poles Number
	• Brushless Permanent Magnetic. • Synchronous Reluctance Motor (SynRM).				
(de Almeida et al. (2014))	Induction Motors and components: • Small induction motor – 1-phase IE1 0.37 kW • Small induction motor – 3-phase IE1 0.37 kW • Medium induction motor (S) – 3-phase IE2 1.1 kW • Medium induction motor (M) – 3-phase IE2 11 kW • Medium induction motor (L) – 3-phase IE2 110 kW • Large induction motor - LV IE2 550 kW • Large induction motor - MV IE2 550 kW • VSD - Very Small 0.37 kW • VSD - Small 1.1 kW • VSD - Medium 11 kW • VSD - Large 110 kW • VSD - Very Large 550 kW • Soft Starter - Small 1.1 kW • Soft Starter - Medium 11 kW • Soft Starter - Large 110 kW • Submersible borehole motor - Small 2.2 kW • Submersible borehole motor - Large 37 kW • Motor + VSD - Very Small 0.37 kW • Motor + VSD - Small 1.1 kW • Motor + VSD - Medium 11 kW • Motor + VSD - Large 110 kW • Motor + VSD - Very Large 550 kW	25%: 20% of time; 50%: 30% of time, 75%: 30% of time; 100%: 20% of time.	400; 6000	6: small motors, VSD very small and small; 10: small borehole motor; 11: S, M, VSD medium and large; 15: large borehole motor; 17: L, LV, VSD very large; 21: MV	NA
(Orlova et al. (2016))	Three motors from three different technologies: (SynRM, PMSynRM - Permanent Magnet Synchronous Reluctance Motor; SCIM) • SynRM – 10 kW; Efficiency – 70%. • PMSynRM – 10 kW; Efficiency – 90%. • SCIM – 10 kW; Efficiency – 87.6%.	NA	3000	15	NA
(Rassolkin et al. (2016))	One SynRM – 11 kW; Efficiency – NA.	NA	3000	12	4
(Auer and Meincke (2018))	Three 3-phase SCIM: • SCIM IE2 – 110 kW; Efficiency – 94% (100% load). • SCIM IE3 – 110 kW; Efficiency – 95.5% (100% load). • SCIM IE4 – 110 kW; Efficiency – 96.4% (100% load).	1st Analyze: 100%: 50% of time; 75%: 25% of time; 50%: 25% of time 2nd Analyze: 100%: 8,3% of time; 75%: 50% of time; 50%: 8,3% of time	1st Analyze: 8760 2nd Analyze: 5,7812	20	4
(Cassoret et al. (2019))	Four 3-phase SCIM with two different cage rotor materials: • SCIM IE2 Copper Cage Rotor – 3 kW; Efficiency – 85.5%. • SCIM IE2 Aluminum Cage Rotor – 3 kW; Efficiency – 85.5%. • SCIM IE2 Copper Cage Rotor – 10 kW; Efficiency – 90.5%. • SCIM IE2 Aluminum Cage Rotor – 10 kW; Efficiency – 89.2%.	NA	2000; 20,000	NA	NA
(Jocanovic et al. (2019))	Four pumping sets with the same configuration, including: • Electric motor (SCIM – 315 kW; Efficiency – 96.3%). • Hydraulic pump. • VSD.	NA	4478	40	NA
(Rassõlkin et al. (2020))	Three motors from three different technologies: (SynRM -Synchronous Reluctance Motor; PMSynRM - Permanent Magnet Synchronous Reluctance Motor; SCIM - Squirrel Cage Induction Motor): • SynRM – 10.5 kW; Efficiency – 89.2% • PMSynRM – 10.5 kW; Efficiency – 92.3% • SCIM – 10.5 kW; Efficiency – 88.5%	95%	3000	15	4

operation, etc. Also, some publications could have provided the power and efficiency of the equipment analyzed. Most publications show the efficiency of electric motors under research but do not refer to which load corresponds to the referred efficiency.

Six publications (30%) did not state the number of electric motor poles under available analysis. Specifying the number of poles is paramount because, in addition to influencing efficiency, it also controls the materials used and allows the decision-makers to make necessary comparisons. It is observed observe that the publications focused on analyzing 4-pole electric motors, which is justified since more than half of the electric motors marketed are 4-pole.

Four publications have not informed the lifetime of the electric motor under analysis. When this information is available, informed lifetimes ranging from 3 to 4 thousand hours of annual use are observed. Some publications sought to study motors in more real conditions with variable usage scenarios. Furthermore, considering all data caveats identified in the 20 publications, 12 publications have some data unavailability, representing 60%. This evaluation only considers data on electric motors and their usage, which describes some of the input for an LCA.

Although some data omission, all publications, except C. Favi et al. (2012) (Favi et al., 2012), referred to the rated power of electric motors under analysis. Fig. 8 brings the number of times authors mention each rated power. Despite some authors referring to the same motor characteristics, Fig. 8 treats each motor in each publication as unique.

All publications sum up 73 motors, considering different technologies, efficiency, and power. Power values range from 0,37–315 kW. The top four most-cited rated power are 110 kW (16 from 73), 11 kW (15 from 73), and 1,1 kW (13 from 73). On the other hand, some rated powers are present in just one publication, such as 15 kW, 0,37 kW, and 315 kW.

4.4. RQ4. What were the environmental impact analysis categories?

Table 5 presents the environmental categories used in each publication of LCA for electric motors in industrial applications, according to the 20 publications under analysis. It quantifies the match between the references (columns) and categories (rows), expressed as a coverage percentage. This percentage indicates the proportion of references that address each category and the extent to which each reference covers the set of categories.

From Table 5, only Auer and Meincke (2018) assess categories at the endpoint level, which is related to the impact on human health. All articles include categories at midpoint level, which measure an environmental change that may ultimately have an effect on human health or biodiversity integrity. Also, it shows a consensus between the categories adopted in the publications that used the MEEUp method and whose analysis spreadsheet already consists of fourteen types of analysis divided into three groups. However, even using the same methodology, some articles excluded some categories, as in publications (Martínez et al., 2008), (Andrada et al., 2009), (Torrent et al., 2012a), (Torrent et al., 2012b) and (Jocanovic et al., 2019).

The publications analyzed feature various motors under different operating conditions and often from different technologies as outlined in Table 4. Consequently, comparing the numerical magnitudes of environmental impacts across different categories would not be appropriate. For this reason, Table 5 presents the categories of impacts analyzed in the publications, rather than the numerical values from each study.

As the most consolidated environmental category, all publications consider greenhouse gas emissions as an impact category. Acidification and eutrophication are the second most cited categories. Although the emission of gases with potential ozone depletion is a primary environmental concern worldwide, it is not displayed even by some publications based on the MEEUp methodology, as the results indicate that this category exhibits negligible values.

Most publications presented analyses that contemplate the typical categories in Table 2. There are, however, publications that cite categories not listed as heavy metal emissions to air and water, categories that are specific because they are LCA carried out for electronic equipment. Similarly, no publications covered some categories in Table 2, such as land competition.

It is observed as well that there is a difference in the level of category desegregation adopted per methodology. While some authors address freshwater toxicity in general, others using the MEEUp methodology refer to water toxicity in terms of heavy metals and Persistent Organic Pollutants (POP) emissions. The same occurs with human toxicity, which could consider heavy metals, POP, or Polycyclic Aromatic Hydrocarbons (PAH emissions). Depletion of fossil fuel and minerals could be split into the use of Energy and depletion of minerals.

As the MEEUp methodology comes from European environmental legislation, it considers that wastes are either landfilled or incinerated. However, it differs from the reality of almost all developing countries that do not use proper solid waste management procedures.

J. Fong (2008) (de Almeida AT et al., 2008) and A. T. de Almeida et al. (2014) (de Almeida et al., 2014) are publications based on the MEEUp methodology that adopted more environmental categories. Ionizing radiation and depletion of minerals are highlighted among categories not included by the MEEUp spreadsheet. The shortage of minerals is crucial when evaluating types of equipment with rare materials; this inclusion could show that some alternatives of low-rare-materials-equipment would fit better.

Comparing the bill of materials of motor technologies presented in each publication leads to Table 6. Composition materials include Electrical Steel (Elect steel); Other steel; Cast iron; Aluminum (Al); Copper (Cu); Packing material (Pack mat); Impregnation resin (Imp Res); Insulation material (Insul mat); Paint; Plastics; Electronics (Elect); and Permanent Magnets (PM). Publications deriving from the same source of electric motor bill of materials are included in the same line.

In some publications, the LCA lacked a detailed description and quantification of materials used in the production phase, focusing solely on the usage phase. For instance, publications such as those by A. T. De Almeida et al. (2008) (De Almeida et al., 2008), W. Boughanmi et al. (2011) (Ferreira et al., 2011), and C. Favi et al. (2012) (Favi et al., 2012) did not adequately report on the material composition during the motor production phase.

Some publications choose to synthesize the composition of the motors in electrical steel, other steels, aluminum, and copper, which is the case of W. Deprez et al. (2006) (Deprez et al., 2006), M. Torrent et al. (2012) (Torrent et al., 2012a), W. Boughanmi et al. (2011) (Boughanmi et al., 2011), M. Torrent (2012) (Torrent et al., 2012b) and A. Rassõlkin et al. (2020) (Rassõlkin et al., 2020). Excluding the two publications that omitted the electric motors' bill of materials, it is noticed that all remaining publications include Electric Steel, Aluminum, and Copper.

J. Auer and A. Meincke (2018) (Auer and Meincke, 2018) sums up other materials with a mass below 5 kg, which includes plastics, insulation, paint, rubber, brass, solder, and grease; according to the authors,

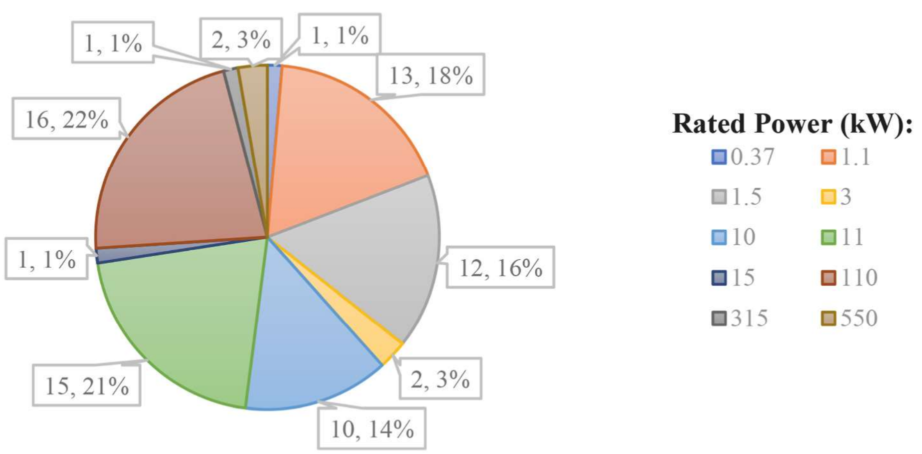

Fig. 8. Distribution of electric motor rated power.

Table 5
Environmental categories used by publications under study.

Environmental Categories	References											% of references covered per category
	(Deprez et al. (2006))	(de Almeida AT et al., 2008), (de Almeida et al., 2014)	(De Almeida et al., 2008), (Ferreira et al., 2011), (Andrada et al., 2012), (Orlova et al., 2016), (Rassõlkin et al., 2020)	(Martínez et al., 2008), (Andrada et al., 2009)	(Torrent et al., 2012a), (Torrent et al., 2012b)	(Boughanmi et al., 2011), (Boughanmi et al., 2012a)	(Boughanmi et al. (2012b))	(Favi et al. (2012))	(Rassolkin et al. (2016))	(Auer and Meincke (2018))	(Cassoret et al. (2019))	(Jocanovic et al. (2019))	
Midpoint Level													
Use of Energy and Electricity		X	X	X	X	X					X	X	**75%**
Depletion of abiotic resources - water		X	X	X	X					X			**60%**
Depletion of abiotic resources - others						X[a]	X[a]			X[c]	X[a]		**25%**
Ionizing radiation										X	X		**10%**
Human toxicity						X	X				X		**20%**
Climate change, greenhouse gases	X	X	X	X	X	X	X	X	X	X	X	X	**100%**
Stratospheric Ozone Depletion	X	X		X		X	X			X	X		**50%**
Acidification	X	X	X	X	X	X	X		X	X	X		**90%**
Photo-oxidant formation/ Emission of VOC	X	X	X	X		X			X	X	X		**75%**
Persistent Organic Pollutants (POP)		X	X						X				**40%**
Heavy metals emission		X	X	X	X				X				**60%**
Polycyclic Aromatic Hydrocarbons (PAHs)		X	X						X				**40%**
Particulate matter Emission, dust		X	X	X	X				X	X			**65%**
Heavy metals emission		X	X	X					X				**50%**
Eutrophication	X	X	X	X	X	X	X		X	X[b]	X		**90%**
Persistent Organic Pollutants (POP)		X											**10%**
Fresh Water Ecotoxicity						X	X			X			**20%**
Water Pollution											X		**5%**
Territorial Ecotoxicity						X				X	X		**20%**

(*continued on next page*)

Table 5 (*continued*)

Environmental Categories	References												% of references covered per category
	(Deprez et al. (2006))	(de Almeida AT et al., 2008), (de Almeida et al., 2014)	(De Almeida et al., 2008), (Ferreira et al., 2011), (Andrada et al., 2012), (Orlova et al., 2016), (Rassõlkin et al., 2020)	(Martínez et al., 2008), (Andrada et al., 2009)	(Torrent et al., 2012a), (Torrent et al., 2012b)	(Boughanmi et al., 2011), (Boughanmi et al., 2012a)	(Boughanmi et al. (2012b))	(Favi et al. (2012))	(Rassolkin et al. (2016))	(Auer and Meincke (2018))	(Cassoret et al. (2019))	(Jocanovic et al. (2019))	
Waste Generation (non-hazardous/landfill)		X	X	X	X								**55%**
Waste Generation (hazardous incinerated)		X	X	X									**45%**
Endpoint Level													
Human toxicity – Cancer effects										X			**5%**
Human toxicity – Non Cancer effects										X			**5%**
% of categories covered per reference	**22%**	**65%**	**57%**	**52%**	**35%**	**43%**	**30%**	**4%**	**39%**	**57%**	**48%**	**9%**	

[a] Include abiotic depletion in general, not only water.
[b] Eutrophication is split into Terrestrial, Fresh Water and Marine.
[c] Depletion of fossil fuel and mineral.

Table 6
Composition of motors.

References	Technology	Elect steel	Other steel	Cast iron	Al	Cu	Pack mat	Imp Res	Insul mat	Paint	Plastics	Elect	PM
(Von Stechow et al. (2016))	**SCIM**	X			X	X							
(Nassani et al., 2019), (Janetschek et al., 2020), (Serôa da Motta, 2019)*	**SCIM**	X	X	X	X	X	X	X	X	X			
(Nassani et al. (2019))	**PMSM**	X			X	X					X	X[a]	X
(European Environment Agency (2019a))	**SCIM**												
(European Environment Agency (2019b))	**SRM**	X	X		X	X	X	X	X	X	X	X	
(Dyer et al., 2008), (Abdelaziz et al., 2011)	**SRM**	X	X		X	X	X	X	X	X	X	X	
	SCIM	X	X		X	X	X	X	X	X	X	X	
(Choi et al. (2018))	**SCIM**	X	X		X	X							
(International Energy Agency (2021))	**SCIM**												
(Saidur (2010))	**SCIM**	X	X		X	X		X	X	X			
(Saidur and Mahlia (2010))	**SCIM**	X	X		X	X		X	X		X		
(Lu (2016))	**SCIM**												
	Shaded poles												
	Brushless												
	Permanent Magnetic												
	SynRM												
(Garcia et al. (2007))	**SCIM**	X	X	X	X	X	X	X	X	X			
(Zuberi et al., 2017), (Prakash et al., 2008)	**SynRM**	X	X		X	X	X	X	X	X			X
	PMSynRM	X	X		X	X	X	X	X	X			X
	SCIM	X	X		X	X	X	X	X	X			X
(Saidel et al. (2010))	**SynRM**	X	X		X	X	X	X	X	X			
(Gó et al. (2020))	**SCIM**	X	X	X	X	X	X	X	X[b]	X[b]	X[b]		
(Agamloh and Cavagnino (2013))	**SCIM Cu - 3 kW**	X	X		X	X							
	SCIM Al - 3 kW	X	X	X	X	X							
	SCIM Cu - 10 kW	X	X		X	X		X	X		X		
	SCIM Al - 10 kW	X	X		X	X		X	X		X		
(Bortoni et al. (2020))	**SCIM**	X	X	X	X	X		X		X	X		
Percentage of mention by material		**77%**	**69%**	**19%**	**77%**	**77%**	**38%**	**58%**	**50%**	**42%**	**31%**	**15%**	**15%**

[a] Include electronic components and PWB (Printed Wiring Boards).
[b] Expressed in other components that include Plastics (injection molding), insulation, paint (painting), rubber, brass (stamping and ending), solder (brazing), and grease.

these materials don't vary between different IE classes. J. Fong et al. (2008) (de Almeida AT et al., 2008) go into detail regarding electronic material used in electric motors, identifying, besides electronic components, the Printed Wiring Boards (PWB).

B. Cassoret et al. (2019) (Cassoret et al., 2019) performs LCA to compare copper and aluminum rotors SCIMs, considering only some minor materials (impregnation resin + insulation material + plastics) in the 10 kW power motors. The outer case of the motor can be made with cast iron on injected aluminum. B. Cassoret et al. (2019) (Cassoret et al., 2019) only assume cast iron in the 3 kW SCIM aluminum rotor, excluding it from the 10 kW SCIM aluminum rotor.

However, most of the publications analyzed (13 out of 20) consider in detail the motor components, including the plastic materials and paint used in the motor frame. It is noted that all publications analyzing PMSM motors consider the magnets in the composition of the motors.

Regarding the components of the electric motors and components studied, the analyzed publications worked predominantly with the projects, or the list of materials provided by the manufacturers, which were not identified by the need for neutrality in scientific journals.

From the publications reviewed, it is concluded that the most relevant impact categories for electric motors are water depletion and global warming potential. These two environmental impacts stem from the amount of electrical energy converted in the electric motors' use phase.

4.5. RQ5. What energy mix was chosen for the analysis?

Low carbon electricity supply is a central feature of an energy system compatible with the 2 °C targets, given the ambitious IPCC scenarios (Rogelj et al., 2018). Therefore, in the LCA, it is necessary to enter the primary energy mix and, if possible, the forecast future electricity mix to allow analysis as close to reality as possible. For electric motors, entering the correct mix at production is essential. However, the mix during the usage phase is usually predominant, as it is an energy-consuming piece of equipment. The twenty publications chose different energy mixes.

Of the 20 publications included in the Systematic Literature Review (SLR), 16 publications employ the average primary energy mix of Europe, with 12 constructed based on the MEEUp methodology, which automatically uses average values of the primary energy mix from the European electrical sector. Two publications did not report the primary electric energy mix utilized. One publication used the French mix (predominantly nuclear) and another the Serbian mix (60% coal and 30% hydroelectric and other sources).

The energy mix is a significant factor in the inventory of environmental impacts. A predominantly coal mix can have an emission factor between 751 and 1095 gCO_2eq./kWh. GHG emissions from wind energy, on the other hand, can vary between 7.8 and 16 gCO_2eq./kWh (United Nations, 2021), (Nieuwlaar et al., 2004). Solar photovoltaic is experiencing major growth around the world, and it is expected to be the dominant renewable electricity source. The life-cycle carbon dioxide (CO_2) emissions for solar PV are now within the range of 25–32 g/kWh. In addition to the already consolidated discussion of climate change caused by GHG emissions, fossil sources in the energy generation matrix are the ones that most contribute to the increase of other environmental impacts, such as eutrophication, ozone depletion, and VOC emissions (Resch and Kaye, 2007).

In the publications using the MEEUp method, the analysis spreadsheet itself already includes the emissions factor for the energy matrix of Europe's interconnected system. With a mix with preponderant participation of non-renewable sources (International Energy Agency, 2024), it is expected that the LCA result using the MEEUp method will highlight the environmental impacts generated in the use phase of the analyzed motors.

In some cases, the energy scenario for use differs from manufacturing and disposal, especially in the case analysis of countries that import electric motors. J. Auer and A. Meincke (2018) (Auer and Meincke, 2018), for instance, considered electric motors built in the German territory. W. Boughanmi (2012) (Boughanmi et al., 2012b) considered waste management scenarios per French Environment and Energy Management Agency data.

Due to a life cycle overview, some publications go beyond the analysis of life cycle environmental impacts, evaluating the Life Cycle Cost (LCC), as well. Half of the 20 publications under investigation include LCC. To perform an LCC, the authors consider some additional cost considerations. E. Martínez et al. (2008) (Martínez et al., 2008), P. Andrada et al. (2009) (Andrada et al., 2009) and P. Andrada et al. (2012) (Andrada et al., 2012) evaluate equipment and electricity costs in Spain. A. Rassolkin et al. (2016) (Rassolkin et al., 2016) consider Estonian electricity prices for LCC.

4.6. RQ6. What were the main results found?

Due to the significant diversity of equipment, scenarios, and evaluation metrics among the twenty selected publications, it was not feasible to compare numeric results across these publications. Additionally, 7 papers (35% of total) bring percentage difference between motors, rather than absolute environmental impact values. Thus, it was decided to summarize in Table 7 the system boundary and main findings highlighted by the authors in each of the publications under study.

From Table 7, only 4 papers (20%) can be considered a cradle-to-grave LCA, as it considers the distribution phase between manufacturing and use phase. All the publications analyzed show that, as an energy-using product, the usage phase is always the most impactful, especially when the annual use period is more extended. The most impactful life phase is the use phase. As presented in the previous section, these results were expected since most publications use the European electricity mix to compute the environmental impacts in the use phase of electric motors.

The main objective of the selected papers was to compare different motor technologies, discussing the trade-off between efficiency gain and increase in environmental impact during the manufacturing phase. In this context, the functional unit, when mentioned, refers to the output power in kW over the lifetime of each motor technology. The only exception is the study conducted by Auer and Meincke (2018), which clearly chooses as functional unit the nominal power of 110 kW, 365 days per year, for a lifespan of 20 years. Also, in all the motor phases studied, the systems are not considered to be multifunctional, which means that there are no secondary functions to the provision of mechanical power and, consequently, no allocation or expansion system was defined.

Auer and Meincke (2018) is the only one that provides a sensitivity analysis to address uncertainties in LCA. The sensitivity analysis in copper and electrical sheet data shows that the source of information can significantly change some environmental impacts. This result was also observed in the energy mix where electric motors consume energy. In the rest of the reviewed papers, the quantitative uncertainties of LCA inventory data were neglected.

In the analyses that presented the results of the impacts distributed by phase, the use of the electric motor, in some cases, represented over 97% of the total impacts. Followed by the production phases, representing just over 1%, and then the end of life and transportation. For this reason, simplifications in other phases do not significantly influence the result, especially for more minor rated powers.

The primary strategy for improving the motor induction technologies (SCIM) efficiency was to increase the fractions of copper material and

Table 7
Main found results.

References	System Boundary	Main analysis and conclusions
(Deprez et al. (2006))	Manufacturing, Use, End-of-life	The most efficient motor had the lowest impact in the use phase and the highest impact in the production phase. The least efficient electric motor had the highest impact in use and the lowest impact in manufacturing because it used less volume of materials.
(de Almeida AT et al. (2008))	Manufacturing, Use, End-of-life	In the LCA conducted the volume of the equipment packaging was considered in the LCA, and for its disposal scenario, the authors assumed that 5% of the materials go to landfills, 90% to incineration, and the remaining 10% to recycling. It was considered that 95% of all metals went under recycling. The environmental impacts of replacing motor + throttle with motor + VSD show a decrease The top 3 reductions were above 37 %, corresponding to total energy, acidification, and greenhouse gases environmental categories. The less significant environmental impact reductions were related to emissions to water: eutrophication (14%) and heavy metals (17%). This comparison also had the materials components of the throttle and VSD attached to the motors.
(De Almeida et al. (2008))	Use	The results show a significant reduction of LCC and environmental impacts for low-power motors and less significant for higher powers. Also, results show that the higher the rated power of the motor, the lower the influence of operating hours on the reduction of LCC and environmental impacts. IE2 and IE3 class motors proved advantageous in replacing IE1 class motors and those that would be below standard. Considering only the use phase, significant reductions in environmental impact were achieved in most operating circumstances (operation, load factor, and electricity prices).
(Martínez et al. (2008))	Manufacturing, Use, End-of-life	From the analysis, the authors concluded that SRMs can generate significant savings, mainly due to their high efficiency. In the use phase, the savings generated by SRMs are comparable to or even better than those of IE3 three-phase induction motors. SRMs are easy to dismantle, enabling high material utilization at the end-of-life phase.
(Andrada et al. (2009))	Manufacturing, Use, End-of-life	At the manufacturing phase, the SRM drive showed lower environmental impacts than SCIMs, while at the end-of-life phase, the opposite occurred. This inversion was due to the SRM using less materials than the SCIMs. The SRM had the lowest environmental impacts during the life phase because it operated more efficiently.
(Ferreira et al. (2011))	Manufacturing, Use, End-of-life	Regarding the recycling of end-of-life materials, the authors assumed that 5% were not recovered (landfill), 1% of plastics were not reused, 9% of plastics were recycled,

(continued on next page)

Table 7 (*continued*)

References	System Boundary	Main analysis and conclusions
		90% of plastics were thermally recycled (non-hazardous incineration optimized for energy recovery), and 95% of metals are recycled. The reduction in environmental impact when VSDs replace butterfly valves is significant, being over 14% in all indicators evaluated and reaching 37% in greenhouse gas emissions. Thus, using VSDs and saving energy and financial resources is also an important technique to reduce the environmental impacts of many electric motor applications.
(Torrent et al. (2012a))	Manufacturing, Use, End-of-life	The publication only evaluated the production and use phases. Tests were also carried out in the laboratory to assess the actual efficiency of the electric motors. The total environmental impact of the IE2 motor is significantly lower than the IE1 motor due to its higher efficiency. The higher efficiency of IE2 came from using more materials (mainly copper) and better-quality magnetic lamination; therefore, the IE2 motor has a higher environmental impact in the production phase.
(Boughanmi et al. (2011)	Manufacturing, Use	The publication described a comparative study via LCA of two different winding technologies for a 10 kW SCIM. The new coil (UV polymerized and thermoset wire) has lower environmental impacts than the conventional coil, showing reductions of 65% in greenhouse gas emissions (IPCC) and 70% of global energy demand compared to the old process. Gains were recorded mainly in saving impregnation varnish and solvent that can bring high environmental liabilities compared to the new process.
(Boughanmi et al. (2012a))	Manufacturing, Use, End-of-life	This publication mainly focused on analyzing the design improvement and impacts at each phase of the electric motor life in ten selected categories. Efficiency improvements in the use phase offset the additional environmental costs of the manufacturing and disposal phase.
(Andrada et al. (2012))	Manufacturing, Distribution, Use, End-of-life	At the manufacturing phase, the SRM drive showed lower environmental impacts than SCIMs, while at the end-of-life phase, the opposite occurred. This inversion was due to the SRM using less materials than the SCIMs. The SRM presented the lowest environmental impacts during the life phase because it performed more efficiently. Moreover, in the noise analysis, the SRM performed worse than the SCIMs.
(Torrent et al. (2012b))	Manufacturing, Use	For most of the mechanical power values studied, the total environmental impact of IE2 motors was lower than that of IE1 motors, even when the former was oversized. The less oversized options showed the lowest environmental impact in applications requiring fewer operating hours, and, in some cases, oversized electric motors may be interesting for applications requiring a high number of operating hours (above 6000 h/year).
(Boughanmi et al. (2012b))	Manufacturing, Use	The end-of-life phase of the electric motor has the lowest impact, except for the indicator related to water pollution. The landfilling of the non-recycled part of the metals (mainly copper) directly influenced this considerable impact. This publication considered the following recycling scenario: aluminum (70%), copper (70%), and steel (45%). The remaining waste was incinerated and buried at 53% and 47%, respectively. In the comparison between the three motors, the SCIMs 9 kW with 125% loading, the SCIMs 11 kW with 100% loading, and 15 kW with 75% loading, the authors evaluated that the 9 kW SCIM was less impactful in the construction phase as it used less material. In the use phase, the oversized 15 kW SCIM showed less overall impact as it operated when the efficiency was higher than the other two SCIMs. Furthermore, since the use phase is the one that passes the most on the result, the oversized motor would be a better choice.
(Favi et al. (2012))	Not available	This publication describes a web-based software platform to configure and simulate customized energy-efficient electric motors. The main advance highlighted is the possibility of a collaborative environment to improve the interaction between remote users involved in the design process of electric motors due to data sharing, so it is possible for the different groups to have simultaneous interaction seeking the optimization of the design, including the LCA factors.
(de Almeida et al. (2014))	Manufacturing, Use, End-of-life	The total environmental impact of VSDs is considerably lower than that of motors, as they have significantly less material volume despite having electronic components that cause other impacts. However, the insertion of VSDs reduces losses over the motor's lifespan, which makes the insertion of the equipment beneficial, especially for mechanical loads with centrifugal characteristics, such as fans and fluid pumps.
(Orlova et al. (2016))	Manufacturing, Distribution, Use, End-of-life	The production phase is the least costly for SynRM, as there are no permanent magnets, and the rotor does not have windings. However, this type of motor generated more impacts than SCIM and PMSynRM in the use phase due to its low efficiency compared to the other two technologies. In the analysis of PMSynRM, the authors conclude that although the use of permanent magnets makes this project expensive, still in its operation, this type of motor causes minor damage to the environment during the use phase due to its high efficiency.

(*continued on next page*)

Table 7 (*continued*)

References	System Boundary	Main analysis and conclusions
(Rassolkin et al. (2016))	Manufacturing, Distribution, Use, End-of-life	This publication presents an LCA of the SynRM calculations also involving the monetary costs involved in the electric motor lifetime. The impacts of heavy metals eutrophication were the only predominant in the production phase. In all other indicators, the use phase was preponderant.
(Auer and Meincke (2018))	Manufacturing, Distribution, Use, End-of-life	The results indicated the dominance of the use phase in the life cycle of electric motors. Thus, a slight increase in efficiency pays off environmentally in the first month of operation in the load-time profiles applied in the research.
(Cassoret et al. (2019))	Manufacturing, Use, End-of-life	The researchers concluded that a copper cage rotor's manufacturing and end-of-life environmental impacts are worse than aluminum rotors, and the use phase environmental impacts are better with a copper cage rotor because their losses are lower. Also, the total environmental impacts are better with a copper rotor if the electric motor is used a lot during its life. A copper cage rotor reduces losses by approximately 13% compared to an aluminum rotor for the same mechanical power.
(Jocanovic et al. (2019))	Manufacturing, Use, End-of-life	The LCA considered a pumping system including the Serbian pumping station's hydraulic pump, electric motor, and VSD. The results also show that 93%–94% of the energy consumed and LCC costs are related to pump operating costs, while the rest is related to auxiliary operations. The same scenario holds for GHG emissions.
(Rassõlkin et al. (2020))	Manufacturing, Use, End-of-life	When analyzing the GHG category for the three compared technologies, SCIMs had the highest impact as they use more material in their manufacture. In the distribution phase, the impacts were the same as the volumes were similar, and the distance traveled was the same. The efficiency of the equipment determines the use phase, so PMSynRM had the lowest impact, as it is the most efficient, followed by SynRM. At the end of life, SCIM was the most impactful due to the more significant material volume than the others; and SynRM had less impact because its composition does not include magnets like PMSynRM and has less material than SCIM.

electrical steel. Moreover, since these two components represent a significant part of the total mass of electric motors, which in their extraction often uses energy from fossil sources, there is an increase in the impacts associated with the production phase of the most efficient electric motors, namely IE3 and IE4.

Among all the motor typologies, the one that presents a more significant impact on production compared to the other life cycle phases is the induction motor. In the usage phase, it is observed that environmental impacts depend more on motor efficiency than its typology. Thus, the smaller the motor efficiency, the greater the impact during the usage phase, consequently, in its entire life cycle.

Analyses that include permanent magnet-based motors show lower impacts during their use phase due to their higher efficiency level. Despite an increase in impact in the production phase of these motors, this increase does not counterbalance their gains during utilization, leaving PMSynRM as a more efficient alternative both in technical and environmental terms, considering the whole life cycle.

Drawbacks of PMSynRM motors include using rare earth metals whose extraction processes have higher impacts when compared to other metals. PMSMs also have limitations in recycling permanent magnets, as they are brittle and can lose their magnetism at high temperatures.

No changes in environmental impacts were observed in the comparative analyses of identical technology electric motors that underwent modifications in material quantities to achieve better efficiency ratings. The more efficient motors greater the amount of material they consume in the production phase, which results in a more significant environmental impact associated with this phase. Nevertheless, they have greater energy efficiency in the use phase. Thus, they have a positive environmental balance, exceeding the liabilities of the production phase.

The evaluation indicates that the primary materials constituting electric motors (copper, iron, and steel) contribute to approximately 90% of the total potential environmental impacts associated with the manufacturing of electric motors, particularly in terms of acidification and global warming (Table 8).

From an environmental perspective, it is observed from Table 8 that increasing the volume of electrical sheets also increases the impacts in the ionizing radiation category, global warming potential, and particulate matter categories. Copper contributes significantly to the impacts of resource depletion and human toxicity (cancer effects) environmental categories.

All publications involving variable flow systems using VSD show that the speed control of electric motors in loads such as pumps, fans, and compressors has not only a large positive economic impact but also a substantially less overall environmental impact. As VSDs are widely used in electric motor drives, these results corroborate the preference of VSD over throttling devices used for flow control (e.g., valves, dampers, vanes) across the entire motor-drive life cycle. Nevertheless, the authors state that VSDs may not be advantageous for motors operating at a constant speed.

4.7. RQ7. What are the restrictions of the research and the main challenges in the field?

The bill of materials involved in the manufacturing phase of electric motors can be divided into two parts: the active part, which participates in energy conversion (magnetic core, winding, and cage), and the inactive part, necessary for other functions (frame, end plates, bearing, and fan). Most publications (except for B. Cassoret et al. (2019) (Cassoret et al., 2019)) did not separate these materials. This division is important because it shows which material is directly linked to the efficiency and losses of the equipment under analysis.

The most relevant data for the manufacturing phase of electric

Table 8
Main impacts observed in the LCA of electric motors at the manufacturing phase.

Main impact category	Main drivers
1 - Resource depletion (fossil and mineral)	Copper refining and processing
2 - Global warming potential	Electrical steel, assembly process, copper, and aluminum.
3 - Particulate matter	Iron (in the die-cast), copper production, electrical steel
4 - Human toxicity (cancer effects)	Electrical steel, cast iron, and other steel
5 - Human toxicity (non-cancer effects)	Electrical steel, other steel, copper
6 - Acidification	Electrical steel, copper, and other steel

motors are the bill of materials and the energy consumption in the assembly process. In most of the publications analyzed, manufacturers were the source of information for the weights of component materials. Typically, the software suite used in LCA uses generic material databases, as it is difficult to precisely quantify the energy and environmental impacts and costs of processes at the point of primary material extraction, then processing and production of the electric motor.

The energy allocated by working hours in the assembly process may present uncertainties. However, due to the predominance of the impacts associated with the production of the materials (mineral extraction and beneficiation/processing), the importance of precision can be classified as low, as the influence on the result is not significant, since in the case of energy consuming equipment, the use phase is predominant in the analysis.

Of the 20 publications analyzed, 40% did not consider the insulation system's materials for producing electric motors. The traditional process for winding the stator coils involves enameled wire with monomer-based insulation deposited on the wire, often using harmful and toxic solvents. Usually, manufacturers use a varnish with other solvents to impregnate the coils made with this wire. A complete analysis would involve the quantities of different resins that make up the insulation of the conductors used in the stator, the amount of solvent used, the energy required to manufacture the enameled wire, and the end of life of all these elements.

As impacts are process-dependent, specifying critical components used in motors manufacturing can maintain the measurement of impacts in their production and disposal phase. LCAs that do not cite materials used in the treatment of the motor casing ignore environmental impacts from using paints, plastics, and resins, contributors to, e.g., volatile organic compound emissions and ecotoxicity (Chandran et al., 2020), (Porwal, 2015).

All publications that considered permanent magnet analysis used the MEEUp methodology, which has some limitations. For example, the method does not consider mining rare earth impacts to obtain the permanent magnets that are the raw material for these motors.

Most reviewed publications deal with electric motor components as a simple list of different materials rather than an assembly alternative firmly based on reducing manufacturing costs. Only E. Martínez et al. (2008) (Martí et al., 2008) regarded design alternatives to minimize the life cycle environmental impacts and costs by easing the disassembly of motor into its various parts and materials, although increasing fabrication expenditures. The optimization of equipment design facilitates equipment recycling as well as has greater acceptance by users (Atlason et al., 2017).

In all LCA publications analyzed, the transportation stage focused on the distribution of the electric motors, and in most cases, was the same for the compared motors. Thus, there were no differences in the impacts observed in this stage, as the volume changes observed were not significant to cause an increase in emissions in transportation when compared unit by unit. At the distribution stage, the impacts are usually so small that they can be disregarded in the LCA. However, in the case of developing countries, which are far from the production centers of electric motors, the transport stage can be significant and should be considered.

There are also transportation steps between the production phase, maintenance, and disposal, as shown in Fig. 5. In most of the publications studied, these steps were not included.

The impacts of electricity generation are decreasing through the increasing contribution of renewable sources, especially wind and photovoltaic solar energy. Therefore, analyzing different energy mix scenarios in LCA was essential to effectively know the possibilities of environmental impacts avoided with the improvement in the efficiency of electric motors.

Most publications did not differentiate electric motors' operation between fixed speed and variable speed. There is a tendency for medium and high-power motors to work with variable speeds through VSD, which in addition to influencing the efficiency of the electric motor, are also composed of electrical materials that must be evaluated in the life cycle of the motor drive.

Most of the analyzed publications did not address the procedure and scenario for waste management carried out for the analysis of the end-of-life phase. It would be necessary for the publications to present the percentage of each material considered for recycling and the percentage that went to landfills or incinerated in the disposal at the end-of-life phase. In developed countries, approximately 95% of the materials from electric motors are recycled (Bj et al., 2000). However, the reality in developing countries is different and, in most cases, unknown.

5. Research gaps and proposals for future studies

From this systematized literature review, one of the major contributions was the identification of eight research gaps to be explored by life cycle analysis researchers.

(Von Stechow et al., 2016) Analyze scenarios with different recycling rates and different energy mix (from a completely fossil to completely renewable) in developing countries with large high electricity consumers. Alternatively, evaluating cases in developed countries with large consumption where no publications were found, such as the case of the USA and China, it is possible to analyze, for example, the effect of reusing certain parts of the motors (spare parts), reflecting circular economy initiatives. Accelerated replacement of old inefficient motors is a major opportunity to meet the IEA 2035 energy efficiency targets, and LCA analysis is required to maximize benefits.

(Nassani et al., 2019) The lifetime applied in the LCA corresponds to the minimum lifetime established in standards. However, electric motors are usually used in factories far beyond their expected lifetime, as recently shown in a large USA DoE Study (Rao et al., 2021). Thus, building LCA with lifetime scenarios closer to the real ones would be interesting.

(Janetschek et al., 2020) Perform the LCA using efficiency and load data of the electric motor in actual conditions commonly found in industries.

(Serôa da Motta, 2019) Besides four-pole motors, build LCA addressing two-pole and six-pole motors because the number of poles within motors directly influences the materials used and the efficiency.

(European Environment Agency, 2019a) The leading technologies that have become viable to achieve the IE5 efficiency level are PMSM and SynRM. Thus, building a thorough LCA that compares these two technology options for users to make decisions is necessary.

(European Environment Agency, 2019b) Comparative studies between assembly strategies for electric motors aiming to study the impact in life-cycle environmental impacts deserve to be investigated. Increasing motor manufacturers' participation in such studies could enhance the discussion of assembly strategy viability.

(Dyer et al., 2008) Creating tools that facilitate the execution of an LCA, such as the MEEUp methodology used for European specificities. These tools should include the countries/regions' particularity across all life-cycle phases of an electric motor.

(Abdelaziz et al., 2011) A framework is proposed in Table 9 to support LCA in motor reproducibility. Three standards are defined: Bronze (basic information), Silver (desirable level of information), and Gold (full level of information). As silver and gold standards cannot be consistently defined, they are considered non-compulsory.

6. Conclusions

LCA is an essential methodology for product selection decision-making by consumers and businesses. Only an analysis throughout the life of the equipment can define its actual impact on the environment, opening possibilities for innovation and seeking to reduce environmental effects. Therefore, LCA should be considered a tool for assessing environmental impacts right from the design phase of the equipment,

Table 9
Framework for electric motor LCAs.

	Bronze	Silver	Gold
ELECTRIC MOTORS CHARACTERISTICS			
Type of Technology	X	X	X
Rated Power	X	X	X
Full-load Efficiency (number or level)	X	X	X
Number of Poles		X	X
Number of phases		X	X
VSD or another type of Driver[a]			X
ENVIRONMENTAL CATEGORIES[b]			
Use of Energy and Electricity	X	X	X
Depletion of abiotic resources - water		X	X
Depletion of abiotic resources - fossil fuel			X
Depletion of abiotic resources - rare materials			X
Ionizing radiation			X
Human toxicity			X
Climate change, greenhouse gases	X	X	X
Stratospheric Ozone Depletion		X	X
Acidification	X	X	X
Photo-oxidant formation/Emission of VOC	X	X	X
Persistent Organic Pollutants (POP) into the air		X	X
Heavy metals emission into the air	X	X	X
Polycyclic Aromatic Hydrocarbons (PAHs)		X	X
Particulate matter Emission, dust	X	X	X
Heavy metals emission into the water	X	X	X
Eutrophication	X	X	X
Persistent Organic Pollutants (POP) into the water		X	X
Fresh Water Ecotoxicity			X
Territorial Ecotoxicity			X
Waste Generation (non-hazardous/landfill)	X	X	X
Waste Generation (hazardous incinerated)		X	X
MANUFACTURING PHASE			
Energy Consumption			X
Energy mix that the manufacturer uses			X
Composition: Electrical Steel	X	X	X
Composition: Other steel	X	X	X
Composition: Cast iron		X	X
Composition: Aluminum	X	X	X
Composition: Copper	X	X	X
Composition: Packing material			X
Composition: Impregnation resin			X
Composition: Insulation material			X
Composition: Paint		X	X
Composition: Plastics			X
Composition: Electronics[a]			X
Composition: Permanent Magnetics[a]	X	X	X
TRANSPORTATION			
Distance covered			X
Transport modal			X
USE PHASE			
Loading		X	X
Annual Use (hours)	X	X	X
Lifetime (years)	X	X	X
Energy mix, which motor electric is connected		X	X
DISPOSAL PHASE			
Percentage of landfilled material	X	X	X
Percentage of incinerated material			X
Percentage of recycled material		X	X

[a] If applicable.
[b] To be elected as gold, at least two environmental categories (one-third) with gray shading should be used.

aiming at optimization from conception and making the best choices of production chains with less impactful materials.

The main reasons for doing LCA of electric motors are: *i*) Need to catalog information about the negative impacts and the ecological influence of the electric motor in its life cycle to find possibilities to reduce environmental damage or impact; *ii*) Present the information about the equipment for eco-certification; *iii*) Comparison of the environmental impact of different electric motor technologies for similar functions.

The publications reviewed showed that the energy efficiency of electric motors is an essential parameter in the overall eco-balance for long cumulative operating times. Thus, the environmental impacts of the construction phase can become progressively more significant when the operating time decreases (e.g., low-duty cycle equipment).

The relationship between increased energy efficiency and reduced potential environmental impact depends on the energy mix used. For example, in the case of a “green” energy mix dominated by electricity generation through renewable resources, efficiency gains in the use of electric motors will result in smaller reductions in environmental impacts compared to energy mixes that rely mainly on fossil sources.

Achieving the overall ecological balance for electric motors is a critical step towards implementing environmental design criteria, which assist engineers in their decision-making during industrial motor design and in the choice of the electric motor during user purchase. Moreover, discussing the bill of materials to be chosen for high-power motors should already be part of the design phase. Doing so will have positive effects in the medium and long term, as loads driven by electric motors account for most electricity consumption worldwide.

According to the LCA study, to increase the motor efficiency, in general, there was an increase in the amount volume of materials used, mainly in the copper windings located in the stator, where the most significant amount of losses of the electric motor occurs, as well as in the magnetic components. New high-efficiency technologies, such as SynRM and PMSynRM, can achieve the highest efficiency levels of IE4 or IE5 and use no more active materials than the now dominant IE3 SCIM technology.

All the LCA analyzed point to the use phase of electric motors as the most impactful in the life cycle of electric motors and include, at least, the greenhouse gas emissions as environmental impact. In the context of the 17 Sustainable Development Goals, this result emphasizes pursuing goal number 13 (Climate Action). As there are publications that include environmental impact concerning water emissions, it can be expected to pursue goal number 14 (conserve and sustainably use the oceans, seas, and marine resources for sustainable development) by using higher efficient electric motors.

Using more mineral or energy resources in the manufacturing phase may be offset by energy savings in the use phase. This scenario can lead decision-makers in the wrong direction, especially when they must take into account to analyze the impacts of the depletion of mineral and metal resources. For this reason, material treatment scenarios at the end of the electric motor life are relevant for further research, namely because at the end-of-life phase, most publications did not address the percentage of materials that would be recycled, which would be incinerated and buried. Knowing that the primary materials used to manufacture electric motors (e.g., steel, aluminum, copper) are recyclable and have a significant market value makes this approach very relevant, primarily if large-scale accelerated replacement of old inefficient motors (IE0 or IE1) is implemented.

Electric motor design software must incorporate ecodesign contents to effectively become a tool for assessing the technology’s viability. Furthermore, integrating ecodesign tools will allow designers to simultaneously control the impact of the production phase, avoiding or minimizing, for example, the use of rare materials that are difficult to mine, manufacture and recycle.

Funding

- National Council for Scientific and Technological Development (CNPq) – project 870814/1999–0, process 142323/2020–9.
- Higher Education Improvement Coordination - Brazil (CAPES) - Finance Code 001.

CRediT authorship contribution statement

Danilo Ferreira de Souza: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Pedro Paulo Fernandes da Silva:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ildo Luis Sauer:** Writing – original draft, Visualization, Validation, Supervision, Conceptualization. **Aníbal**

Traça de Almeida: Writing – original draft, Visualization, Validation, Supervision. **Hédio Tatizawa:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Danilo Ferreira de Souza reports financial support was provided by Coordination of Higher Education Personnel Improvement. Danilo Ferreira de Souza reports financial support was provided by National Council for Scientific and Technological Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors extend their gratitude to Walter Aguiar and Kenny Kawaguchi for their invaluable assistance in crafting the figures and data visualization; to Researcher Richardson M. Abraham-A and Lars Eirik Frantzen for refining the manuscript's English; and to Researchers Maria Luiza Almeida and Jônatas Augusto Manzolli for their contributions to the research's progression. The authors sincerely thank the reviewers for their insightful comments and suggestions, which have significantly enhanced this manuscript's quality and rigor.

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APPENDIX G

DE SOUZA, Danilo Ferreira; FONG, João; DE ALMEIDA, Aníbal Traça; SAUER, Ildo Luis; TATIZAWA, Hédio. Environmental Impacts of Electric Motor Technologies: Life Cycle Approach Based on EUP Eco-Report. **Environmental Impact Assessment Review**. (IN REVIEW)

Environmental impacts of electric motor technologies: life cycle approach based on EuP Eco-Report

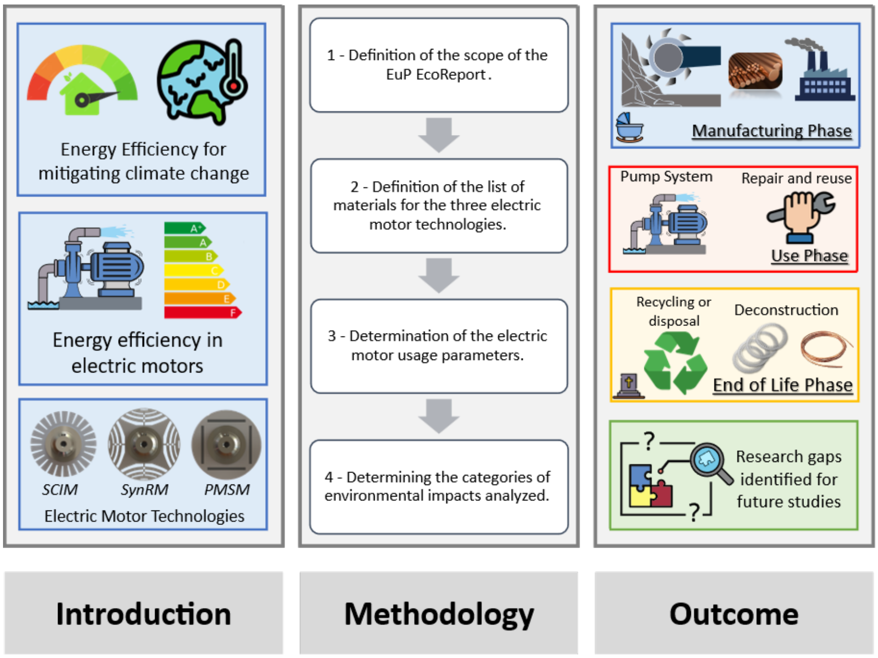
ABSTRACT - Electric motors and their systems are pivotal loads in the industrial sector, and enhancing their efficiency is a crucial step in addressing climate change. Historically, research in this field has primarily focused on the operational phase of electric motors, often neglecting the environmental impacts associated with their production, maintenance, and disposal. The IE4 energy efficiency level has been mandated in the European market for motors ranging from 75 to 200 kW power since July 2023. Motors with power below 75 kW must meet at least the IE3 efficiency level with Squirrel Cage Induction Motors (SCIMs) technology. In contrast, the highest efficiency level in the market is IE5, found in Synchronous Reluctance Motors (SynRM) and Permanent Magnet Synchronous Motors (PMSM) technologies. This investigation addresses a critical research question: What are the environmental impacts across the life cycle of each of the three available motor technologies – SCIMs at the lowest permissible efficiency (IE3) and SynRM and PMSM at the highest efficiency (IE5)? The study evaluates the environmental impacts of three distinct electric motor technologies: the widely used SCIMs and the more advanced SynRM and PMSM. Utilizing the EuP Eco-Report tool, developed under the Methodology for the Ecodesign of Energy-related Products (MEErP), this research analyzes the environmental repercussions of low-power (11 kW) motors with a 4-pole configuration. The findings reveal that IE5 SynRMs offer superior operational energy efficiency compared to IE3 SCIMs but incur more significant environmental impacts during manufacturing, mainly due to the increased volume of materials required. PMSMs emerge as the most energy-efficient option among the three. However, they present the highest environmental costs, particularly in the manufacturing and end-of-life phases, attributed to the significant water pollution risk during the extraction processes of rare earth metals and the complexities associated with recycling these materials.

Keywords: Ecodesign, Electric Motor Efficiency, Sustainable Technology Transition, Industrial Energy Efficiency, Clean Production

Highlights

- The EcoReport tool provides vital information for assessing the environmental impacts of motors across their life stages.
- The environmental impacts of materials used and recycling challenges in motors.
- SynRMs and PMSMs are efficient but have higher manufacturing phase environmental impacts than SCIMs.
- PMSMs are identified as the most energy-efficient yet pose significant environmental costs in manufacturing and end-of-life.

Abstract Graphical



1.0 Introduction

The challenges of energy transition, energy efficiency, and climate change are at the forefront of the international discourse on sustainable development [1], [2]. A report by the European Environment Agency highlighted that, in 2019, the energy sector was a significant source of greenhouse gas (GHG) emissions, accounting for around 77 % of the total global GHG emissions [3]. The GHG emissions in the energy sector are primarily distributed in three key segments: electricity generation, fuel production, and transportation. Each segment contributes roughly one-third of the total GHG emissions [4].

The role of energy efficiency in reducing GHG emissions has been widely acknowledged by researchers, the government, and society in general [5]–[9]. The International Energy Agency (IEA) projects that energy efficiency could reduce up to 40 % of the necessary GHG emissions by 2040, aligned with the global climate goals established in the Paris Agreement [10], [11]. Further emphasizing this point, the IEA's 2021 Energy Outlook report advocates for the mandatory adoption of electric motors with the highest efficiency by 2035 as a crucial step toward achieving the stipulated decarbonization targets [12].

The industrial sector is significantly dependent on electricity, encompassing a wide range of applications, including electric motors (fluid motion, material processing, handling, air compressors, refrigeration, and boiler auxiliary operations), heating, and lighting [13], [14]. In 2021, electric motor systems represented around 70 % of the electricity demand in the industrial sector [12]. As a result, implementing strategies to improve the energy efficiency of electric motor-driven systems is crucial [15]. Besides contributing to a more competitive industry, this approach effectively can reduce the electricity demand on the grid, consequently increasing available capacity and offering an alternative to creating new, costly, and time-intensive infrastructure [16]–[19].

Since 1990, various countries implemented regulations that specify the minimum requirements of energy efficiency for equipment, known as Minimum Energy Performance Standards (MEPS) [18], [20]. The objective of MEPS is to increase the energy efficiency of products and to guide consumers in selecting the most efficient equipment, even if its initial cost is higher [21].

MEPS for electric motors are based on efficiency classes, allowing for different levels that increase as technological advancements are made and market acceptance grows. Internationally, motor efficiency classes are harmonized with the IE (International Efficiency) code in the IEC 60034-30-1 and 60034-30-2 standards [22], widely recognized as the global benchmark, making efficiency classes comparable worldwide. This standard defines efficiency classes IE1 to IE4, where IE1 is the least efficient, and IE4 is the most efficient motor efficiency class [23], as shown in Figure 1. Similarly, in the United States, the IE1 to IE4 efficiency classes are termed Standard, High efficiency, Premium efficiency, and Super-Premium efficiency, according to NEMA [24]. The new IE5 class (Ultra-Premium efficiency) has yet to be defined but is anticipated for potential products in a future standard edition. IE5 motors aim to reduce losses by about 20% compared to the IE4 class [25].

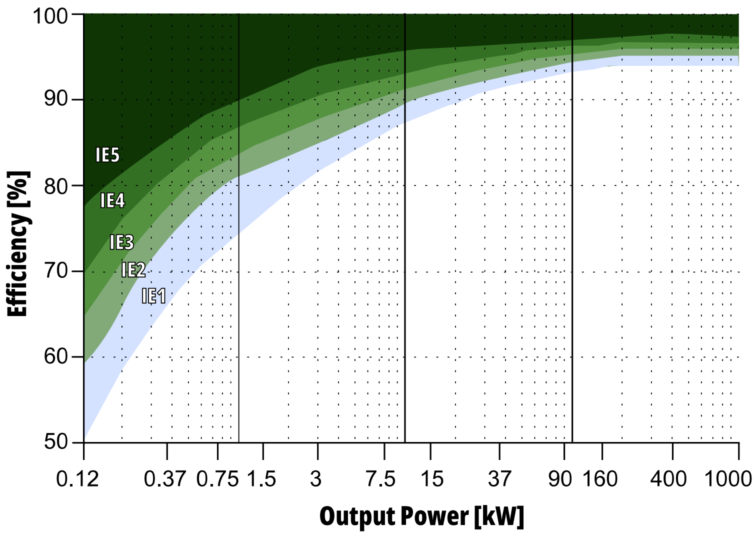


Figure 1 – IE efficiency classes for four pole motor at 50 Hz [26], [27].

In light of the imperative to enhance energy efficiency in motor-driven applications, it is noteworthy that Squirrel Cage Induction Motors (SCIMs), which account for over 95% of all drive applications in the industrial sector, present inherent significant losses in the rotor, achieving the IE5 level of efficiency a challenging endeavour [28]. Acknowledging this limitation of traditional SCIMs, Synchronous Reluctance Motors (SynRM) and Permanent Magnet Synchronous Motors (PMSM) have emerged as viable alternatives, offering the potential to significantly boost energy efficiency in industrial motor-driven actions and feasibly achieve the IE5 efficiency level:

- Synchronous Reluctance Motors (SynRM) use the same constitutive materials as SCIMs and do not have rotor losses [29]. The material differences mainly arise from SynRMs not having aluminum in the rotor [30], [31].
- Permanent Magnet Synchronous Motors (PMSM) also do not have rotor losses [29]. PMSMs typically incorporate permanent magnets made of Neodymium, Iron, and Boron (also known as “NdFeB”," “Neo,” or “NIB” magnets) in their rotors [32]. It can be highlighted that rare earth metals, such as Neodymium, besides their limited availability, have raised concerns due to the environmental impacts of mining and handling hazardous materials while producing magnets. In addition, challenges in recycling these materials have also been noted [33], [34].
- In general, to enhance the efficiency of an electric motor, the following strategies are observed: *i*) increasing the quantities of materials used, *ii*) improving the quality of materials and design, or *iii*) employing novel materials [21], [25].

Considering the differences in material composition among SCIM, SynRM, and PMSM technologies, it becomes essential to assess the environmental impacts of each technology throughout the electric motor’s lifecycle. Consequently, consumers, who typically evaluate cost and technical performance aspects, can also incorporate sustainability as a criterion for selecting technology for load drive systems.

Until recently, the evaluation of the environmental impacts of electric motors has been focused on the operational phase (use phase). Concerns over material use and circularity highlight the importance of other phases. Therefore, it is necessary to employ methodologies that assess electric motors’ environmental life cycle “cradle-to-grave” impacts [35]. Figure 2 illustrates the life cycle of electric motors, including *i*) raw material extraction and production of electric motors (Manufacturing phase), *ii*) operational phase (Use phase), and *iii*) end-of-life treatments (End life phase) [36], [37].

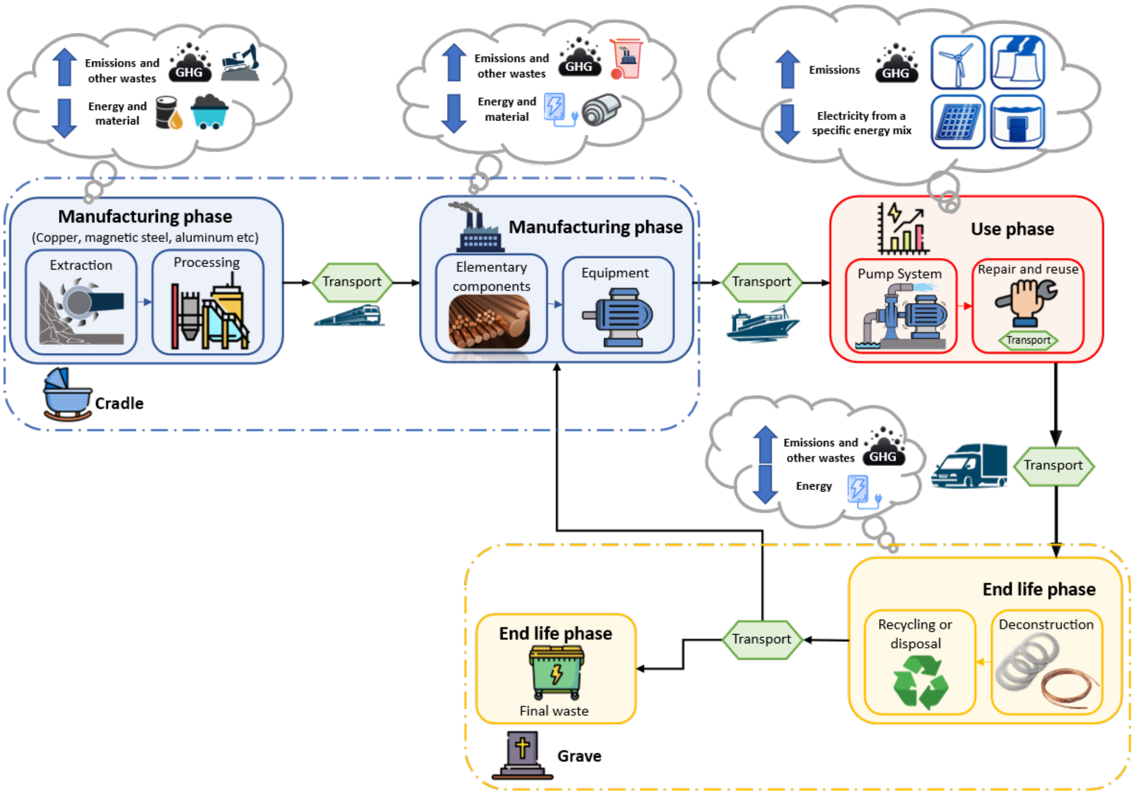


Figure 2 - Life Cycle stages of electric motors.

A valuable tool for assessing impacts throughout a product's lifecycle is the Methodology for Ecodesign of Energy-related Products (MEErP), which was developed to determine whether and to what extent a product meets the criteria outlined in the Directive on the Ecodesign of energy-using products (EuP 2005/32/EC and after 2009/125/CE) [38]–[40]. MEErP offers an independent tool called "EuP EcoReport", designed to facilitate the evaluation of energy-consuming products, providing an evaluation perspective from manufacturing through the use phase to end-of-life.

The establishment of the industrial policy for sustainability aimed to promote environmentally and energy-efficient products in the European internal market. Revising the Ecodesign Directive 2009/125/EC was a cornerstone of this approach [41]. The Ecodesign Directive sets a framework of requirements (Figure 3) for the Ecodesign of energy-related products, intending to ensure the free movement of these products within the European internal market [42].

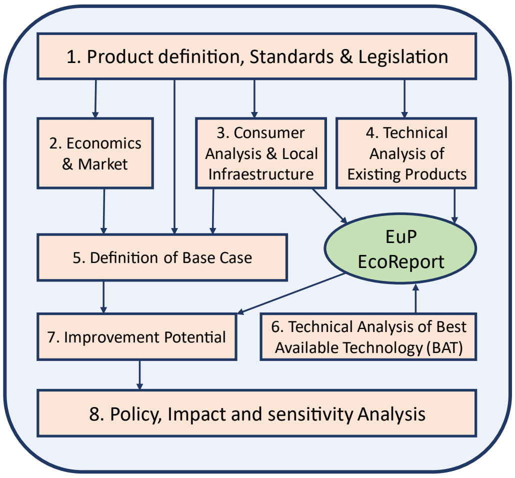


Figure 3 - Methodology for Ecodesign of Energy-using Products (EuP) [43].

The Methodology for Ecodesign of Energy-Related Products (MEErP) [43] was initially developed in 2005 and has undergone several updates since its inception. Within the MEErP framework, the EuP EcoReport spreadsheet is an independent tool designed to facilitate the assessment of energy-consuming products, providing a cradle-to-grate perspective (see Figure 3). The EuP EcoReport spreadsheet includes the environmental impacts of raw material extraction, production processes, distribution, use phase, and end-of-life treatments [44]. This study used the EuP EcoReport tool to analyze the three driving technologies available on the market: SCIM, SynRM, and PMSM.

Since July 2023, the IE4 energy efficiency level has become mandatory in the European market for motors in the 75 to 200 kW [11]. Therefore, the minimum efficiency level permitted for powers less than 75 kW is IE3 – usually SCIM technology. On the other hand, the highest efficiency level in the market is IE5 in SynRM and PMSM technologies, which use either more materials or critical raw materials (rare earth magnets). Consequently, this study aims to answer the following research question: *What are the environmental impacts throughout the lifecycle for each of the three technological options available in the market: SCIM with the lowest permitted efficiencies (IE3), and SynRM and PMSM with the highest available efficiencies (IE5)?*

2.0 Materials and Methods

This study was primarily divided into three stages. Initially, the impacts at the production stage of electric motors were analyzed, involving processes from material extraction and processing to the electric motor assembly. Subsequently, the study examined the electric motor's usage stage. In the end-of-life stage, the primary materials used to produce the electric motor were considered recyclable, as shown in Figure 4.

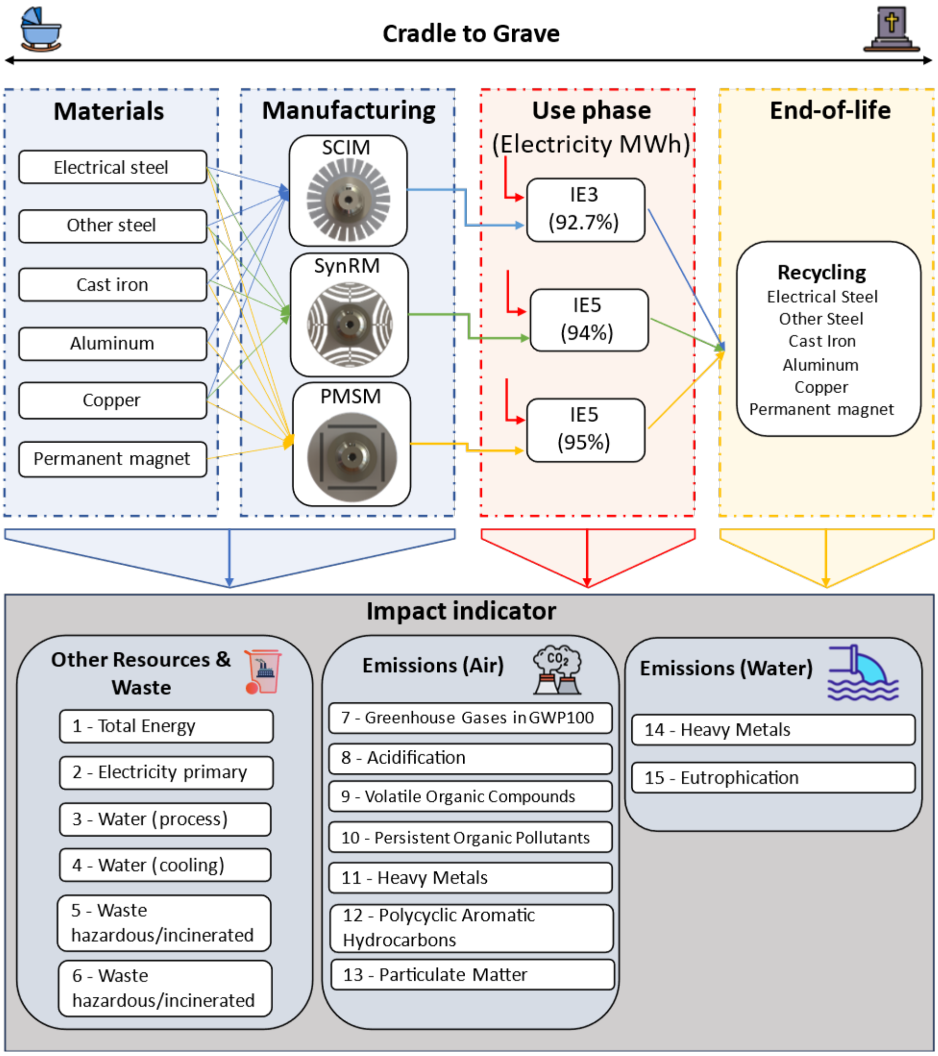


Figure 4 - Flowchart of the methodology used in this study.

2.1 Characteristics of the electric motors analyzed

The study used a power rating of 11 kW to ensure statistical representativeness. Based on the research, in the industrial sector, most drives are associated with electric motors with nominal powers ranging between 4.5 and 15 kW [45]. In addition, 4-pole motors were chosen due to their prevalence, as this speed represents between 50 to 70 % of all-electric drive systems [28], [46].

Although the frame sizes by SCIM, SynRM, and PMSM have varying dimensions, the construction materials of the stator remain consistent across the board. Figure 5 illustrates the distribution of materials in a typical stator and frame for the three technologies under analysis.

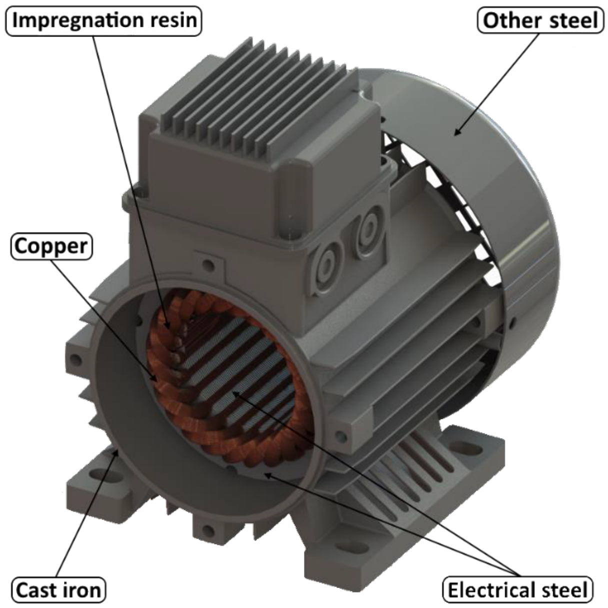


Figure 5 - Typical stator and its primary materials.

Fundamentally, the distinction among the three analyzed technologies lies in the rotor. It is in the rotor where different materials are arranged, characterizing the differences between the technologies. Figure 6 visually displays the rotors' shape and materials for the three technologies under examination.

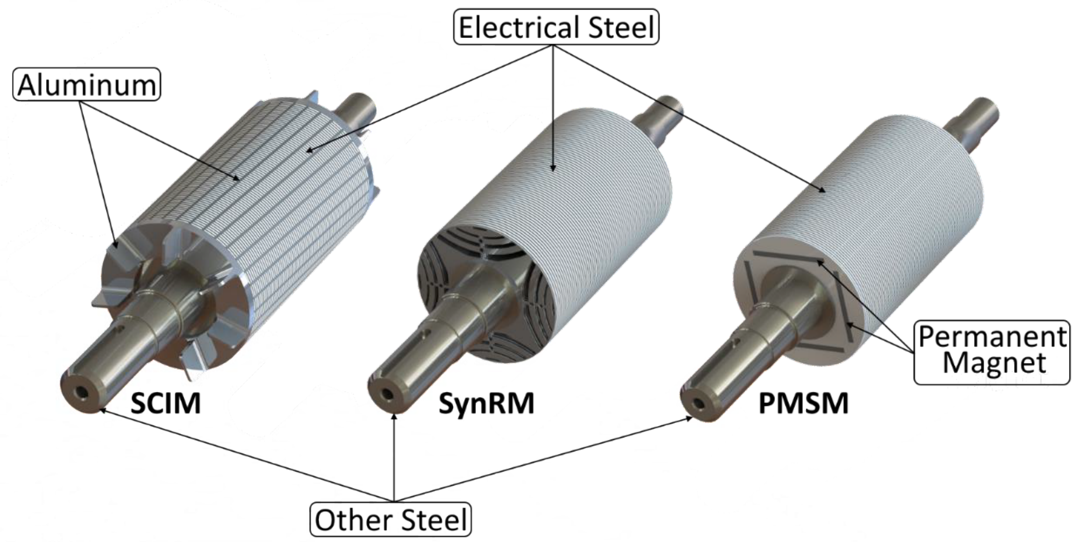


Figure 6 - Rotor of the analyzed technologies with identification of the materials used.

Table 1 shows the bill of materials for the electric motors analyzed: SCIM, SynRM, and PMSM, each representing a specific technology and efficiency level. The bill of materials was provided through a partnership with two large electric motor manufacturing companies worldwide. Therefore, the data shown in Table 1 represents the current market for electric motors.

Table 1 - Bill of materials for 11 kW motor manufacturing for each technology analyzed.

Material	SCIM (IE3)	SynRM (IE5)	PMSM (IE5)
		[kg]	
Electrical Steel (sheets) [Fe, Si]	48.4	80.5	39.0
Other Steel (bearings, shaft, fan shroud)	9.7	13.3	6.1
Cast iron (flange, end bell)	38.1	47.2	18.0
Aluminum (housing, short circuit ring) [Al]	3.7	-	0.6
Copper (winding) [Cu]	11.0	15.8	9.6
Copper (leads) [Cu]	0.2	0.2	0.2
Permanent Magnet (rotor) [Nd, Fe, B]	-	-	1.8
Total	111.1	156.9	75.3

The materials are quantified in kilograms for each motor type (Table 1): the Standard Induction Motor (SCIM) with an International Efficiency (IE) level of IE3, the Synchronous Reluctance Motor (SynRM) with IE5, and the Permanent Magnet Synchronous Motor (PMSM) also with IE5. The table breaks down the constituent materials, including electrical Steel, other types of Steel, cast iron, aluminum, copper, and permanent magnets in the case of the PMSM. Notably, the SynRM (IE5) motor requires the most materials at 156.9 kg, with exceptionally high use of electrical Steel (80.5 kg). In contrast, the PMSM (IE5) is the most material-efficient, weighing 75.3 kg, including the unique component of permanent magnets (1.8 kg).

In the comparative analysis of material composition for different motor technologies, as presented in Figure 7, a distinct distribution pattern emerges when evaluated in percentage terms. For the SCIM (IE3), electrical Steel (Fe, Si) comprises 43.6% of the total material mass, while cast iron (flange, end bell) represents 34.3%, and copper (winding and leads) accounts for 10.1%. In contrast, the SynRM (IE5) demonstrates a higher reliance on electrical Steel, constituting 51.3% of its total mass, with cast iron and copper (winding and leads) contributing 30.1% and 10.1%, respectively. Notably, aluminum is absent in the SynRM composition.

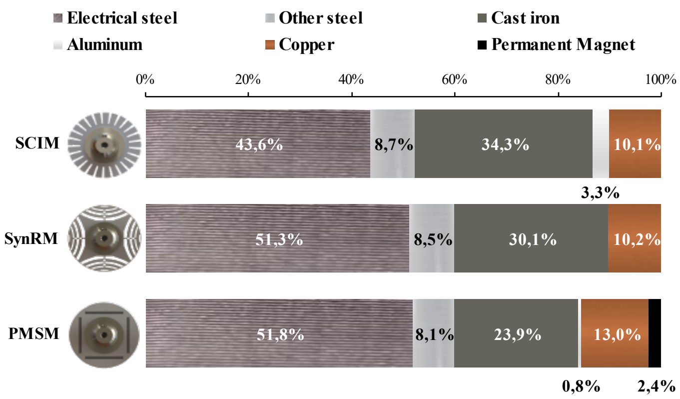


Figure 7 - Percentage of each material used in the electric motors analyzed.

According to Figure 7, the PMSM (IE5) presents a unique material profile, with electrical Steel forming 51.8% of its total mass, closely mirroring the SynRM. However, including permanent magnets (Nd, Fe, B) at 2.4% distinctly sets it apart. The proportions of cast iron and copper (winding and leads) in the PMSM are 23.9% and 12.8%, respectively. Additionally, the

PMSM features the lowest percentage of other steel materials at 8.1%, compared to 8.7% for the SCIM and 8.5% for the SynRM. These percentages reflect the specific material priorities and design considerations of each motor type.

2.2 Characteristics of the stage of use

The analysis aims to compare three technologies. Therefore, electric motors of the same power, which include those with the same load, designed for continuous cycle operation (S1), powered at low voltage, of the same insulation class, and of index protection, were chosen. Table 2 shows the main parameters of the electric motors used in the life cycle analysis.

Table 2 - Parameters Important for the Use Stage of Motors.

Parameter	Value		
	SCIM	SynRM	PMSM
Lifetime [Years]	15	15	15
Operating [hours per year]	3,236	3,236	3,236
Load factor [%]	75	75	75
Full-Load Efficiency [%]*	IE3 - 92.7%	IE5 - 94%	IE5 - 95%
Output power [kW]	11	11	11
FRAME IEC	160M	160ML	132
Torque [Nm]	60	71.5	58.6
Poles	4	4	4

*A loading of 75% does not necessarily represent the point of optimal efficiency; however, it falls within the region of higher efficiency.

In the environmental impact analysis of electric motors during their usage phase, the annual operating hours of the motor emerge as a critical variable. The selected power rating for this analysis, 11 kW, is observed to operate for an average of 3,236 hours annually in the industrial sector of the United States [45]. Consequently, this value has been employed in the comparative life cycle analysis of different motor technologies, as indicated in Table 2.

The electric motors have different frames because the internal volume of the material differs. In the case of the PMSM, the volume of materials is significantly smaller, and consequently, they have a lower frame size. For this reason, it is impossible to make a direct substitution between the PMSM, the SynRM and SCIM because the couplings need to be adapted, requiring more work, material, and energy input. The SynRM and SCIM, on the other hand, have a similar frame, which makes them easier to replace.

In industry, electric motors sometimes operate for more than 30 or 40 years [47]. The life expectancy of a motor depends on factors such as operating hours, maintenance, installation conditions, etc. [48]. However, the IEC 60034-30-1 [22] sets a life expectancy based on shaft power. For this reason, as shown in Table 2, a conservative 15-year service life was used for the 11 kW electric motor.

Most electric motors do not operate at full load nor near the region of optimal efficiency [49], [50]. They often work with misaligned shafts, under non-ideal temperature and humidity conditions, or even with unbalanced voltages [51]–[53]. However, to compare technologies, it is necessary to assume that the operating conditions are ideal. For this reason, as shown in Table 2, the motor was considered to operate at load (75%) with the best efficiency.

2.3 Analysis categories provided by Eco-Report

Table 3 displays the available environmental impact categories in the EuP EcoReport output from the MEErP. Additionally, Table 3 briefly explains each category, its metric unit, and the indication number used as an abbreviation for the category name in the subsequent sections of this study.

Table 3 - Environmental impact categories provided by Eco-Report.

Indicator number	Impact indicator	Units	Description of impact indicators
-	**Other Resources & Waste**	-	-
1	Total Energy (GER)	MJ	Comprehensive energy demand of a process or product, encompassing primary energy requirements, including energy used for electricity (measured in megajoules) and the net calorific value of feedstocks.
2	of which electricity primary	MJ	It signifies the primary energy used for generating electric power, measured in megajoules (MJ) in energy analysis. It encompasses energy consumption across various modes of a product's lifecycle.
3	Water (process)	ltr	The use and management of water within industrial processes, particularly in sectors like mining and beneficiation. It primarily focuses on 'process water', where the water used in operations is often sourced from the public grid and then released as waste or vapor.
4	Water (cooling)	ltr	It refers to the water, often sourced from nearby natural bodies like rivers, used primarily for temperature regulation in industrial processes, such as cooling ovens. The water is then returned to its source, typically at a slightly elevated temperature, leading to "thermal pollution."
5	Waste, non-hazard/landfill	g	It is defined as solid waste material that does not pose a direct chemical or biological risk to the environment or human health. This waste category, typically disposed of in landfills, encompasses a variety of materials considered benign in terms of toxicity and reactivity.
6	Waste, hazardous/ incinerated	g	It refers to waste materials that are inherently dangerous due to their toxic, corrosive, reactive, or ignitable properties. These substances are often disposed of through incineration without heat recovery, a method that significantly reduces the volume and toxicity of the waste.
-	**Emissions (Air)**	-	-
7	Greenhouse Gases in GWP100	kg CO_2 eq.	It refers to the Global Warming Potential of greenhouse gases over 100 years, as standardized by the Intergovernmental Panel on Climate Change (IPCC). This metric quantifies the relative impact of different greenhouse gases, such as CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6, regarding CO_2 equivalence.
8	Acidification, emissions	g SO_2 eq.	It refers to the release of acidifying pollutants like sulfur dioxide (SO_2), nitrogen oxides (NOx), and ammonia (NH_3) into the atmosphere. These emissions contribute to environmental acidification, leading to acid rain that can harm ecosystems, aquatic life, and infrastructure.
9	Volatile Organic Compounds (VOC)	g	They are essential in environmental monitoring and regulation, particularly as precursors to ozone and smog. Subject to EU directives to limit emissions, mainly from organic solvents, VOCs are significant for public health, with high concentrations posing neurological risks.
10	Persistent Organic Pollutants (POP)	ng i-Teq	POPs, including PCBs, dioxins, and furans, are defined under the Stockholm Convention for their long-lasting environmental and health impacts. Often linked to specific products, these pollutants, particularly dioxins and furans from incomplete combustion, are measured in TCDD equivalents.
11	Heavy Metals	mg Ni eq.	They are pollutants, including cadmium, lead, and mercury, known for their persistence and potential health and ecological impacts. These metals are regulated under various directives, with specific emission limit values to control their release into the environment.
12	Polycyclic Aromatic Hydrocarbons (PAHs)	mg Ni eq.	They constitute a significant group of regulated organic compounds, including substances like carbon monoxide and benzene. These compounds are a major focus in air quality studies due to their potential health impacts. Scientifically, PAHs are measured in terms of ng/m^3 Benzo(a)pyrene equivalent, a metric used for consistency with legislative standards and to facilitate comparison with other pollutants, such as heavy metals, using a conversion to nickel equivalent.
13	Particulate Matter (PM, dust)	g	referred to as dust, is a key indicator of smog and human respiratory toxicity. It is categorized into sizes like PM10 and PM2.5, with different health impacts. Scientifically, PM is regulated by setting emission limits,

			such as a 24-hour limit of 50 µg/m³ for PM10, which should not be exceeded more than 35 times a year.
-	**Emissions (Water)**	-	-
14	Heavy Metals	mg Hg/20	In the context of water emissions, they refer to metals and their compounds that have significant environmental impacts, particularly in aquatic ecosystems. This category includes elements like mercury, cadmium, lead, and nickel, each with varying toxicity and potential for bioaccumulation.
15	Eutrophication	g PO_4	Water emissions refer to the nutrient enrichment of water bodies, primarily due to excessive nitrogen and phosphorus. This process leads to the overgrowth of algae and aquatic plants, disrupting the oxygen balance and harming marine life.

The EuP EcoReport does not include the environmental impact inventory of Permanent Magnets [Nd, Fe, B] in its library. Therefore, one of the contributions of this study is the execution of an assessment considering the environmental impacts of manufacturing and end-of-life of permanent magnets, utilizing the Ecoinvent database and additional references. [54]–[57].

In energy-consuming equipment such as electric motors, the life cycle stage is the environmental hotspot [58].

Therefore, the electricity mix consumed in the operational phase is critical in assessing the environmental impacts, and the EuP EcoReport utilizes the electricity mix from the interconnected European grid [59].

3.0 Results and Discussion

Section 3.1 explores the manufacturing phase, highlighting the environmental impacts of material extraction and processing. Section 3.2 shifts focus to the use phase, examining the significant role of motor efficiency in determining energy consumption and emissions over 15 years. Finally, Section 3.3 delves into the end-of-life phase, assessing the challenges in recycling and disposal, particularly concerning materials like Permanent Magnets and Electrical Steel.

3.1 Analysis of the manufacturing phase

The manufacturing phase of electric motors encompasses a complex and multi-faceted process, beginning with the extraction and processing of minerals and culminating in the manufacturing of the equipment. This phase involves various raw materials, such as iron, Silicon, copper, aluminum, and, for PM motors, rare earth elements like Neodymium. These materials undergo rigorous processing to achieve the desired properties for motor components, including electrical steel sheets and permanent magnets. Subsequently, these processed materials are transported to manufacturing facilities, further processed/machined into parts, and intricately assembled into electric motors. This manufacturing stage requires substantial energy input and encompasses various manufacturing processes, including casting, winding, and assembly, each contributing to the overall environmental footprint of the electric motors.

The environmental impacts of the electric motors analyzed (SCIM, SynRM, and PMSM), as detailed in Table 4, are related to the materials used in the production phase, as shown in Table 1. The SCIM, SynRM, and PMSM each use different materials and quantities, influencing their environmental impacts. It can be noted that SynRM motors have the highest consumption of materials, for instance, electrical Steel (80.5 kg compared to 48.4 kg in SCIM and 39.0 kg in PMSM). This is reflected in the environmental impacts, particularly in total energy consumption

(GER) and primary electricity use. SynRM motors have the highest values (7,095 MJ and 1,086 MJ, respectively).

Table 4 - Environmental impacts of the electric motor manufacturing phase.

Indicator number	Impact indicator	SCIM	SynRM	PMSM
-	**Other Resources & Waste**	-	-	-
1	Total Energy (GER) [MJ]	4,863	7,095	4,501
2	of which electricity primary [MJ]	689	1,086	520
3	Water (process) [ltr]	57	73	1,172
4	Water (cooling) [ltr]	378	548	246
5	Waste, non-hazard/landfill [g]	107,607	170,345	80,866
6	Waste, hazardous/incinerated [g]	9	13	8
-	**Emissions (Air)**	-	-	-
7	Greenhouse Gases in GWP100 [kg CO_2 eq.]	336	493	387
8	Acidification, emissions [g SO_2 eq.]	4,196	6,005	3,840
9	Volatile Organic Compounds (VOC) [g]	13	19	9
10	Persistent Organic Pollutants (POP) [ng i-Teq]	1,824	2,686	1,296
11	Heavy Metals [mg Ni eq.]	1,029	1,519	1,433
12	Polycyclic Aromatic Hydrocarbons (PAHs) [mg Ni eq.]	132	96	273
13	Particulate Matter (PM, dust) [g]	756	993	686
-	**Emissions (Water)**	-	-	-
14	Heavy Metals [mg Hg/20]	334	470	2,949
15	Eutrophication [g PO_4]	7	10	6

Regarding water usage, PMSM stands out with a significantly higher requirement for process water (1,172 litres), linked to the rare earth elements in the permanent magnets (1.8 kg of Nd, Fe, B). The processing of these elements typically demands extensive water use, contributing to PMSM's higher water footprint. However, PMSM motors require less cooling Water (246 litres) due to more efficient thermal management enabled by their design and material composition.

SynRM motors present the highest GHG emissions (493 kg CO_2 eq.) and acidification emissions (6,005 g SO_2 eq.) due to a higher material and energy consumption. The PMSM motors have a higher release of heavy metals in water (2,949 mg Hg/20) despite their lower total material weight (75.3 kg).

Figure 8 graphically represents the data from Table 4, aiming to facilitate the comparison of the three technologies across various categories. It was observed that SynRM exhibited a higher impact in almost all categories, primarily due to the increased use of materials during the manufacturing phase. Having utilized fewer materials, PMSM demonstrated lower impacts in most categories. However, in the categories of water (process), Polycyclic Aromatic Hydrocarbons (PAHs), and Heavy Metals, PMSM showed significantly higher impacts compared to the other technologies, attributable to the use of rare earth metals (Permanent Magnets).

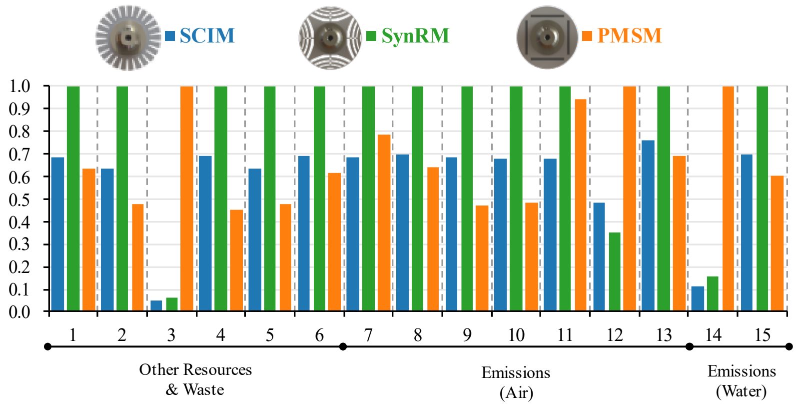


Figure 8 - Environmental impacts of the electric motor manufacturing phase.

3.2 Analysis of the use phase

The environmental impacts during the use phase of electric motors are significantly influenced by their efficiency levels. The Squirrel Cage Induction Motors (SCIM), rated at IE3 with 92.7% efficiency (Table 2), consumed substantially more total energy (3.88 TJ) over 15 years compared to the more efficient IE5-rated Synchronous Reluctance Motors (SynRM) and Permanent Magnet Synchronous Motors (PMSM), which consumed 3.83 TJ and 3.79 TJ, respectively (Table 5 and Figure 9). This lower energy consumption for the ultra-higher efficiency motors resulted in proportionately less primary electricity usage, with PMSM using the least, demonstrating the environmental advantage of adopting ultra-higher efficiency motors.

Table 5 - Environmental impacts of the electric motor use phase in 15 years.

Indicator number	Impact indicator	SCIM	SynRM	PMSM
-	**Other Resources & Waste**	-	-	-
1	Total Energy (GER) [MJ]	3,889,176	3,833,489	3,794,158
2	of which electricity primary [MJ]	3,889,148	3,833,449	3,794,130
3	Water (process) [ltr]	23,632	23,300	23,064
4	Water (cooling) [ltr]	172,852	170,377	168,629
5	Waste, non-hazard/landfill [g]	2,004,988	1,976,738	1,955,828
6	Waste, hazardous/incinerated [g]	61,362	60,483	59,863
-	**Emissions (Air)**	-	-	-
7	Greenhouse Gases in GWP100 [kg CO_2 eq.]	166,016	163,640	161,961
8	Acidification, emissions [g SO_2 eq.]	734,646	724,138	716,696
9	Volatile Organic Compounds (VOC) [g]	86,858	85,614	84,736
10	Persistent Organic Pollutants (POP) [ng i-Teq]	9,088	8,964	8,862
11	Heavy Metals [mg Ni eq.]	39,331	38,771	38,373
12	Polycyclic Aromatic Hydrocarbons (PAHs) [mg Ni eq.]	9,076	8,945	8,855
13	Particulate Matter (PM, dust) [g]	15,562	15,341	15,182
-	**Emissions (Water)**	-	-	-
14	Heavy Metals [mg Hg/20]	16,744	16,505	16,355
15	Eutrophication [g PO_4]	735	725	717

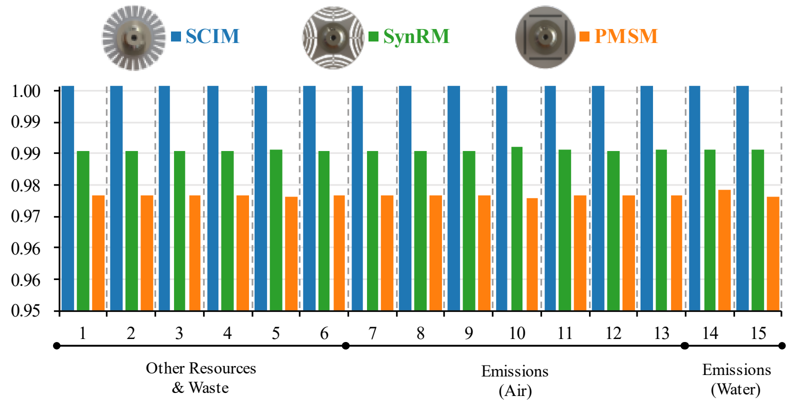


Figure 9 - Environmental impacts of the electric motor use phase.

Waste production also displayed a clear distinction between technologies. SCIM motors produced the most non-hazardous waste for landfill (2,01 tons) and hazardous/incinerated waste (61.4 kg). In contrast, SynRM and PMSM (Table 5 and Figure 9), particularly the latter with waste figures at 1.95 tons and 59.9 kg, respectively, generated less waste, correlating with their higher efficiencies.

Greenhouse gas emissions from SCIMs were the highest (166 tCO_2 eq.), while PMSMs were responsible for the lowest emissions (161.9 tCO_2 eq.). This trend was observed across other emission categories, including acidification emissions and particulate matter, with PMSM showing less environmental impact (716.7 kg SO_2 eq. for acidification and 15.2 kg for particulate matter), which underscores the environmental benefits of higher efficiency as evidenced by PMSM's 95% efficiency in Table 2.

The analysis underscores that as electric motor technologies evolve towards higher efficiency levels, as exemplified by the transition from IE3 to IE5, there is a significant reduction in their environmental impacts during the use phase. This reduction is manifested across various indicators, from energy consumption to emissions, highlighting the critical role of motor efficiency improvements during the use phase. Other benefits are anticipated since the lower losses lead to lower operating temperatures, allowing longer lifetimes (cooler bearings and windings).

Although the total weight of different types of electric motors shows variations, the impacts among phases in transportation are relatively small and, therefore, negligible for this analysis. The study's primary objective involves comparing the technologies themselves and assuming that the emissions associated with transportation are minimally different among the three types of motors. Thus, transportation impacts during the motors' life phase and maintenance are less relevant in this study; therefore, they were not included in the analysis.

Additionally, SynRM and PMSM motor technologies present improved operating characteristics in part-load operation. As shown in Figure 10, the part-load efficiency of SynRM and PMSM motors is much improved compared to induction motors, which can sometimes translate into significant energy savings in applications operating at part load.

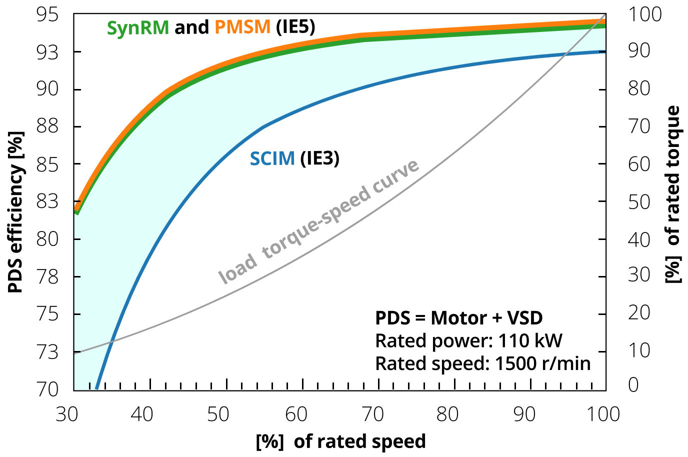


Figure 10 - Efficiency comparison of a 110-kW PDS (Power Drive System) with IE3-class SCIM and IE5-class SynRM and PMSM considering a quadratic-torque load fan or pumping system without a static head.

3.3 Analysis of the end-of-life phase

During the end-of-life phase of electric motors, the environmental impacts varied significantly across Squirrel Cage Induction Motors (SCIM), Synchronous Reluctance Motors (SynRM), and Permanent Magnet Synchronous Motors (PMSM), as indicated in Table 6 and Figure 11. SCIMs, with a relatively simple design and lesser material usage (Table 1), resulted in a lower total energy consumption (GER) of 702 MJ at the end-of-life. In contrast, SynRMs, which required more Electrical Steel to achieve higher efficiency, showed a notable increase in total energy consumption (1,009 MJ) and waste generation (1,774 g non-hazardous).

Table 6 - Environmental impacts of the electric motor end-of-life phase.

Indicator number	Impact indicator	SCIM	SynRM	PMSM
-	**Other Resources & Waste**	-	-	-
1	Total Energy (GER) [MJ]	702	1,009	510
2	of which electricity primary [MJ]	0	0	0
3	Water (process) [ltr]	0	0	0
4	Water (cooling) [ltr]	0	0	0
5	Waste, non-hazard/landfill [g]	1,255	1,774	948
6	Waste, hazardous/incinerated [g]	0	0	0
-	**Emissions (Air)**	-	-	-
7	Greenhouse Gases in GWP100 [kg CO_2 eq.]	52	75	38
8	Acidification, emissions [g SO_2 eq.]	102	147	74
9	Volatile Organic Compounds (VOC) [g]	2	3	2
10	Persistent Organic Pollutants (POP) [ng i-Teq]	47	66	35
11	Heavy Metals [mg Ni eq.]	198	284	144
12	Polycyclic Aromatic Hydrocarbons (PAHs) [mg Ni eq.]	0	0	0
13	Particulate Matter (PM, dust) [g]	903	1,298	657
-	**Emissions (Water)**	-	-	-
14	Heavy Metals [mg Hg/20]	59	85	43
15	Eutrophication [g PO_4]	3	5	2

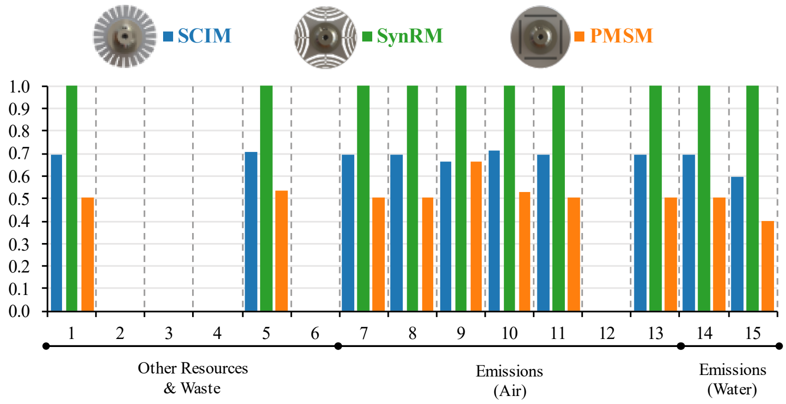


Figure 11 - Environmental impacts of the electric motor end-of-life phase.

PMSMs, despite using the least amount of materials overall (75.3 kg), as shown in Table 1, faced specific challenges at the end of life due to the inclusion of Permanent Magnet materials. These magnets, composed of rare earth elements, are notoriously difficult to recycle, leading to a heightened environmental impact in specific categories. For instance, PMSMs recorded a total energy consumption of 510 MJ, which was less than SynRMs but more impactful due to the nature of the materials involved. Additionally, their waste generation (948 g non-hazardous) and emissions of heavy metals in water (43 mg Hg/20) were significant, reflecting the complexities of recycling these specialized materials.

The analysis underscored that the end-of-life environmental impacts of electric motors are, as expected, intrinsically linked to the quantity and recyclability of materials used. While SCIMs demonstrated lower implications due to their more straightforward construction and more readily recyclable materials, SynRMs and PMSMs encountered more significant challenges due to their use of materials like Electrical Steel and Permanent Magnets.

In the case of Permanent Magnets, predominantly composed of NdFeB with the addition of Dysprosium (Dy) to increase the maximum temperature range of operations without demagnetization, the following recycling challenges were observed: i) they are fragile, brittle, and difficult to mold after production; ii) the Curie point (the temperature at which they lose magnetization) is relatively low compared to other magnetic materials; iii) there is a lack of developed, efficient, and integrated recycling routes; and iv) few products require permanent magnets for non-noble uses [60]–[63]. However, recycling strategies have been increasingly explored due to the increasing use of Permanent Magnets in sectors such as wind turbine alternators, electric motors, and motors for hybrid and electric vehicles [64], [65]. Since this is a major growing market, permanent magnets were also considered recycled at the end of the PMSM lifetime.

The electrical Steel used in electric motors consists of Steel and Silicon. Silicon was added to the material because it reduces its conductivity, resulting in lower losses due to eddy currents. It narrows the hysteresis loop (area of magnetic losses), resulting in lower hysteresis losses. The amount of Silicon added to the alloy in a commercial product typically reaches up to 3.2%, as higher concentrations could cause brittleness during the cutting of the material into sheets (cold rolling) [58].

In the case of Electrical Steel, which accounted for nearly half of the materials used in each of the electric motors in this study, two primary challenges in the recycling process were fundamentally observed:

1. Silicon steel's use is limited; it is essentially applied to electrical equipment, electric motors, and transformers. Based on this study, efficiency is a central element in these devices, making using recycled materials in their composition uncommon. In the case of transformers, the Electrical Steel used is of the 'grain-oriented' type. In contrast, 'non-grain-oriented' Steel is used in electric motors, reducing its re-usability to just electric motors [66].
2. Metal recycling circuits are generally for direct use as mixtures in Steel for less noble applications rather than in the active parts of energy-consuming equipment. However, Silicon acts as a contaminant, and only small quantities of Electrical Steel can be added to each melting batch without compromising the process [67].

Nevertheless, electrical Steel was considered recycled in this study, as its use in less noble applications, such as civil construction, is possible, provided appropriate care is taken in the recycling process.

3.3 Analysis of total environmental impacts

SCIMs, with a total energy consumption (GER) of 5,191,573 MJ, were less efficient than SynRMs and PMSMs. This higher energy consumption of SCIMs was a direct consequence of their lower efficiency, as shown in Table 1. SynRMs were more efficient and showed notable saved energy in the total life cycle compared to SCIM. Furthermore, due to the higher material usage, particularly electrical Steel, and mainly the lower efficiency, the SynRMs presented more environmental impacts in life cycle assessment than PMSM in most categories (Table 7 and Figure 12).

Table 7 – Total environmental impacts of the electric motor.

Indicator number	Impact indicator	SCIM	SynRM	PMSM
-	**Other Resources & Waste**	-	-	-
1	Total Energy (GER) [MJ]	3,894,741	3,841,593	3,799,169
2	of which electricity primary [MJ]	3,889,837	3,834,535	3,794,650
3	Water (process) [ltr]	23,689	23,373	24,236
4	Water (cooling) [ltr]	173,230	170,925	168,875
5	Waste, non-hazard/landfill [g]	2,113,850	2,148,857	2,037,642
6	Waste, hazardous/incinerated [g]	61,371	60,496	59,871
-	**Emissions (Air)**	-	-	-
7	Greenhouse Gases in GWP100 [kg CO_2 eq.]	166,404	164,208	162,386
8	Acidification, emissions [g SO_2 eq.]	738,944	730,290	720,610
9	Volatile Organic Compounds (VOC) [g]	86,873	85,636	84,747
10	Persistent Organic Pollutants (POP) [ng i-Teq]	10,959	11,716	10,193
11	Heavy Metals [mg Ni eq.]	40,558	40,574	39,950
12	Polycyclic Aromatic Hydrocarbons (PAHs) [mg Ni eq.]	9,208	9,041	9,128
13	Particulate Matter (PM, dust) [g]	17,221	17,632	16,525
-	**Emissions (Water)**	-	-	-
14	Heavy Metals [mg Hg/20]	17,137	17,060	19,347
15	Eutrophication [g PO_4]	745	739.5	725

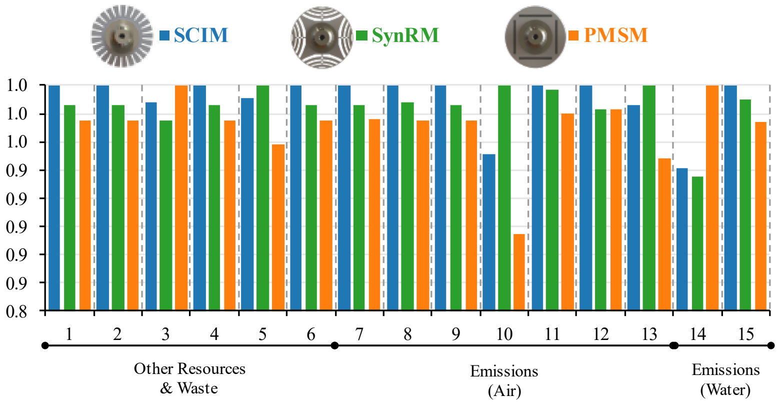


Figure 12 - Total environmental impacts of the electric motor.

The waste generation and emissions categories highlighted the impact of materials used in motor construction. SynRMs produced the most non-hazardous waste (1.15 tons) compared to SCIMs and PMSMs (Table 7 and Figure 12)`. This increased waste and emissions were primary to the more significant amount of Electrical Steel used in SynRMs, as stated in Table 1. In contrast, PMSMs, despite their use of Permanent Magnets, which are also difficult to recycle, managed to keep their total energy consumption and waste generation relatively lower (3.79 TJ and 2.04 ton, respectively).

The potential for reducing environmental impacts through recycled materials is substantial in electric motor manufacturing, particularly for specific components. While Electrical Steel (sheets) [Fe, Si] and Permanent Magnets [Nd, Fe, B] present challenges in recycling due to their complex compositions and specialized properties, other materials such as other Steel (bearings, shaft, fan shroud), cast iron (flange, end bell), aluminum (housing, short circuit ring), and copper (winding and leads) are more amenable to recycling. Utilizing recycled materials for these components can significantly lower the environmental burden of raw material extraction and processing.

As illustrated in Figures 13, 14, and 15, the usage phase of electric motors proved to be the most impactful for all technologies, given that these motors are highly energy-intensive. In most impact categories analyzed, the usage phase accounted for over 90% of the impacts for the time used for 15 years (3,236 hours per year), indicating that minor gains in efficiency can significantly influence the life cycle impacts of electric motors.

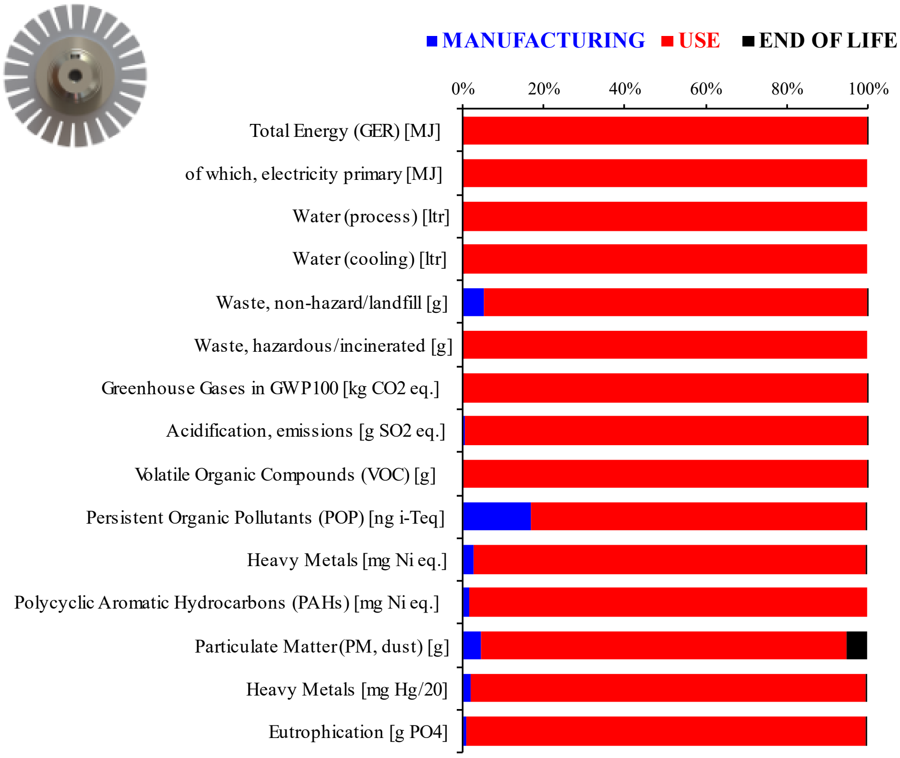


Figure 13 - Comparison of environmental impacts between the three main phases - SCIM.

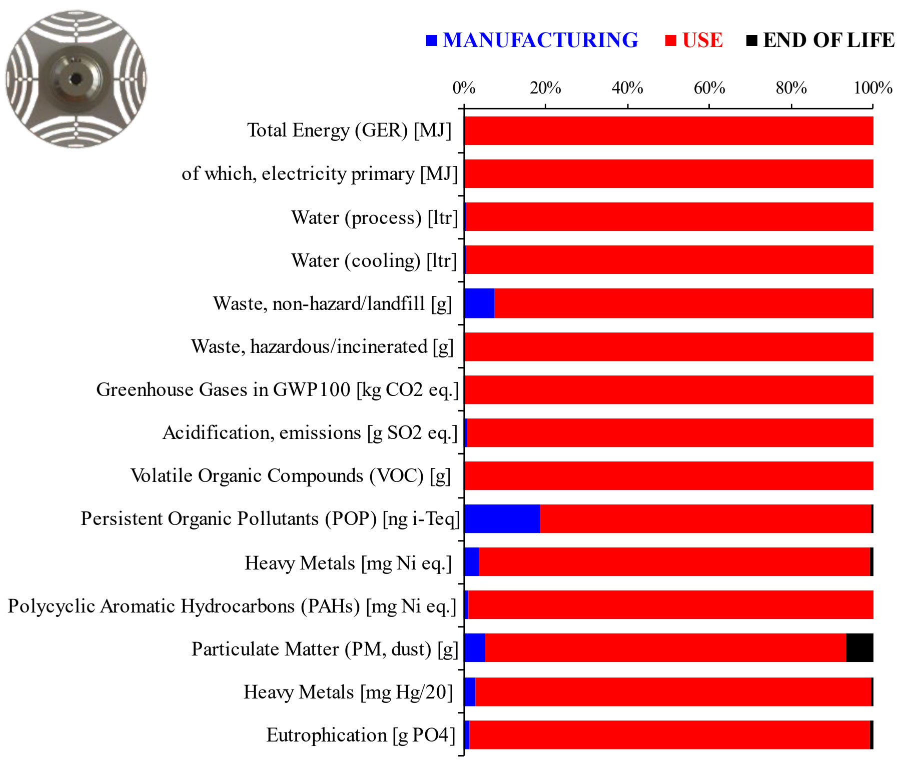


Figure 14 - Comparison of environmental impacts between the three main phases - SynRM.

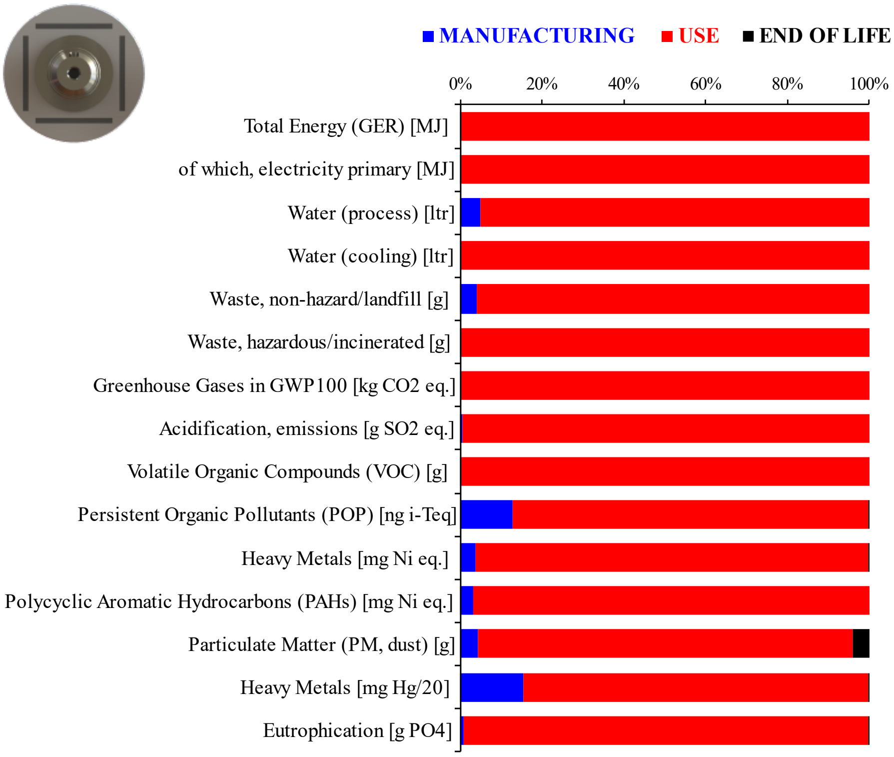


Figure 15 - Comparison of environmental impacts between the three main phases - PMSM.

Out of the 8760 hours in a year, the manufacturing phase and the end-of-life of electric motors only begin to predominate in the life cycle analysis for annual usages below 100 hours, as exemplified by the PMSM in Figure 16.

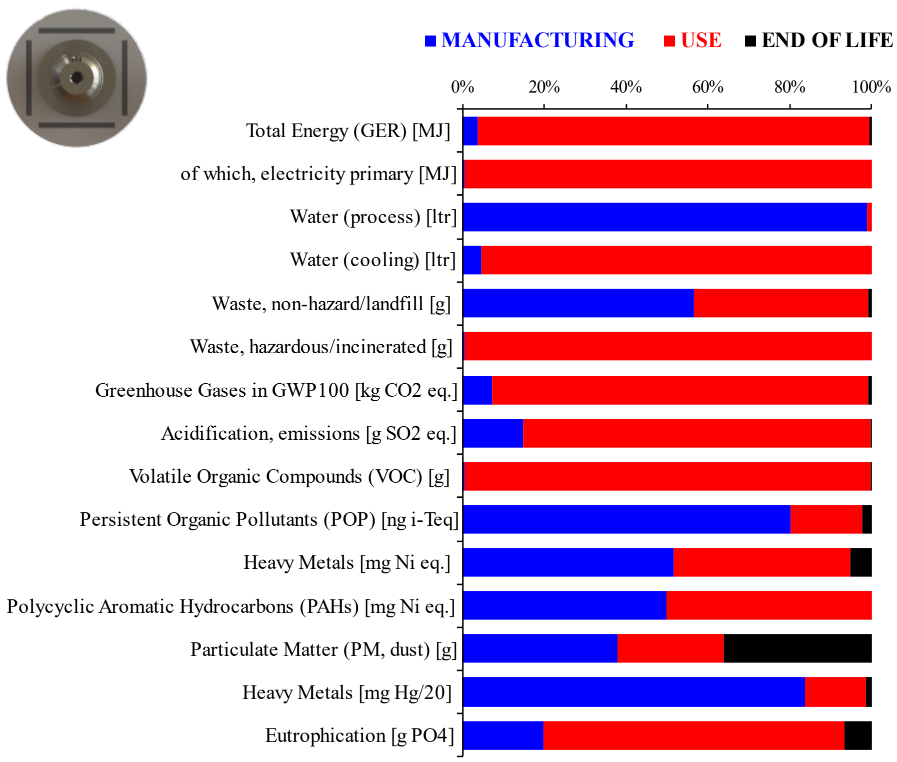


Figure 16 - Comparison of environmental impacts between the three main phases operating 100 hours per year - PMSM.

4.0 Conclusion

A significant effort is being taken worldwide to encourage energy efficiency and energy-efficient motor technologies, namely IE5, as recommended by the International Energy Agency, which can only be achieved by new alternative technologies, such as SynRM and PMSM. The analysis conducted in this research provides a deep understanding of the environmental life cycle impacts of different electric motors: Squirrel Cage Induction Motors (SCIM), Synchronous Reluctance Motors (SynRM), and Permanent Magnet Synchronous Motors (PMSM). The EuP EcoReport, utilized in this study, emerges as a straightforward and effective tool for the life cycle assessment of energy-consuming equipment. This tool proved instrumental in highlighting the differences in environmental impacts based on material use and efficiency levels.

The production phase demonstrated varied impacts among the motor technologies driven by different materials. PMSMs exhibited more significant impacts in some categories, notably due to using rare earth metals for permanent magnets. Conversely, SynRMs showed increased impacts across numerous production categories attributed to their higher material usage. Thus, the more efficient IE5 motors (SynRM and PMSM) presented more significant production impacts than the less efficient IE3 motor (SCIM).

During the use phase, SCIMs, with the lowest energy efficiency, were the most impactful. This finding underscores the significant environmental benefits of replacing IE3 motors with the more efficient IE5-rated SynRM or PMSM, especially considering the entire life cycle. The comprehensive analysis revealed that despite higher manufacturing impacts, the overall environmental advantages of IE5 motors are evident in their operational phase.

The end-of-life analysis showed that most electric motor components are recyclable, resulting in lower impacts in this phase. Despite the challenges posed by materials like Electrical Steel and Permanent Magnets, the high recyclability of most components mitigates the end-of-life environmental burden.

The usage phase accounted for most environmental impacts across most categories. This dominance of the usage phase in the overall environmental impact highlights the critical importance of focusing on operational efficiency in motor design and selection.

The life cycle analysis of energy-consuming equipment, such as electric motors, is crucial for a more sustainable future. It informs the selection of technologies based on operational efficiency and emphasizes the need to consider environmental impacts at every stage of the product's life.

4.1 Limitations and Research gaps for further study

During the literature review and execution of this study, five research gaps were identified for the continuation of studies:

[1] During the usage phase of electric motors, preventive and corrective maintenance is frequently conducted. In corrective maintenance, the windings located in the stator and the bearings are typically replaced. Therefore, it would be beneficial to consider replacing these components in the life cycle analyses of electric motors according to their operational cycle.

[2] The use of materials in electric motors does not increase linearly with power. Thus, investigating the environmental impact of the life cycle of different technologies for less commonly used power ratings, such as higher (above 100 kW) and lower (below 5 kW) capacities, is of interest.

[3] To achieve the IE4 efficiency level, SCIMs need to increase the amount of copper in their stator windings significantly. Consequently, it is important to compare the environmental impacts in the life cycle of IE4-level SCIMs with SynRM at IE4 and IE5 levels to assess the feasibility of using SCIMs at the IE4 level.

[4] Life Cycle Assessments (LCAs) for electric motors typically focus on the most quantitatively significant materials, as they produce the greatest environmental impacts. However, a more detailed LCA could be conducted by also evaluating less representative items, such as Insulation material (terminal board, winding insulation), Impregnation resin (winding impregnation), Plastics (fans), Paint, and Packing.

[5] For loads that benefit from speed/torque control (estimated over 50% of all motor loads), variable speed drive (VSD) is widely used in SCIMs to enhance energy efficiency and optimize process control. For SynRM and PMSM, drivers are mandatory for starting and speed control. Consequently, it is pertinent to include the electronic materials of these drivers in future Life Cycle Assessments (LCAs). Additionally, for low-power electric motors, conducting LCAs of Line-Starters, which feature a squirrel cage in their rotor for starting, similar to SCIMs, is advisable. This inclusion of materials could also differentiate the environmental impacts.

[6] The usage phase of electric motors was the most impactful in the life cycle. The most significant factor in determining the environmental impacts during the usage phase was the primary energy mix of resources used for electricity conversion. For this reason, it was important to assess the life of electric motors operating in different energy mixes, ranging from the cleanest (100% renewable) through various scenarios to the dirtiest (100% coal).

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