energies

MDPI

Review

The Impact of Air Renewal with Heat-Recovery Technologies on Energy Consumption for Different Types of Environments in Brazilian Buildings

York Castillo Santiago [1,2,*], Daiane Busanello [3], Alexandre F. Santos [3], Osvaldo J. Venturini [4] and Leandro A. Sphaier [1]

1 Laboratory of Thermal Sciences (LATERMO), Mechanical Engineering Department (TEM/PGMEC), Fluminense Federal University, Rua Passo da Pátria 156, Niterói 24210-240, RJ, Brazil; lasphaier@id.uff.br
2 Laboratório de Otimização, Projeto e Controle Avançado, Falculdade de Engenharia Química, Universidade Estadual de Campinas (UNICAMP), Av. Albert Einstein 500, Campinas 13083-852, SP, Brazil
3 Escola Técnica Profissional, Grupo ETP, Rua Eng. Rebouças 2213, Curitiba 80230-040, PR, Brazil; daiane.etp@gmail.com (D.B.); projetos.etp@gmail.com (A.F.S.)
4 Excellence Group in Thermal Power and Distributed Generation (NEST), Federal University of Itajubá (UNIFEI), Av. BPS 1303, Itajubá 37500-903, MG, Brazil; osvaldo@unifei.edu.br
* Correspondence: yorkcastillo@id.uff.br

Abstract: This work evaluates the impact of air renewal on energy consumption for indoor environments. For this purpose, an analysis of the problem of air renewal at a Brazilian level was carried out, as well as research into the energy impact of air renewal without energy recovery and the different existing technologies for recovering energy from renewed air. On the other hand, the influence of heat-recovery systems was analyzed in three Brazilian cities (Manaus, São Paulo, and Brasília) for different environments, where a classroom in Manaus has an approximately 50% external air factor and a 42% sensible heat factor. However, classrooms in São Paulo and Brasília have a lower external air factor (27% and 8%, respectively) and a higher sensible heat factor (61% and 78%, respectively). Considering a system with heat recovery, the external air factor decreases to 23%, 10%, and 3% for Manaus, São Paulo, and Brasília, respectively. This allows us to understand the influence of heat-recovery systems, which reduce the external air factor and increase the sensible heat factor.

Keywords: heat-recovery technologies; Köppen classification; air conditioning; HVAC systems; residential buildings; energy efficiency

check for updates

Citation: Castillo Santiago, Y.; Busanello, D.; Santos, A.F.; Venturini, O.J.; Sphaier, L.A. The Impact of Air Renewal with Heat-Recovery Technologies on Energy Consumption for Different Types of Environments in Brazilian Buildings. *Energies* **2024**, *17*, 4065. https://doi.org/10.3390/en17164065

Academic Editors: Marek Pavlík and Ján Zbojovský

Received: 8 July 2024
Revised: 11 August 2024
Accepted: 13 August 2024
Published: 16 August 2024

1. Introduction

The International Energy Agency indicates that the global air conditioning (AC) system count has surpassed 500 million. Furthermore, only 8% of the 2.8 billion people in the world's warmest regions have access to AC. This number is projected to rise to 5.6 billion by 2050, a staggering increase from 1.6 billion in 2018 [1]. Through rapid growth, the energy demand for air conditioning by 2050 will be equivalent to the current electrical demand of the United States (US), the European Union, and Japan. Therefore, ten AC units could be sold every second, a scale that is difficult to comprehend [2]. In 2018, the households with AC reached an average of 90% in some countries (such as the US and Japan) and less than 10% in others. Furthermore, around 69% of units installed worldwide are attributed downwardly to China and the US, among others [1]. However, this is expected to change considerably over the next thirty years. The use of AC units will become increasingly popular due to population and economic growth in warm regions [3]. It is worth mentioning that, in economies with a higher cost of capital, such as Brazil, or with lower hours of use, higher-efficiency ACs cause a higher cost of saved electricity when compared to India or the United Arab Emirates. In countries like Japan, where ACs are used for both heating and cooling, while in India or the United Arab Emirates, where ACs are used for many hours annually, it is possible to obtain a very high ESEER (European seasonal energy-efficiency ratio) at a low cost per unit of electrical energy saved [4].

It is essential to highlight that the previously mentioned estimates only consider a market where customers can pay for refrigeration facilities. If we include all populations that need access to refrigeration facilities regardless of ability to pay, 14 billion refrigeration units would be required by 2050 [5]. Around 70% of the projected increase in the refrigeration section will occur in economically developing countries located in tropical regions, with economically developing countries expected to see a five-fold increase in AC units by 2050 [6]. AC sales in Brazil and India have increased between 10 and 15% each year [5].

ACs consume around 20% of the total electrical energy in residential, corporate, and government buildings worldwide. In China, Brazil, and India, AC puts pressure on electrical systems, changes the peak load, and increases greenhouse-gas (GHG) emissions. This trend, if left unchecked, could have severe environmental consequences [7]. In some regions of Brazil, AC is responsible for 7% of electricity consumption in residential use. In Minas Gerais state, AC is responsible for 38–63% of the total electricity consumed in the banking sector. The principal reasons for the rapid diffusion of AC in Brazil are the inhabitants and economic expansion, especially in hot climate regions. The ACs in Brazilian homes are estimated to increase from 19% (2019) to 27% (2029) [8].

The use of energy has intensified substantially in the last few years. In 2018, the electric energy consumption worldwide corresponded to 23,031 TWh, 57% higher than in 2000 [9]. Given the sector's increased energy demand, residential buildings are essential. In Brazil, the Energy Research Office (EPE) estimated that, in 2018, the total electric energy demand (25.4%) across the country came mainly from the residential sector [10]. In addition, this sector's energy required is projected to rise by around 3.9% by 2029 [11]. Considering the augmented acquiring power of inhabitants in economically developing countries and the climate-change challenge, a substantial demand exists for AC in residential buildings. According to the EPE's report titled Ten-Year Energy Expansion Plan, the devices that will utilize the most electricity by 2029 will be the ACs, which are in fourth place, only surpassed by the fridge–freezer, TV, and electric shower [12].

Furthermore, in Brazil, electricity consumption for cooling warmer environments tripled between the early 1990s and 2016. During these years, the consumption increased from 10 TWh to almost 32 TWh and continues to increase. The demand for AC in Brazilian buildings is rising and will represent a significant fraction of national electricity consumption in the future, which could cause negative impacts on the global environment [13]. The sale of ACs stretched out to 27 million units in 2016 and is currently predicted to surpass 30 million, with sales higher than 3 million units by year between 2018 and 2021 [7]. Regardless of this increase, the electric energy consumption per unit of population for refrigerated areas remains lower in Brazil than in industrialized countries, even those with cold temperatures. In Brazil, the purchase of AC units in the household sector is approximately 16.7%. Nevertheless, most buildings in Brazil are characterized by being in bioclimatic zones, where a hot and humid climate prevails in the summer and dry and cold temperatures in the winter [14].

The AC systems installed in government and particular buildings are related to higher electrical consumption in equatorial countries due to the elevated temperatures, where the Brazilian Northeast region is localized. This region is characterized by high payments on electric energy invoices [15]. Usually, the electricity consumption due to AC use is approximately 50% of the total bill since conventional ACs (vapor compression) are mostly installed [16]. The general efficiency of conventional AC systems used in Brazil is between 30 and 40% [17].

According to the National Electric Energy Conservation Program (PROCEL) [18], heating, ventilation, and air conditioning systems contribute 48% of total electricity use in Brazilian buildings, with unitary AC systems predominant, such as unitary windows and split units. On the other hand, heater systems are uncommon in Brazil because of the higher temperatures during the year. Therefore, electricity consumption corresponded to

92.3% of the electric energy consumed in Brazilian service buildings in 2019 [19]. Only 10.5% of homes in Brazil have a heating, ventilation, and air conditioning (HVAC) system. The use of HVAC systems is different for each region and is not related to the average in-come level. For example, the Brazilian North region has the highest purchase tax of HVAC systems (16.5%) and the lowest average income in Brazil. The South Region, the 2nd high-est-income Brazilian region, follows closely with 16.1% [20]. The high HVAC purchase is congruent in the Northern region, characterized by the Amazon region's presence, which has high temperatures and humidity. The Southern region has many HVAC systems installed, although it is a Brazilian region with a milder climate and cold temperatures, and in the winter season, it is close to freezing. PROCEL [18] indicated that some HVAC sys-tems of the South region could be operated in a reverse cycle, thus allowing spaces to be heated and cooled. This adaptability to different climate conditions reassures the effec-tiveness of these systems.

AC units that operate at a capacity lower than 18,000 BTU/h are the predominant refrigeration systems of all types in Brazil. This widespread use underscores the urgency of addressing their energy efficiency [21]. Another type of system well-known in the refrigeration market is Variable Refrigerant Flow (VRF), developed in Japan in 1982 and entered the HVAC market in Europe in 1987 [22]. The VRF and split AC units make up 82% of the world's AC systems, so it's crucial to rethink the types of AC systems for sustainability from a refrigerant perspective. Despite their energy efficiency, these systems must be ana-lyzed for their environmental impact. [1]. Approximately 113 million split units were dis-tributed worldwide in 2018, with China and APAC nations contributing 70% of the 113 million [23]. Around 3 million splits with a capacity of less than 30 thousand BTU/h were distributed in 2014 in Brazil, corresponding to 70% of trades for AC systems. In addition, split units were installed in 72% of residential and corporate buildings in Brazil in 2018. Consequently, the Brazilian air conditioning and refrigeration sector in 2021 showed a percentage growth of 9.8% until 2020, while the number of split units manufactured sur-passed 3.5 million in 2021 [24].

This work aims to measure the energy impact associated with air renewal and compare different technologies with and without heat recovery, indicating the effects of each. For this purpose, the energy problem involved in air renewal in air conditioning systems without or using energy-recovery technology is analyzed. Consequently, the economic and environmental impact of the technologies considered is evaluated, taking as a reference the air renewal rates provided for in internationally accepted standards and adopted in Brazil. Thus, a case study is developed, considering three Brazilian cities with different climate zones, tariffs, types of buildings, etc. The results allow us to identify the energy advantages of adopting air renewal technologies with energy recovery in Brazil.

2. Analysis of the Brazilian Bioclimatic Zones

The energy sector's significant role in human environmental impact, mainly through GHG emissions from energy production, underscores the urgent need for energy efficiency measures [25]. The construction sector has higher energy consumers than all industrial sectors [26]. In 2021, Brazilian buildings accounted for 52% of energy consumption; there is a significant opportunity to promote energy efficiency and contribute to sustainable development [27]. As professionals in the construction sector, your role in achieving energy efficiency is crucial. Understanding the complex factors that affect electric energy consumption in buildings, such as surroundings, climate, equipment and its O&M, occupant behavior, and indoor air quality, is key to this endeavor [9]. Therefore, optimizing a building involves understanding the thermal trends inside and outside the building. It is worth noting that household buildings account for 9.3% of the electricity consumption in Brazil. Furthermore, household-building electricity consumption indicates growth behavior, with an average augment by year of 5.7% from 1975 to 2015 [28]. Therefore, the implementation of energy-efficiency programs and the installation of eco-friendly ACs are essential.

The National Energy Plan (PNE) 2030 [29] has projected a concerning trend. Brazil's annual energy electric consumption is set to double, leading to a significant augment in the non-renewable sources used. To address this, the PNE set a crucial goal for the first time in 2010: a 10% decrease in the estimated energy demand. This underscores the urgent need for implementing energy-efficiency strategies [30]. A tariff flag was implemented in 2015 to transfer the electricity generation costs to these accounts due to unfavorable hydrological conditions since the Brazilian energetic matrix comprises mainly hydrological sources. The tariff flag is used by considering the thermal generation necessity associated with the low levels of hydroelectric reservoirs, which impact the bills of consumers. A significant effort in search of greater energy efficiency is being studied, where intelligent home meters implement distribution-system automation. Smart-grid pilot projects were executed in Brazilian cities as a joint effort by the National Bank for Economic and Social Development (BNDES), the National Electric Energy Agency, and the Brazilian Financier of Studies and Projects [31]. While energy-efficiency initiatives in Brazil have made significant strides, they have also encountered barriers, such as social and cultural assortment, leading to varying levels of consumer ignorance, underscoring the need for targeted education and awareness campaigns. Overcoming these barriers and fostering a culture of energy efficiency will require concerted efforts and policies that incentivize energy conservation.

One option to diminish construction energy consumption is establishing standards for evaluating and categorizing buildings concerning energy performance, which are accepted and utilized globally. Thus, the Brazilian building energy-efficiency labeling program was launched in 2009 and used a model based on equations to regulate the energy-efficiency classification [32]. Nevertheless, this approach was considered simple. Therefore, upgrading the method with more severe requirements was considered. Thus, the labeling program of Brazil was reviewed and updated, allowing for the determination of the energy-efficiency class using building simulation [33].

Parallel with this energy-focused initiative, in 2005, the initial standard (ABNT NBR 15220–3) [34] that evaluates the thermal performance of buildings was established. This standard's main contribution was to the definition of the bioclimatic zones of Brazil (Figure 1), specifying bioclimatic plans per zone. NBR 15220–3 also included calculating the thermal properties and construction guidelines for residential houses.

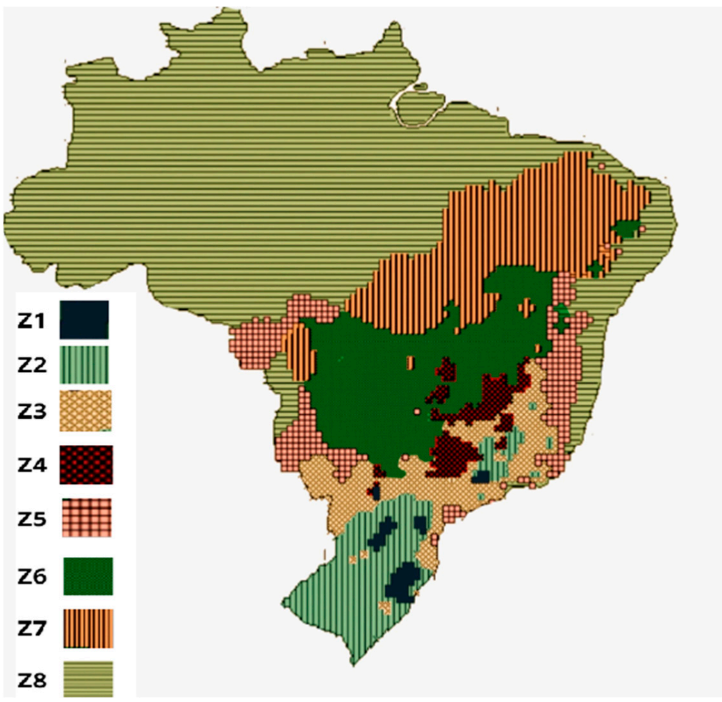

Figure 1. The eight bioclimatic zones of Brazil. Source: [28].

In Brazil, eight bioclimatic zones could be defined, where the colder zones correspond to Z1 and Z2. The hotter zones are Z7 and Z8. Figure 2 shows the temperatures of three cities in the Z1, Z3, and Z8 Brazilian zones in a year, where significant differences are observed, mainly between Z1 and Z8. Brazil has a warmer climate in seven bioclimatic zones compared to countries in the Northern Hemisphere. The residential constructions of Brazil are aired through opening windows and infrequently using mechanical aeration for air renewal, aiming to improve the quality of interior air (except for bathrooms) [35]. Artificial refrigeration is mainly used at night in most zones of Brazil (restricted to bedrooms), except for residences in regions near the equator, such as the North and Northeast [36]. Regarding artificial heating, these systems are utilized in some Brazilian zones, mainly Z1 and Z2. Thus, evaluating the performance of residential constructions in Brazil strengthens bioclimatic options, such as natural ventilation and lighting, which is different from some countries that focus on buildings only installing HVAC systems.

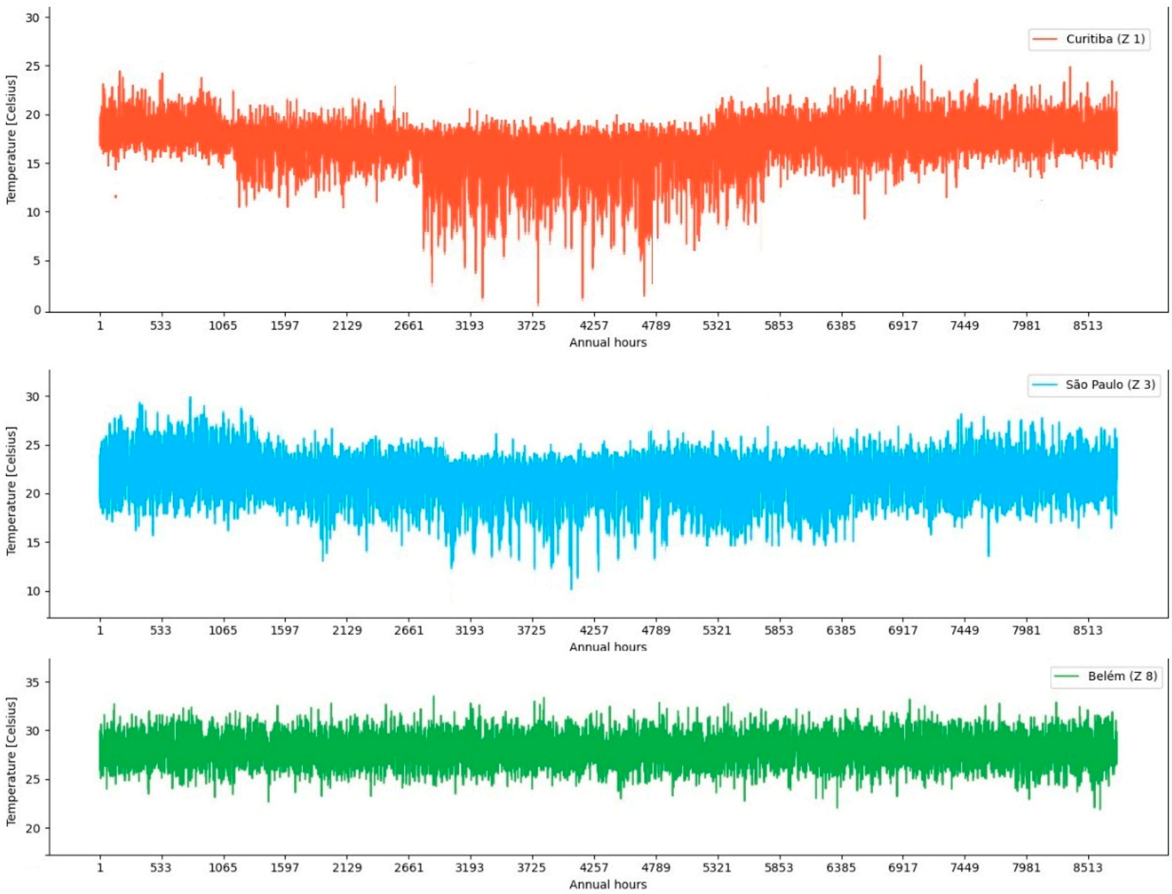

Figure 2. Temperatures of three cities located in different bioclimatic zones: Curitiba (Z1), São Paulo (Z3), and Belém-PA (Z8). Source: [28].

Another important climate classification was established by Köppen in 1900, which considers the precipitation and temperatures periodically per month, aiming to state limits for diverse climates. Since its creation, this system has been developed and widely used by geographers and climatologists worldwide [37]. The system's popularity lies in its capacity to connect climate and natural flora [38]. Although German scientists have tried to establish different methods of classifying climate change, the Köppen classification remains the most utilized [39]. The Köppen classification consists of five main groups with various subtypes, as displayed in Table 1. All groups depend on temperature alone (except group B). All subtypes are established considering the temperature and precipitation of the season (except subtype E). Therefore, the Köppen classification represents diverse climate regimes, considering severe combinations of temperature and rainfall [37].

Table 1. Characteristics of the main climatic groups and subtypes of Köppen classification.

Major Group	Sub-Types
A: Humid climate	AF: Tropical rainforest AM: Tropical jungle AW: Tropical humid and dry grassland (AS is utilized if the dry season occurs during higher sunlight and days more long)
B: Dry Climate	BWh, BWk: Desert BSh, BSk: Savanna
C: Mild temperate	CSC, CSD, CSE: Mediterranean sea CFA, CWA: Humid subtropical CFB, CFE, CWC, CWE: Ocean
D: Snow ambient	DFE, DWA, DFF, DWB, DSE, DSF: Humid DFG, DWC, DFH, DWD, DSG, DSG: Sub-arctic
E: Polar ambient	ET: Tundra EI: Icecap

Brazilian cities at latitudes close to the equator have higher temperatures and humidity in the country, where the typical winter does not happen. Solar irradiation increases the air temperature throughout the day, whereas the higher humidity content avoids temperatures falling lower than 20 °C during a nocturnal period [40]. A previous work has shown the inefficiency of that strategy in an experiment performed in dormitories in China [41]. Another work [42] evaluated the condition when the external temperature was higher than 31 °C and the internal climate was higher than 32 °C. The combination of the operating environment of 30 °C and humidity of 70% relative to the Brazilian Northeast zone was evaluated by [43]. In the Brazilian Northeast region, ventilators are actively utilized to increase air circulation within constructions, but active cooling is often required under scorching conditions. Therefore, adopting AC units as an option in the corporate sector and academic and service constructions in regions with tropical climates is necessary and is usually accomplished.

Adequate passive project is utilized in zones with dry summer conditions, where the temperature decreases at night, with minimum temperatures lower than 20 °C and everyday ranges over 10 °C. This behavior shows the nighttime aeration potential for passive chilling, enhancing daytime temperature comfort. On the other hand, the recurrent use of AC in hot regions has attracted attention, where some works focus on the excessive cooling of buildings (inhabitants uncomfortable because of the cold thermal sensations in conditioned rooms), the air quality in the buildings [44], and the energy consumption [45,46]. Inhabitants in equatorial regions are usually more disappointed with the internal cool temperatures than inhabitants accustomed to living in regions with spontaneous cold temperatures during winter. Furthermore, people who live in cities or regions at higher latitudes experience minor average temperatures due to an adjustable mechanism to behave to internal cold temperatures.

In addition, it is worth mentioning that recent events that broke temperature records, such as heat waves, affected the world population [47], predominantly in megacities [48]. The direct impacts of heat on the human anatomy generate damage to health [49], which may be aggravated in some population groups at greater risk, such as young people, people who are elderly, the poorest, and populations with heart, respiration, or previous diabetic diseases [50]. Even though some works indicate that increased fatality is attributed to high temperatures, measuring the universal risk of heat/temperature-correlated mortality is demanding because of the absence of precise data [47]. Excess heat/temperature correlated demises are expected to be exacerbated, given inevitable temperature increases under different climate-change situations. The strength and duration of heat waves could increase in some regions worldwide [51,52].

The Barcelona Institute for Global Health indicated that approximately a population of 70,066 will die from excessive temperature in the European summer of 2022. This number captures just part of the effects of climate change on health, which is on track to be exceeded in 2024 after scorching temperatures break the historical data worldwide [53]. For Brazil, during 2000–2018, 48,075 (40,448–55,279) excess deaths were attributed to increasing heat waves (a quantity twenty times higher than that of landslide-related demises simultaneously). However, the event-based investigation did not detect the correlation between heat waves and mortality, supporting that higher heat/temperature event experiments are an ignored adversity in the Brazilian context. The main causes of diseases are cardiovascular and breathing illnesses and neoplasm issues [54].

On the other hand, some studies have found that elevated temperatures and air humidity lead to a deterioration in the perception of indoor air quality. However, a rise in air movement meaningfully enhances satisfaction with the quality of the air [55]. Studies about natural ventilation in classrooms have indicated a mighty connection between carbon dioxide concentration (CO_2) and humidity as the population breathes H_2O in the vapor phase and CO_2 [56]. Considerable CO_2 content differences were evidenced in the constructions defined as mixed mode, achieving superior concentrations than buildings that use a central AC configuration [57].

In the urban environment, wind flow is affected by constructions and flora, among others. The collective effects of the merging of different contaminant causes and the presence of stagnation zones can conduct critical pollution [58]. Chemical compounds like carbon monoxide, sulfur dioxide, and nitrogen are considered principal contaminants whose primary source is the combustion process [59]. In contrast, nitrogen dioxide and ozone are produced in the earth's atmosphere due to the reactions of some compounds favored by solar radiation's influence [60]. Particulate matter can be formed from burning fossil fuels in prime movers, wear on car tires and brakes, and natural processes [61]. The main Brazilian regulation for air quality is CONAMA 491/18 [62]. In the case of Paraná, it is considered the Environment and Water Resources 054/2006 [63] regulation state, which is based on CONAMA 491/18 but is not as imperative as the World Health Organization (WHO) regulations for the chemical compounds evaluated [64]. The regulations/laws about air quality in Brazil establish a couple of standards for the concentration of chemical compounds that are considered pollutants. The first is the higher permissible limit for the existence of pollutants, which guarantees the safeguarding of human health without considering the animals and vegetation. The second characterizes the presently accorded limit under which nominal harmful effects occur on human life, fauna and flora conservation, and the environment [32].

3. Energy Impact of Air Renewal without Energy Recovery

The use of HVAC systems has increased significantly due to global economic growth, expanding building development, and improving life quality [65]. Nevertheless, a consumption of 40% for primary energy and a value of 38% for carbon dioxide emissions are associated with the construction sector in the US [66]. In the case of the European Union [67], the energy consumption and emissions values were 39% and 40%, respectively, while China [68] reached energy consumption and emission values of 40% and 30–40%, respectively. Thus, the "Ecodesign Directive" imposes requirements on heat-recovery efficiency in the European Union [69]. The investment fee of heat-recovery technologies is associated with profitability, construction regulations, and the innovation scope. In their research, Carlsson et al. [70] determined that the modernization combination consisted of sealing the building envelope and using heat-recovery technology, which reached a decrease of 78% in energy consumption for room heating and an 83% decrease in GHG emissions.

In recent years, buildings have been characterized by their excellent insulation and airtightness, allowing for a decrease in electricity consumption in residential constructions. However, these specifications can affect indoor air quality mainly by infiltration [71]. Although natural ventilation can provide relatively good IAQ, given the excellent quality of outdoor air, it can generate high energy for space heating in cold regions in winter [72]. Therefore, mechanical aeration appeared as the main approach for guaranteeing air quality and temperature comfort in the recently constructed commercial and residential constructions in zones with cold temperatures [73]. Through mechanical ventilation, the heat deficit from ventilation systems in household buildings can range between 35 and 40 kWh/m^2 [74]. However, a significant percentage of the heat deficit (60–95%) through ventilation could be returned through heat-recovery technologies [75].

Bai et al. [76] reviewed the literature on heat-recovery systems for mechanical aeration in household constructions, specifically for cold-climate applications. For this purpose, they considered the Building America guidelines that determine construction practices in the US, considering the classification of the climate regions through the heating degree day (HDD) concept. An area with cold temperatures is related to 5400–9000 HDDs (18.3 °C as baseline). A zone with freezing temperatures has between 9000 and 12,600 HDDs. A zone with a subarctic climate is correlated with 12,600 HDDs or more. In the work developed, the authors concluded:

- In most countries, the minimal efficiency of sensible heat recovery varies between 70% and 80%, while this minimal efficiency is uniquely necessary in some countries of North America and Europe, such as the US, Finland, and Canada;
- Thermal wheels, also called energy-recovery wheels, are extensively utilized, principally due to their elevated efficiency as heat-recovery systems and frost resistors in cold temperatures. A limitation of energy-recovery wheel use is cross-contamination, which involves pressure transfer and leaks. A purge section and a suitable fan can reduce cross-contamination;
- Flat plate exchangers, another heat-recovery ventilation system, are considered to be attractive for their reliability. Easy duct sealing avoids transfer problems. Additionally, water-vapor-permeable membranes recuperate sensible and latent heat. The moisture recovery during winter operation increases freezing limits;
- The quasi-counterflow system has been recently developed and is characterized by offering a simpler duct isolate compared with the conventional counterflow system, which increases the efficiency by around 5% compared to the traditional crossflow exchanger.

Rafati Nasr et al. [77] compared preheating and bypass in a heat-recovery stove in three cold temperatures. The findings indicated that the preheating configuration surpasses the bypass method, as the heat-recovery stove effectiveness coupled with preheating was similar compared to the efficacy without freezing. Furthermore, in a Canadian city, the percentage of energy savings, considering the preheating configuration, was around 44%, double that of bypass savings (22%). Wang et al. [78] analyzed the energy economy for a technology with a flexible air volume and energy-recovery ventilators (ERV) in different temperature conditions. The maximum energy savings from this technology varies between 39% and 49% in winter conditions.

Furthermore, it is worth mentioning that, currently, global attention is focused on the climate and climate change. Suburban zones and urban constructions require significant energy and are indicated as the primary sources of GHG [79]. From works available in the literature, it could be mentioned that the construction sector uses approximately 30% of the energy demand worldwide, mostly in HVAC systems or for the generation of hot water used mainly inside residential constructions. It is worth noting that China is responsible for 9.78% of total electricity consumption worldwide, as presented in Figure 3, of which 30% is used by households [80]. On the other hand, the construction sector shares 40% of the total energy consumption in Europe, which is associated with 36% of all carbon dioxide emissions, as indicated by [81].

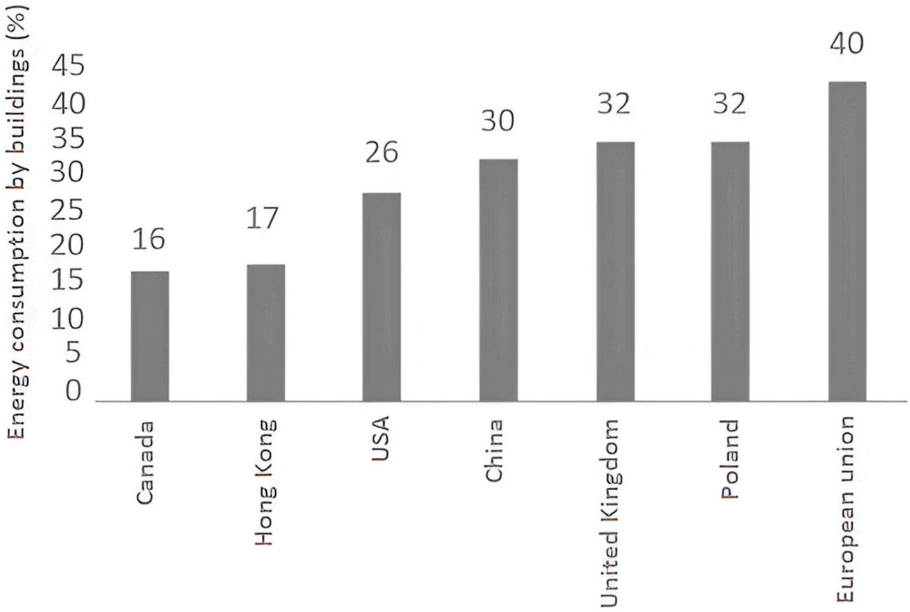

Figure 3. Total energy consumption by buildings of various nations. Source: adapted from [82].

Water heating characterizes the greater input to electricity consumption in buildings, and from the energy restoration viewpoint, wastewater at high temperatures disposed in the discharge network from washbasins, dishwashing machines, and showers is contemplated as a potential cause of heat deficit. Analysis of heat-recovery systems aimed at wastewater use, considering diverse methods, has recently increased, as described by [82]. Therefore, this configuration is considered to be an active technology in the United Kingdom, Norway, the US, and the Netherlands, countries where a significant quantity of hot wastewater is generated yearly, particularly from household constructions. In a Dutch residential building, the drainage water temperature is around 27 °C, offering a thermal demand of 21.3 MJ/house/day [83]. Usually, hot water produced in residential constructions has a large thermal potential because the temperature ranges from 40 to 50 °C. In countries such as the Netherlands and Switzerland, the heat deficit from residential constructions originates in sewage systems and hot wastewater, giving around 40% and 30% of the building's energy deficit, respectively, reserving the remainder for the construction envelopes and other zones of the building [84].

Murr et al. [85] developed an analysis of the heat-recovery configuration using a multi-drain installed in Lebanon aiming at warming cold water. The findings indicated that the drainage temperature of 25 °C is related to an energy savings that varies between 102.2 kWh and 410.9 kWh per month, while economically, the benefit is from USD 13.3 to USD 53.4. In addition, the emissions avoided varies from 72.5 kg to 291.7 kg per month. Wong et al. [86] studied energy savings in bath time, water flow, and inlet temperature using a horizontal heat exchanger in Hong Kong. The obtained energy savings are around 15%, representing an increase that varies from 104 MWh to 406 MWh, considering a 50 mm diameter drainpipe and a 1.5 m long counterflow heat exchanger.

McNabola and Shields [87] determined that the drain water heat-recovery system installation across all households in Ireland could potentially equate to a saving of 808 GWh for one shower per household, reducing by more than 400,000 tons the CO_2 in that country. Dong et al. [88] evaluated a heat pump associated with shower drain water. The preheated water circuits showed a superior performance associated with higher waste heat from the shower drain water, which can be recuperated through a coefficient of performance augmented from 2.19 up to 3.21. The configuration analyzed can reach 70% energy savings compared to a conventional water heater.

HVAC is responsible for approximately between 50 and 82% of electricity consumption, where 40% of total electricity is consumed in construction at a worldwide level [89]. In constructions that are not industrial, HVAC systems are responsible for approximately between 18 and 35% of electricity consumption [90], while in corporate constructions, they correspond to around 30% [91]. In Sweden, HVAC systems are often utilized to decrease radioactive gas issues, whereas heat-recovery systems are essential for reducing electricity consumption [92]. Furthermore, energy-recovery systems, especially those based on sensible and latent heat recovery such as enthalpy exchangers [93,94], also called total energy exchangers, are often utilized in HVAC systems because of their efficiency and excellent control of humidity. Nevertheless, high-powered fans may be needed to surpass the pressure drop in the system and provide adequate ventilation airflow [95]. In winter, enthalpy devices appear to recover more than 25% of the energy. While enthalpy exchangers, commonly found as passive desiccant wheels, can provide humidity control (thus preventing freezing and condensation) to heat-recovery systems, active desiccant wheels can be used for greater humidity control in AC systems [96,97]. Indeed, desiccant technologies can have a vital function in diminishing the electric energy requirement significantly when associated with evaporative coolers, leading to the so-called desiccant cooling systems [98]. Moreover, when related to indirect evaporative coolers, the cooling effect can be achieved with strict humidity control [99].

Geothermal technologies can offer considerable energy savings in constructions that have HVAC technologies, making geothermal systems an attractive technology [100]. Geothermal energy is an old process for energy generation and, coupled with ventilation configuration, reduces the charge by pre-cooling the supplied air between 25 and 75%, with energy savings between 30 and 70% for demand and electricity consumption of HVAC units installed in buildings in Central and Northern region of the European Union [101]. Water-to-ground and ground-to-air exchangers are two configurations associated with geothermal energy that, coupled with other configurations, reduce energy consumption considerably [102]. Research on heat pumps indicated that a value superior to 85% of heat pump owners suggests using this technology and avoiding others [103]. Therefore, geothermal configurations contribute to HVAC systems because geothermal sources diminish the electricity consumed in processes that require heating/cooling utility.

4. Technologies for Recovering Energy from Renewed Air

4.1. Desiccant Wheel Heat-Recovery Units

The concept of solid desiccant dehumidifiers used in air conditioning applications has been introduced previously. The first works in this field were conducted by Clark et al. [104], Lavan et al. [105], Gunderson et al. [106], Pesaran and Mills [107,108], and Biswas et al. [109], which were developed between the 1970s and 1980s. Desiccant wheels are used in various heating applications, such as in residences, to prevent the growth of mold and mildew, and in industry to avoid equipment degradation due to air humidity. In hot and humid climates, desiccants are responsible for removing the moisture load (latent heat), since conventional air conditioning systems have limitations when used [110].

More than 20 variables affect desiccant dehumidifiers' performance, but manufacturers commonly adopt good practices by setting variables to ensure consistent performance. The main variables that change from project to project are inlet dry bulb temperature, inlet absolute humidity, and air velocity at the desiccant face, which can be used to establish the demands of the dehumidification and regeneration processes. Every project to be developed must consider these variables influenced by climatic conditions [111].

On the other hand, the rotating desiccant wheel is the most commonly used technology regarding dehumidifiers with solid desiccants. This technology is advantageous because it can provide air with uniform humidity at the outlet and eliminate batch mode operation (i.e., simultaneous lateral adsorption and desorption processes), allowing continuous rotation [112].

Desiccant wheel heat-recovery units contain substances that adsorb moisture from the air. Consequently, desiccants can complement the traditional vapor compression systems whose latent load is eliminated by air humidity condensation in the evaporator. Desiccants are excellent at managing latent loads and effectively reducing humidity [113]. At the same time, the evaporator in vapor compression systems is suitable for meeting sensible cooling demands and efficiently decreasing the air temperature. The benefits of using a desiccant wheel heat-recovery unit include [114]:

- the level of humidity control achieved is superior compared to that achieved using vapor compression systems;
- the system begins to show efficiency when the latent heat load exceeds the sensible heat load;
- it can eliminate polluting particles in the air;
- it uses negligible amounts of electrical energy, and due to its regenerative nature, the system allows solar and waste energy to be used throughout;
- reduces fossil fuel consumption and equivalent emissions of GHG in the HVAC process;
- improvement in indoor air quality is often attributed to the greater quantity of outside air;
- in specific scenarios, the energy cost for desiccant regeneration can be lower than that associated with dehumidifying the air by cooling it below its dew-point temperature.

4.2. Air-to-Air Enthalpy Wheel

Indoor environments, whether air-conditioned or not, require air renewal to maintain high levels of IAQ. Generally, the outside air needs to be conditioned to match indoor ambient requirements, which can require a lot of energy due to vapor compression systems. In this scenario, the air-to-air enthalpy wheel or enthalpy wheel, a heat exchanger that reuses process energy, can reduce energy consumption [115]. An air-to-air enthalpy wheel consists of a rotating, cylindrical device made of rolled corrugated sheets of metallic material (such as aluminum) to obtain many parallel channels with typical sinusoidal or triangular cross-sectional geometry. Two air streams pass through the cross-sectional area of the device, typically called the external air stream, called supply air, and the exhaust air stream, which is the return airflow from the building. A purge sector between the exhaust and process air streams can be used to reduce contamination of the external air stream [116]. The air-to-air enthalpy wheel continues to rotate to perceive the total heat-transfer process, and it can work in air conditioning and waste heat-recovery systems [95].

For air-to-air enthalpy wheels, operational parameters, such as rotation speed, inlet and outlet air temperature, humidity, and speed, influence the component behavior [117]. When an energy analysis of buildings and HVAC systems is assessed, the performance of the air-to-air enthalpy wheel must be properly evaluated. A simplified approach is often used in the literature, in which sensible and latent effectiveness are considered constant or are determined by the linear interpolation of values at different air flows [75]. From a qualitative point of view, enthalpy and desiccant wheels share the turnover, air inlet and outlet, and sensible and latent heat exchange. Both have a common basis of psychrometric study but differ in the internal specificities of their physical heat-exchange components. However, if the absolute humidity of the air-to-air enthalpy wheel inflation is below the external absolute humidity, the wheel can also have a desiccant function, albeit a lightweight one [110].

Air-to-air enthalpy wheels have the advantages of moisture transfer, compact equipment, low air-pressure loss, and availability for installation in various air treatment systems. The main disadvantage is the initial investment required [95]. In addition, even with the air-to-air enthalpy wheel system, it will always be necessary to use the conventional air treatment system [118]. Another disadvantage is the four ways cross-contamination can occur, such as peripheral leakage, leakage from the outside air side to the exhaust air side, contamination loading through the honeycomb, and exhaust leakage to the supply air. These leaks in the heat-recovery system can impair the cooling performance and the indoor air quality [119].

4.3. Plate Heat-Recovery Units

The plate heat-recovery unit changes the temperature and removes excess moisture from the outside air before it is supplied inside the room. In summer, the core of a heat-recovery unit removes heat from the outside air and transfers it to the air sent outside. If the summer air is humid, the heat-recovery unit can remove excess moisture before sending the air conditioning into a room [32]. Men et al. [120] found that the efficiency of this type of heat-recovery unit depends mainly on the efficiency of sensible heat in winter and the efficiency of latent heat in summer. The authors observed that, in both summer and winter conditions, the weighted coefficient of efficiency of sensible heat decreases with decreasing outside temperature. Meanwhile, the weighted coefficient of efficiency of latent heat increases, but the trend is milder in winter.

The air-to-air enthalpy wheel and the plate-type heat recovery aim to balance external and internal air, maintaining energy efficiency and saving costs. Nevertheless, both technologies differ in the internal specificities of their physical heat-exchange components and their emphases. On the other hand, it is worth mentioning that the difference between the sensible heat exchanger and the plate heat-recovery unit is between the exchanger's operating devices because, when using plastic or metal for its manufacture, only the sensible exchange occurs between the air flows. However, when it is a device made of porous/absorbent material (a membrane), the exchange of sensible heat and latent heat occurs [121].

5. Analysis of Technology Implementation with Energy Recovery

5.1. Review of Implemented Systems

Camargo et al. [122] performed experimental tests on a direct evaporative cooler installed at the University of Taubaté, and the experimental results were used to determine the convective heat-transfer coefficient. The results showed that the system consumes approximately 200 W at maximum airflow, representing a small consumption compared to the conventional air conditioning system, and concluded that the evaporative cooler is more efficient when temperatures are higher. Melo [123] experimentally evaluated a hybrid artificial air conditioning system based on desiccant and vapor compression air conditioning (VCC) technologies. The adsorptive rotors used were a desiccant rotor and an enthalpic rotor. The rotary heat exchanger was a regenerative type, and the compact heat exchanger was the constituent evaporator of a residential window VCC system. Through the joint action of the rotors at flow rates of 909 and 1204 m^3/h, reductions in heat source consumption of 57.6% and 61.8% were obtained, respectively.

Funded by the European Union's THERMIE program, an air conditioning equipment manufacturer has installed a solar desiccant air conditioning system in Sintra, Portugal [124]. The system is powered by 75 m^2 composite parabolic collectors connected to a 3 m^3 intermediate tank with a plate heat exchanger. The desiccant cooling unit operates with variable airflow, up to a maximum of 9600 m^3/h, with a maximum cooling power of 75 kW and a maximum electrical load of 15 kW. On the other hand, a solar desiccant cooling system equipped with 22.5 m^2 flat plate solar collectors and coupled to a 76.1 m^2 radiant ceiling was installed at the University of Palermo, Italy [125]. Two cooling coils are placed before and after the desiccant wheel to pre-cool and pre-dehumidify the process air. This solar desiccant air conditioning system covered a summer peak load of 28.8 kW, with an expected thermal COP of 0.86.

Five pilot rotary desiccant cooling systems, which are part of Task 25 on "Solar-assisted air-conditioning of buildings" in the International Energy Agency's Solar Heating and Cooling Program, have been installed and monitored in Freiburg, Germany; Hartberg, Austria; Mataro, Spain; Lisbon, Portugal; and Waalwijk, the Netherlands. The corresponding design values of cooling capacity are 50 kW, 30 kW, 55 kW, 36 kW, and 22 kW, respectively, as reported by [126]. In China, a demonstration solar village that integrated the technologies of a solar desiccant cooling system, solar hot water system, solar heated swimming pool, and sunshade was built at Himin Solar Company [118]. Typical run results showed that, when the outdoor temperature was 29.3 °C and 36.2% relative humidity (RH), the desiccant cooling unit released air of 20.3 °C and 76.2% RH, which kept the rooms at 24.2 °C and 54% RH.

Ge et al. [127] studied a two-stage, single-rotor rotary desiccant cooling system installed at Shanghai Jiao Tong University. The designed cooling capacity of this system is 5 kW. 15 m^2 solar air collectors to produce hot air. Solar-heated air is fed into the unit in summer to regenerate the desiccant wheel. In winter, the system can work in two different modes, namely direct solar-heating mode and solar-heating mode with desiccant humidification. Niemann and Schmitz [128] studied the Hamburg University of Technology test facility, where air initially passes through an enthalpy wheel on the process air side. Thus, the outside air is re-humidified and reheated using the exhaust air stream. If necessary, the humidified and preheated air is finally heated to the desired supply air temperature in a water-to-air sensible heat exchanger before being supplied to the conditioned space.

According to the Environmental Protection Agency (EPA) [129], in the Whitehead biomedical research building at Emory University (United States), an HVAC system was designed to operate at constant volume and include energy recovery. Four enthalpy wheels recover thermal energy from the exhaust air and use the facility's exhaust air to preheat the outside air in winter and pre-cool the outside air in summer. Moreover, a solid desiccant-based ventilation system was installed on the roof to provide ventilation to The Robert L. Preger Intelligent Workplace (IW) at Carnegie Mellon University (USA), as described by Masson et al. [130]. When connected to a heat-recovery preconditioner, the overall system offers the best performance in total energy transfer. Furthermore, this ventilation unit can be operated as an air conditioning system assisted by IW cooling/heating or as a dedicated outside air system that processes only ventilation air.

5.2. Considerations for Various Brazilian Regions: Study Case

Based on the discussion in the previous sections and to establish a more in-depth view of the use of heat-recovery units (enthalpy wheels) with air renewal in various Brazilian regions, this study evaluated the use of these technologies in six different types of environments in which the thermal loads were calculated, comparing the use of heat-recovery units with the absence of them. The environments considered were the following: (a) classroom; (b) theater (equivalent to cinemas and large capacity auditoriums); (c) offices (equivalent to office environments and meeting rooms); (d) hotel room (equivalent to residential rooms); (e) restaurant (equivalent to cafés and snack bars); and (f) medical room (generally non-critical environments in healthcare facilities).

The same materials and colors were used in each comparison regarding the building envelope materials. The climatic characteristics, such as dry bulb temperature and wet bulb temperature, were obtained from the ASHRAE Data Viewer, which simulated 8760 annual hours. The external air flow rate to be supplied was determined following Brazilian technical standard NBR 16.401—Part 3—Level 2 [131], compared with ANVISA's Normative Resolution 09 of 2002. The flow rate was considered the highest value between the two standards. Table 2 presents the data on the flow rates used in the evaluated enclosures.

Table 2. Data considered for calculating thermal load.

Environment	Amount of People	Airflow Rate (m^3/h)	Heat per Person (kcal/h/Person)	
			Sensible	Latent
Medical Room	3	81	70	45
Office	36	1054	75	55
Hotel Room	2	54	70	45
Restaurant	124	2655	70	45
Theater	108	1836	70	45
Classroom	37	1048	70	45

Based on the data in Table 2, the thermal loads of the six environments (classroom, theater, office, hotel room, restaurant, medical room) are shown. When the use of the heat-recovery unit was considered, the following equations were used:

$$\eta_t = \frac{t(OA) - t(SA)}{t(OA) - t(RA)} \times 100\% \quad (1)$$

$$\eta_i = \frac{i(OA) - i(SA)}{t(OA) - t(RA)} \times 100\% \quad (2)$$

where *OA* (outdoor fresh air) is the dry and wet bulb temperature characteristic of the 0.4% of the hottest annual hours of the simulated city; *SA* (internal supply air to the enclosure) is the external air supplement; *RA* (return air) is the dry and wet bulb temperature characteristic of the internal conditions of the air-conditioned environment; η_i is the global enthalpy efficiency; and η_t is the sensible efficiency.

It is essential to highlight that, for the thermal load calculation, only the effect of sensible and latent heat on the global enthalpy efficiency was considered. The assessment was carried out using Microsoft® Excel® version 2407.

5.3. Assessment of Brazilian Case Considering the Köppen Classification

Brazilian regions were compared using the Köppen classification, considering the thermal load-saving factor, as indicated in Figure 4. The results suggest that a dry season with stronger solar radiation and longer days (AS) has a greater advantage in installing equipment with heat recovery. Similar results were obtained for the climate subtypes AW (tropical wet and dry savanna), AF (tropical forest), and CSC (Mediterranean). However, the humid subtropical (CFA) and oceanic (CFB) subtypes presented the worst results associated with their climates.

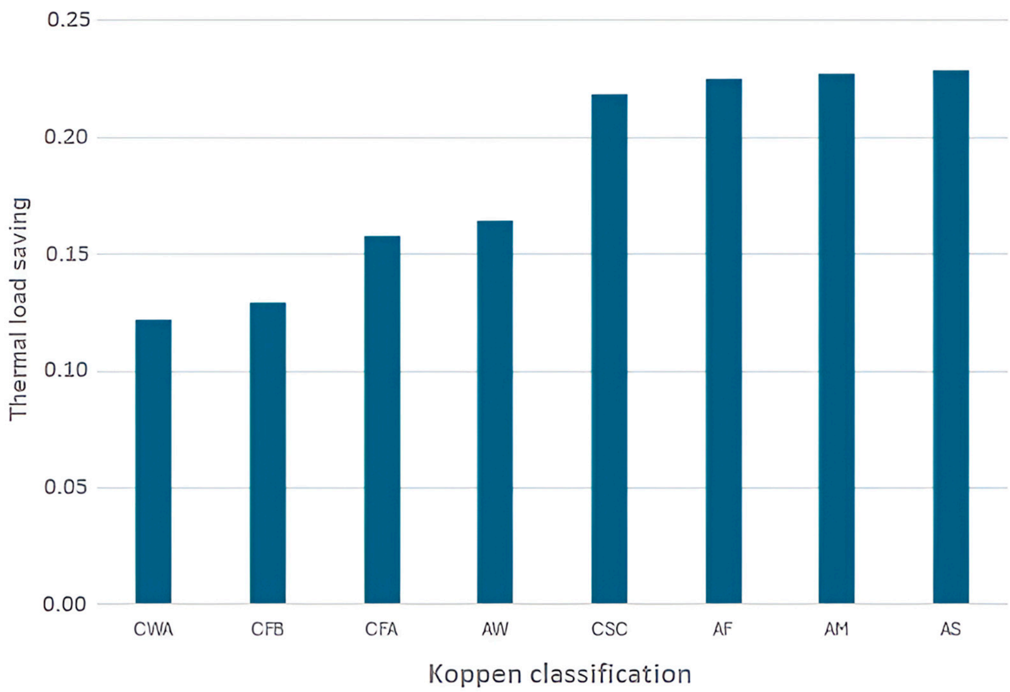

Figure 4. Thermal load saving of Köppen classification groups in the Brazilian context.

Figure 5 compares different environments in the São Paulo, Manaus, and Brasília cities, considering the external air and sensible heat factors. The environments that were compared were a restaurant, classroom, theater, hotel room, consulting room, and office. In the case of the city of Manaus, it is possible to observe that the classroom has an approximately 50% external air factor but a 42% sensible heat factor. However, compared to the classrooms in São Paulo and Brasília, they have a lower external air factor (27% and 8%, respectively) but a higher sensible heat factor (61% and 78%, respectively). It is worth highlighting that these results do not consider heat recovery and indicate the influence of the climate subtype of the Köppen classification on external air and sensible heat factors in Brazilian city environments with different climates.

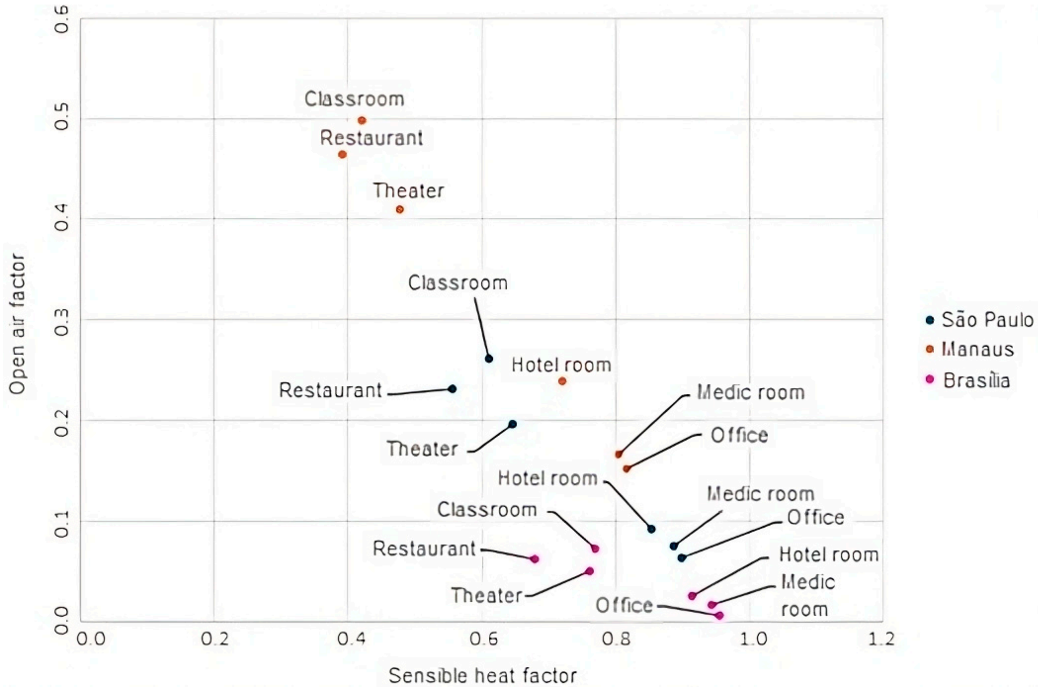

Figure 5. Comparison of environments in the São Paulo, Manaus, and Brasília cities without heat-recovery technologies.

On the other hand, Figure 6 shows an analysis of the same environments in the cities compared to Figure 5, but it considers the installation of equipment with heat-recovery technology. It is possible to observe from Figure 6 that the external air factors have decreased considerably, with the highest being 26%, corresponding to the classroom in Manaus. Comparing the environment of a restaurant between the three cities, it can be seen that the highest external air factor is associated with the city of Manaus, with 23%, followed by São Paulo, with approximately 10%, and Brasília with 3%. However, the order is reversed when analyzing the sensible heat factor, with 72% for Brasília, 66% for São Paulo, and Manaus, with approximately 57%. The sensible heat factor values are higher than those presented in Figure 5, indicating that heat-recovery technology reduces the external air factor but increases the sensible heat factor.

The changes in thermal load from using systems with and without heat recovery for 15 cities are presented in the Supplementary Material (Figures S1–S15). Therefore, the analysis of the feasibility of using heat-recovery systems in different Brazilian cities highlights the importance of considering the climatic factors and bioclimate of each region. While in cities with more stable climates throughout the year, such as Vitória (Figure S15) and Salvador (Figure S14), the use of heat-recovery systems is advantageous. In regions with more pronounced climatic variations, such as Anápolis (Figure S1) and São Paulo, this technology may not offer the same benefits. The bioclimate of cities plays a crucial role in the energy demand and effectiveness of heat-recovery systems, and it is essential to consider it when assessing the feasibility of this technology in different regional contexts.

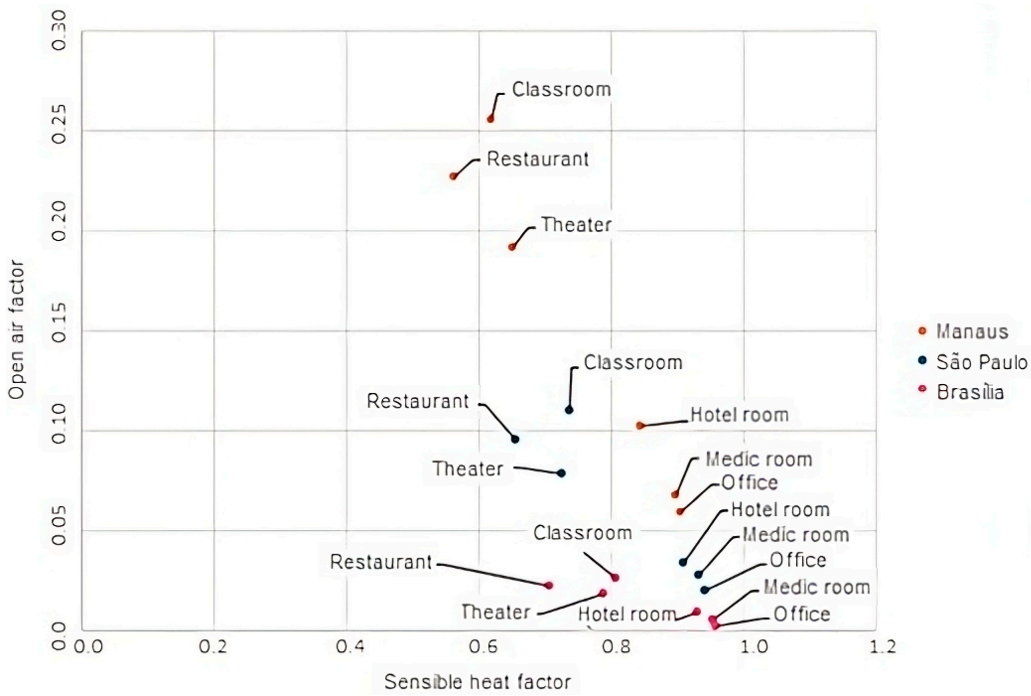

Figure 6. Comparison of environments in the São Paulo, Manaus, and Brasília cities with heat-recovery technologies.

Finally, Figure 7 shows the energy savings for a system using a heat-recovery unit installed in several Brazilian cities belonging to the different climate subtypes of the Koppen classification. It is essential to highlight that these results were obtained by considering the analysis performed in Figures 4–6 and the Supplementary Material (Figures S1–S15). It could be observed that cities in the north of the country, such as Manaus, Belém, and Porto Velho (group A according to Koppen), present some of the highest energy-savings values when considering heat-recovery technology (varying between 77,000 and 82,000 kWh/year approximately) due to higher use of the systems associated with the hot and humid climate of these cities, which are located close to the equator (discussed in Section 2). Regarding the Northeast Brazilian region, cities such as Salvador, Recife, and Fortaleza present values between 70,000 and 73,000 kWh/year of energy savings. Finally, in the Southern region cities (e.g., Curitiba, Porto Alegre, and Florianópolis) and the Southeastern region (Belo Horizonte, Vitória, and Rio de Janeiro), the energy-savings value varied between 13,000 and 53,000 kWh/year, which was associated with the fact that many of these cities do not require AC systems during a large part of the year.

Table 3 briefly compares the maximum estimated energy savings using heat-recovery energy units obtained in a Brazilian city with those previously discussed in Section 3.

Table 3. Maximum estimated energy savings of different energy-recovery units.

Equipment	Energy Saving	Localization	Ref.
Heat-recovery unit using a multi-drain	410.9 kWh/month	Lebanon	[85]
Horizontal heat exchanger	406 MWh/year	Hong Kong	[86]
Drain water heat-recovery system	808 GWh/year	Irland complete	[87]
Preheating heat-recovery stove	3.3 MWh/month	Saskatoon, Canada	[77]
ERV	181.3 kWh/month	Minneapolis, US	[78]
Enthalpy wheel	82 MWh/year	Belen, Brazil	This work

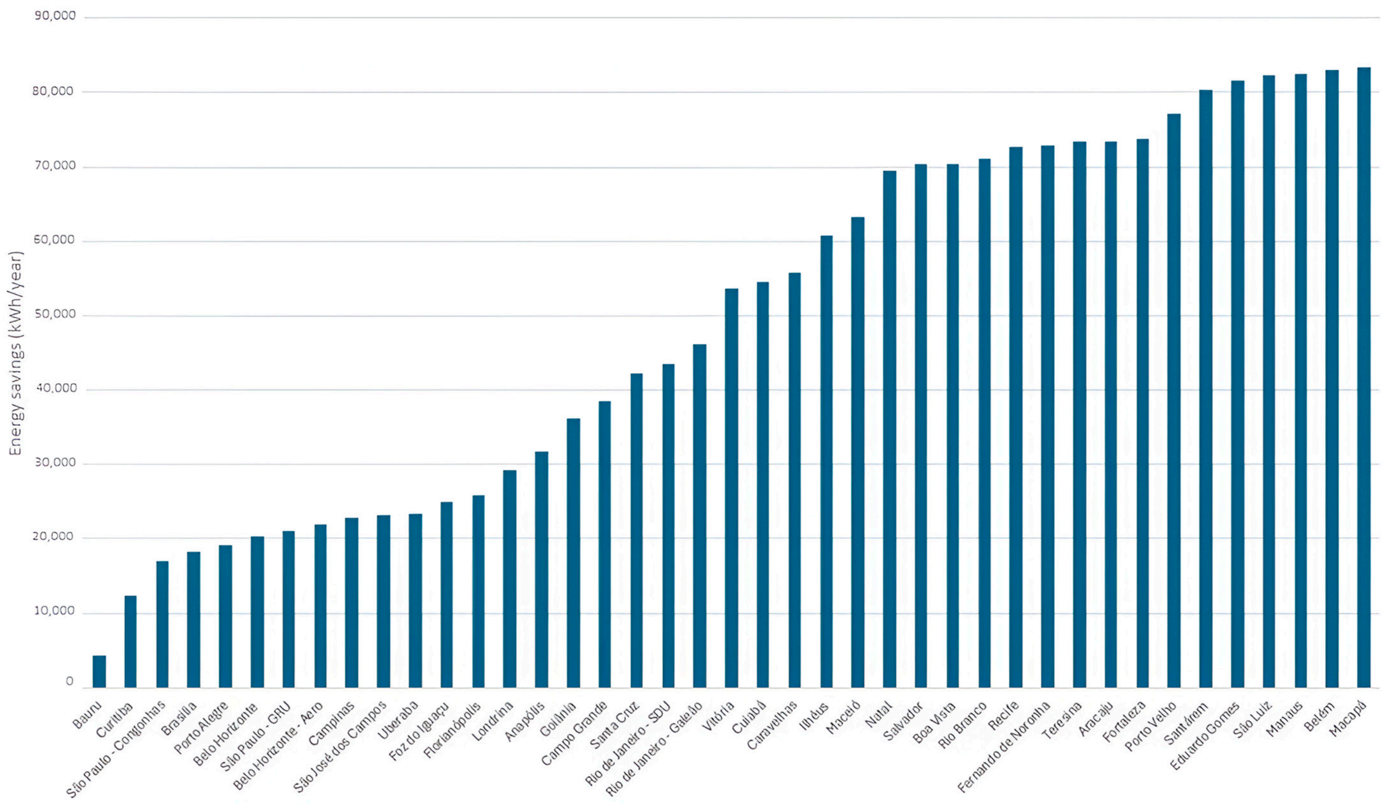

Figure 7. Energy savings using a heat-recovery system installed in some Brazilian cities.

6. Conclusions

In this work, an analysis of the problem of air renewal in Brazil was carried out, as well as research into the energy impact of air renewal without energy recovery and the different existing technologies for heat recovery in air renewal. Subsequently, an evaluation of the application of technologies that consider energy recovery in air renewal processes in Brazil was performed, considering the Köppen classification.

The literature review highlights that desiccant air conditioning systems can be classified into solar-powered desiccant air conditioning systems and desiccant air conditioning systems powered by other low-grade heat sources. Solar-powered desiccant air conditioning systems are installed in countries such as the United States, Italy, Germany, Portugal, the Netherlands, and China, which shows the feasibility of this type of system. Regarding enthalpy wheels, it is observed that parameters such as rotation speed, inlet and outlet air temperature, humidity, and speed influence the performance of this type of wheel. On the other hand, to perform an energy analysis of buildings and HVAC systems, the performance of the enthalpy wheel must be adequately evaluated. In the literature, an approach has been reported where the sensible and latent efficiencies are considered constant or determined by the linear interpolation of values at different air flows.

The heat-recovery implementation analysis showed that the classroom environment with many people in the city of Anápolis has a reduction in the thermal load of 19%. However, the total thermal load has a reduction of only 10%. In the case of the city of Goiânia, it is noted that the differences in thermal loads between the system without and with heat recovery vary from 3% to 17% for all environments. For the city of Natal, the differences in thermal load between the system with and without heat recovery vary from 11% to 47%. For Recife, in environments such as theaters, restaurants, and classrooms, the reductions in thermal load reach an impressive 41% to 54%. Finally, for the city of São Paulo, the difference in thermal load between the two systems varies from 3% to 21%. Based on these results, it is worth mentioning that depending on the region of Brazil, energy-savings data and the benefits of heat-recovery systems can vary significantly. Therefore, it is also essential to consider a classification of climate subtypes, such as the Koppen classification, used to compare different regions of Brazil. It was possible to see that a dry season during the period of strongest sunlight and longest days (AS) has a greater advantage in installing equipment with heat recovery. However, climate subtypes, such as humid subtropical (CFA) and oceanic (CFB), presented the worst results for installing this technology.

On the other hand, the influence of heat-recovery systems was analyzed in three Brazilian cities for different environments, where a classroom in Manaus has an approximately 50% outdoor air factor and a 42% sensible heat factor. However, a classroom in São Paulo and Brasília has a lower outdoor air factor (27% and 8%, respectively) and a higher sensible heat factor (61% and 78%, respectively). Considering a system with heat recovery, the outdoor air factor decreases to 23%, 10%, and 3% for Manaus, São Paulo, and Brasília, respectively. This allows us to understand the effects of systems with heat recovery, which decreases the outdoor air factor and increases the sensible heat factor. Finally, an energy-savings calculation was carried out for a system using a heat-recovery unit installed in several Brazilian cities, where cities in the north of the country, such as Manaus, Belém, and Porto Velho (group A according to Koppen) present some of the highest energy-savings values, varying between approximately 77,000 and 82,000 kWh/year.

Finally, it is suggested that the impact of different controlling variables, such as seasonal changes, on the implementation of air conditioning systems with heat recovery be analyzed for future work. An economic assessment to evaluate the viability of these configurations is recommended in order to conduct a more comprehensive evaluation of the heat-recovery units in the AC systems.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en17164065/s1, Figure S1: Comparison of thermal load in Anápolis. Figure S2: Comparison of thermal load in Bauru. Figure S3: Comparison of thermal load in Belo Horizonte. Figure S4: Comparison of thermal load in Campo Grande. Figure S5: Comparison of thermal load in Curitiba. Figure S6: Comparison of thermal load in Florianópolis. Figure S7: Comparison of thermal load in Fortaleza. Figure S8: Comparison of thermal load in Goiânia. Figure S9: Comparison of thermal load in Natal. Figure S10: Comparison of thermal load in Porto Alegre. Figure S11: Comparison of thermal load in Porto Velho. Figure S12: Comparison of thermal load in Recife. Figure S13: Comparison of thermal load in Rio de Janeiro. Figure S14: Comparison of thermal load in Salvador. Figure S15: Comparison of thermal load in Vitória.

Author Contributions: Conceptualization, Y.C.S. and D.B.; methodology, A.F.S.; software, L.A.S.; validation, Y.C.S., D.B. and O.J.V.; formal analysis, A.F.S.; investigation, Y.C.S.; resources, O.J.V.; data curation, D.B.; writing—original draft preparation, Y.C.S.; writing—review and editing, L.A.S.; visualization, Y.C.S.; supervision, D.B.; project administration, A.F.S.; funding acquisition, O.J.V. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare that this study received funding from ELETROBRAS, CAPES, CNPq, FAPEMIG, PRH/ANP, and FAPERJ. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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

References

1. IEA. *The Future of Cooling*; IEA: Paris, France, 2018.
2. Santos, A.F.; Gaspar, P.D.; de Souza, H.J.L. New HVAC Sustainability Index-TWI (Total Water Impact). *Energies* **2020**, *13*, 1590. [CrossRef]
3. Alawadhi, M.; Phelan, P.E. Review of Residential Air Conditioning Systems Operating under High Ambient Temperatures. *Energies* **2022**, *15*, 2880. [CrossRef]
4. Shah, N.; Waide, P.; Phadke, A. *Cooling the Planet: Opportunities for Deployment of Superefficient Room Air Conditioners*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2013.
5. Dreyfus, G.; Borgford-Parnell, N.; Christensen, J.; Fahey, D.W.; Motherway, B.; Peters, T.; Picolotti, R.; Shah, N.; Xu, Y. *Assessment of Climate and Development Benefits of Efficient and Climate-Friendly Cooling*; Institute for Governance & Sustainable Development and Centro Mario Molina: Washington, DC, USA, 2020.

6. Campbell, I.; Kalanki, A.; Sachar, S. *Solving the Global Cooling Challenge How to Counter the Climate Threat from Room Air Conditioners*; Rocky Mountain Institute: Basalt, CA, USA, 2018.
7. Augustus de Melo, C.; Cunha, K.B.; Santiago Suárez, G.P. MEPS for Air Conditioners in Brazil: Regulatory Developments and Future Perspectives. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112504. [CrossRef]
8. Vettorazzi, E.; Figueiredo, A.; Rebelo, F.; Vicente, R.; Feiertag, G.A. Beyond Passive House: Use of Evolutionary Algorithms in Architectural Design. *J. Build. Eng.* **2023**, *76*, 107058. [CrossRef]
9. Yoshino, H.; Hong, T.; Nord, N. IEA EBC Annex 53: Total Energy Use in Buildings—Analysis and Evaluation Methods. *Energy Build.* **2017**, *152*, 124–136. [CrossRef]
10. Empresa de Pesquisa Energética. *Atlas of Energy Efficiency Brazil 2019*; Empresa de Pesquisa Energética: Brasília, Brazil, 2019.
11. Empresa de Pesquisa Energética. *Plano Decenal de Expansão de Energia 2029*; Empresa de Pesquisa Energética: Brasília, Brazil, 2020.
12. Eli, L.G.; Krelling, A.F.; Olinger, M.S.; Melo, A.P.; Lamberts, R. Thermal Performance of Residential Building with Mixed-Mode and Passive Cooling Strategies: The Brazilian Context. *Energy Build.* **2021**, *244*, 111047. [CrossRef]
13. da Silva Oliveira Morais, T.; de Hollanda Cavalcanti Tsuha, C.; Neto, L.A.B.; Singh, R.M. Effects of Seasonal Variations on the Thermal Response of Energy Piles in an Unsaturated Brazilian Tropical Soil. *Energy Build.* **2020**, *216*, 109971. [CrossRef]
14. ELETROBRAS. *Pésquisa de Posse é Hábitos de Uso de Equipamentos Elétricos Na Classe Residencial*; ELETROBRAS: Rio de Janeiro, 2019.
15. Corton, M.L.; Zimmermann, A.; Phillips, M.A. The Low Cost of Quality Improvements in the Electricity Distribution Sector of Brazil. *Energy Policy* **2016**, *97*, 485–493. [CrossRef]
16. Tubelo, R.; Rodrigues, L.; Gillott, M.; Gonçalves Soares, J.C. Cost-Effective Envelope Optimisation for Social Housing in Brazil's Moderate Climates Zones. *Build. Environ.* **2018**, *133*, 213–227. [CrossRef]
17. Silva, H.C.N.; Dutra, J.C.C.; Costa, J.A.P.; Ochoa, A.A.V.; dos Santos, C.A.C.; Araújo, M.M.D. Modeling and Simulation of Cogeneration Systems for Buildings on a University Campus in Northeast Brazil—A Case Study. *Energy Convers. Manag.* **2019**, *186*, 334–348. [CrossRef]
18. Ministério de Minas e Energia. Procel—Programa Nacional de Conservação de Energia Elétrica. Available online: https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/procel (accessed on 11 April 2024).
19. da Silva, P.P.F.; Neto, A.H.; Sauer, I.L. Evaluation of Model Calibration Method for Simulation Performance of a Public Hospital in Brazil. *Energies* **2021**, *14*, 3791. [CrossRef]
20. Pacheco, M.; Lamberts, R. Assessment of Technical and Economical Viability for Large-Scale Conversion of Single Family Residential Buildings into Zero Energy Buildings in Brazil: Climatic and Cultural Considerations. *Energy Policy* **2013**, *63*, 716–725. [CrossRef]
21. Letschert, V.E.; Karali, N.; Park, Y.; Shah, N.; Jannuzzi, G.; Costa, F.; Lamberts, R.; Borges, K.; Carvalho Machado, S. The Manufacturer Economics and National Benefits of Cooling Efficiency for Air Conditioners in Brazil. *ECEEE Summer Study Proc.* **2019**, 1563–1572. Available online: https://escholarship.org/uc/item/4c92s28m (accessed on 12 August 2024).
22. Aynur, T.N. Variable Refrigerant Flow Systems: A Review. *Energy Build.* **2010**, *42*, 1106–1112. [CrossRef]
23. da Silva Júnior, A.; Mendonça, K.C.; Vilain, R.; Pereira, M.L.; Mendes, N. On the Development of a Simplified Model for Thermal Comfort Control of Split Systems. *Build. Environ.* **2020**, *179*, 106931. [CrossRef]
24. ABRAVA. *Boletim Econômico ABRAVA*; ABRAVA: São Paulo, Brazil, 2022.
25. de Oliveira Silva Della Colletta, L.; Venturini, O.J.; Andrade, R.V.; Arrieta, A.R.A.; Barbosa, K.P.; Santiago, Y.C.; Sphaier, L.A. Oil Sludge Pyrolysis Kinetic Evaluation Based on TG-FTIR Coupled Techniques Aiming at Energy Recovery. *J. Therm. Anal. Calorim.* **2023**, *148*, 12795–12809. [CrossRef]
26. IRENA. *Renewable Power Generation Costs in 2019*; IRENA: Abu Dhabi, United Arab Emirates, 2020.
27. e Silva Machado, R.M.; Geraldi, M.S.; Bavaresco, M.; Olinger, M.S.; Pereira de Souza, L.; Kamimura, A.M.; Gapski, N.H.; de Castro Quevedo, T.; Garlet, L.; Melo, A.P.; et al. Metamodel to Predict Annual Cooling Thermal Load for Commercial, Services and Public Buildings: A Country-Level Approach to Support Energy Efficiency Regulation. *Energy Build.* **2023**, *301*, 113690. [CrossRef]
28. Fossati, M.; Scalco, V.A.; Linczuk, V.C.C.; Lamberts, R. Building Energy Efficiency: An Overview of the Brazilian Residential Labeling Scheme. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1216–1231. [CrossRef]
29. Brasil Ministério de Minas e Energia. Plano Nacional de Energia 2030: Eficiência Energética. Available online: https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/publicacoes/plano-nacional-de-energia/plano-nacional-de-energia-2030#:~:text=O%20Plano%20Nacional%20de%20Energia,desse%20segmento%20nas%20pr%C3%B3ximas%20d%C3%A9cadas (accessed on 24 March 2024).
30. De Oliveira, L.S.; Shayani, R.A.; De Oliveira, M.A.G. Proposed Business Plan for Energy Efficiency in Brazil. *Energy Policy* **2013**, *61*, 523–531. [CrossRef]
31. Di Santo, K.G.; Kanashiro, E.; Di Santo, S.G.; Saidel, M.A. A Review on Smart Grids and Experiences in Brazil. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1072–1082. [CrossRef]
32. Castillo Santiago, Y.; Nunes, B.G.; Fontana, G.S.; Busanello, D.; Santos, A.F.; Santos, S.M.; Mello, E.N.; Sphaier, L.A. Desiccant Technologies for Improving Air Quality: An Overview of the Brazilian Scenario and Comparison of Available Design Software for Manufactured Desiccant Wheels. *Processes* **2023**, *11*, 2031. [CrossRef]
33. Melo, A.P.; Versage, R.S.; Sawaya, G.; Lamberts, R. A Novel Surrogate Model to Support Building Energy Labelling System: A New Approach to Assess Cooling Energy Demand in Commercial Buildings. *Energy Build.* **2016**, *131*, 233–247. [CrossRef]

34. *ABNT NBR 15220-3:2005*; Desempenho Térmico de Edificações Parte 3: Zoneamento Bioclimático Brasileiro e Diretrizes Construtivas Para Habitações Unifamiliares de Interesse Social. ABNT: São Paulo, Brazil, 2005.
35. Cakyova, K.; Figueiredo, A.; Oliveira, R.; Rebelo, F.; Vicente, R.; Fokaides, P. Simulation of Passive Ventilation Strategies towards Indoor CO_2 Concentration Reduction for Passive Houses. *J. Build. Eng.* **2021**, *43*, 103108. [CrossRef]
36. Krelling, A.F.; Eli, L.G.; Olinger, M.S.; Machado, R.M.E.S.; Melo, A.P.; Lamberts, R. A Thermal Performance Standard for Residential Buildings in Warm Climates: Lessons Learned in Brazil. *Energy Build.* **2023**, *281*, 112770. [CrossRef]
37. Chen, D.; Chen, H.W. Using the Köppen Classification to Quantify Climate Variation and Change: An Example for 1901–2010. *Environ. Dev.* **2013**, *6*, 69–79. [CrossRef]
38. Bailey, R.G. Ecoclimatic Zones of the Earth BT. In *Ecosystem Geography: From Ecoregions to Sites*; Bailey, R.G., Ed.; Springer: New York, NY, USA, 2009; pp. 83–92, ISBN 978-0-387-89516-1.
39. Domroes, M. Climatological Characteristics of the Tropics in China: Climate Classification Schemes between German Scientists and Huang Bingwei. *J. Geogr. Sci.* **2003**, *13*, 271–285. [CrossRef]
40. Buonocore, C.; De Vecchi, R.; Scalco, V.; Lamberts, R. Thermal Preference and Comfort Assessment in Air-Conditioned and Naturally-Ventilated University Classrooms under Hot and Humid Conditions in Brazil. *Energy Build.* **2020**, *211*, 109783. [CrossRef]
41. Zhang, Y.; Liu, Q.; Meng, Q. Airflow Utilization in Buildings in Hot and Humid Areas of China. *Build. Environ.* **2015**, *87*, 207–214. [CrossRef]
42. Huang, L.; Ouyang, Q.; Zhu, Y.; Jiang, L. A Study about the Demand for Air Movement in Warm Environment. *Build. Environ.* **2013**, *61*, 27–33. [CrossRef]
43. Buonocore, C.; De Vecchi, R.; Scalco, V.; Lamberts, R. Influence of Relative Air Humidity and Movement on Human Thermal Perception in Classrooms in a Hot and Humid Climate. *Build. Environ.* **2018**, *146*, 98–106. [CrossRef]
44. Cheung, T.C.T.; Schiavon, S.; Gall, E.T.; Jin, M.; Nazaroff, W.W. Longitudinal Assessment of Thermal and Perceived Air Quality Acceptability in Relation to Temperature, Humidity, and CO_2 Exposure in Singapore. *Build. Environ.* **2017**, *115*, 80–90. [CrossRef]
45. Damiati, S.A.; Zaki, S.A.; Rijal, H.B.; Wonorahardjo, S. Field Study on Adaptive Thermal Comfort in Office Buildings in Malaysia, Indonesia, Singapore, and Japan during Hot and Humid Season. *Build. Environ.* **2016**, *109*, 208–223. [CrossRef]
46. De Vecchi, R.; Candido, C.; de Dear, R.; Lamberts, R. Thermal Comfort in Office Buildings: Findings from a Field Study in Mixed-Mode and Fully-Air Conditioning Environments under Humid Subtropical Conditions. *Build. Environ.* **2017**, *123*, 672–683. [CrossRef]
47. Mora, C.; Dousset, B.; Caldwell, I.R.; Powell, F.E.; Geronimo, R.C.; Bielecki, C.R.; Counsell, C.W.W.; Dietrich, B.S.; Johnston, E.T.; Louis, L.V.; et al. Global Risk of Deadly Heat. *Nat. Clim. Chang.* **2017**, *7*, 501–506. [CrossRef]
48. Papalexiou, S.M.; AghaKouchak, A.; Trenberth, K.E.; Foufoula-Georgiou, E. Global, Regional, and Megacity Trends in the Highest Temperature of the Year: Diagnostics and Evidence for Accelerating Trends. *Earths Future* **2018**, *6*, 71–79. [CrossRef] [PubMed]
49. Gasparrini, A.; Guo, Y.; Hashizume, M.; Lavigne, E.; Zanobetti, A.; Schwartz, J.; Tobias, A.; Tong, S.; Rocklöv, J.; Forsberg, B.; et al. Mortality Risk Attributable to High and Low Ambient Temperature: A Multicountry Observational Study. *Lancet* **2015**, *386*, 369–375. [CrossRef] [PubMed]
50. Mazdiyasni, O.; AghaKouchak, A.; Davis, S.J.; Madadgar, S.; Mehran, A.; Ragno, E.; Sadegh, M.; Sengupta, A.; Ghosh, S.; Dhanya, C.T.; et al. Increasing Probability of Mortality during Indian Heat Waves. *Sci. Adv.* **2017**, *3*, e1700066. [CrossRef] [PubMed]
51. Gasparrini, A.; Guo, Y.; Sera, F.; Vicedo-Cabrera, A.M.; Huber, V.; Tong, S.; de Sousa Zanotti Stagliorio Coelho, M.; Nascimento Saldiva, P.H.; Lavigne, E.; Matus Correa, P.; et al. Projections of Temperature-Related Excess Mortality under Climate Change Scenarios. *Lancet Planet. Health* **2017**, *1*, e360–e367. [CrossRef]
52. Wilson, A.; Reich, B.J.; Nolte, C.G.; Spero, T.L.; Hubbell, B.; Rappold, A.G. Climate Change Impacts on Projections of Excess Mortality at 2030 Using Spatially Varying Ozone–Temperature Risk Surfaces. *J. Expo. Sci. Environ. Epidemiol.* **2017**, *27*, 118–124. [CrossRef]
53. FORBES. Extreme Heat Killed over 70,000 in Europe Last Year, Study Finds. This Year Is on Track to Be Even Worse. Available online: https://www.forbes.com/sites/roberthart/2023/11/21/extreme-heat-killed-over-70000-in-europe-last-year-study-finds-this-year-is-on-track-to-be-even-worse/?sh=31301bc57929 (accessed on 27 March 2024).
54. Monteiro dos Santos, D.; Libonati, R.; Garcia, B.N.; Geirinhas, J.L.; Salvi, B.B.; Lima e Silva, E.; Rodrigues, J.A.; Peres, L.F.; Russo, A.; Gracie, R.; et al. Twenty-First-Century Demographic and Social Inequalities of Heat-Related Deaths in Brazilian Urban Areas. *PLoS ONE* **2024**, *19*, e0295766. [CrossRef] [PubMed]
55. Guyot, G.; Sherman, M.H.; Walker, I.S. Smart Ventilation Energy and Indoor Air Quality Performance in Residential Buildings: A Review. *Energy Build.* **2018**, *165*, 416–430. [CrossRef]
56. Gładyszewska-Fiedoruk, K. Correlations of Air Humidity and Carbon Dioxide Concentration in the Kindergarten. *Energy Build.* **2013**, *62*, 45–50. [CrossRef]
57. Asif, A.; Zeeshan, M.; Jahanzaib, M. Indoor Temperature, Relative Humidity and CO_2 Levels Assessment in Academic Buildings with Different Heating, Ventilation and Air-Conditioning Systems. *Build. Environ.* **2018**, *133*, 83–90. [CrossRef]
58. Derome, D.; Kubilay, A.; Defraeye, T.; Blocken, B.; Carmeliet, J. Ten Questions Concerning Modeling of Wind-Driven Rain in the Built Environment. *Build. Environ.* **2017**, *114*, 495–506. [CrossRef]
59. Castillo Santiago, Y.; Pérez, J.F.; Sphaier, L.A. Reaction-Front and Char Characterization from a Palm Kernel Shell—Oil Sludge Mixture under Oxygen Lean Regimes in a Fixed-Bed Gasifier. *Fuel* **2023**, *333*, 126402. [CrossRef]

60. Singh, P.; Yadav, D.; Pandian, E.S. Link between Air Pollution and Global Climate Change. In *Global Climate Change*; Singh, S., Singh, P., Rangabhashiyam, S., Srivastava, K.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 79–108, ISBN 978-0-12-822928-6.
61. Harrison, R.M.; Allan, J.; Carruthers, D.; Heal, M.R.; Lewis, A.C.; Marner, B.; Murrells, T.; Williams, A. Non-Exhaust Vehicle Emissions of Particulate Matter and VOC from Road Traffic: A Review. *Atmos. Environ.* **2021**, *262*, 118592. [CrossRef]
62. Ministério do Meio Ambiente RESOLUÇÃO No 491, DE 19 DE NOVEMBRO DE 2018. Brasil, 2018; pp. 155–155. Available online: https://www.in.gov.br/web/guest/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/51058895/do1-2018-11-21-resolucao-n-491-de-19-de-novembro-de-2018-51058603 (accessed on 12 August 2024).
63. Secretaria de Estado de Meio Ambiente e Recursos Hídricos RESOLUÇÃO SEMA No 54, DE 22-12-2006. Brazil, 2006; pp. 1–87. Available online: https://venus.maringa.pr.gov.br/residuos/arquivo.php?id=112 (accessed on 12 August 2024).
64. Krüger, E.L.; Minella, F.O.; Rasia, F. Impact of Urban Geometry on Outdoor Thermal Comfort and Air Quality from Field Measurements in Curitiba, Brazil. *Build. Environ.* **2011**, *46*, 621–634. [CrossRef]
65. Guo, S.; Yan, D.; Hu, S.; Zhang, Y. Modelling Building Energy Consumption in China under Different Future Scenarios. *Energy* **2021**, *214*, 119063. [CrossRef]
66. de Oliveira, C.C.; Rupp, R.F.; Ghisi, E. Influence of Environmental Variables on Thermal Comfort and Air Quality Perception in Office Buildings in the Humid Subtropical Climate Zone of Brazil. *Energy Build.* **2021**, *243*, 110982. [CrossRef]
67. Ahmad, A.S.; Hassan, M.Y.; Abdullah, M.P.; Rahman, H.A.; Hussin, F.; Abdullah, H.; Saidur, R. A Review on Applications of ANN and SVM for Building Electrical Energy Consumption Forecasting. *Renew. Sustain. Energy Rev.* **2014**, *33*, 102–109. [CrossRef]
68. Lin, B.; Liu, H. CO_2 Emissions of China's Commercial and Residential Buildings: Evidence and Reduction Policy. *Build. Environ.* **2015**, *92*, 418–431. [CrossRef]
69. Zender–Świercz, E. A Review of Heat Recovery in Ventilation. *Energies* **2021**, *14*, 1759. [CrossRef]
70. Carlsson, M.; Touchie, M.; Richman, R. Investigating the Potential Impact of a Compartmentalization and Ventilation System Retrofit Strategy on Energy Use in High-Rise Residential Buildings. *Energy Build.* **2019**, *199*, 20–28. [CrossRef]
71. Van Tran, V.; Park, D.; Lee, Y.C. Indoor Air Pollution, Related Human Diseases, and Recent Trends in the Control and Improvement of Indoor Air Quality. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2927. [CrossRef] [PubMed]
72. Izadyar, N.; Miller, W.; Rismanchi, B.; Garcia-Hansen, V. Impacts of Façade Openings' Geometry on Natural Ventilation and Occupants' Perception: A Review. *Build. Environ.* **2020**, *170*, 106613. [CrossRef]
73. Kavanaugh, S. *Engineered Systems*; Troy, MI, USA, 2020; p. 3. Available online: https://www.esmagazine.com/articles/100699-probing-the-effectiveness-of-ansi-asrae-ies-standard-901 (accessed on 29 March 2024).
74. Dodoo, A.; Gustavsson, L.; Sathre, R. Primary Energy Implications of Ventilation Heat Recovery in Residential Buildings. *Energy Build.* **2011**, *43*, 1566–1572. [CrossRef]
75. Mardiana-Idayu, A.; Riffat, S.B. Review on Heat Recovery Technologies for Building Applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1241–1255. [CrossRef]
76. Bai, H.Y.; Liu, P.; Justo Alonso, M.; Mathisen, H.M. A Review of Heat Recovery Technologies and Their Frost Control for Residential Building Ventilation in Cold Climate Regions. *Renew. Sustain. Energy Rev.* **2022**, *162*, 112417. [CrossRef]
77. Rafati Nasr, M.; Kassai, M.; Ge, G.; Simonson, C.J. Evaluation of Defrosting Methods for Air-to-Air Heat/Energy Exchangers on Energy Consumption of Ventilation. *Appl. Energy* **2015**, *151*, 32–40. [CrossRef]
78. Wang, L.; Curcija, D.; Breshears, J. The Energy Saving Potentials of Zone-Level Membrane-Based Enthalpy Recovery Ventilators for VAV Systems in Commercial Buildings. *Energy Build.* **2015**, *109*, 47–52. [CrossRef]
79. Zhou, W.; Moncaster, A.; O'Neill, E.; Reiner, D.M.; Wang, X.; Guthrie, P. Modelling Future Trends of Annual Embodied Energy of Urban Residential Building Stock in China. *Energy Policy* **2022**, *165*, 112932. [CrossRef]
80. Yang, P.; Li, L.; Wang, J.; Huang, G.; Peng, J. Testing for Energy Recovery Ventilators and Energy Saving Analysis with Air-Conditioning Systems. *Procedia Eng.* **2015**, *121*, 438–445. [CrossRef]
81. Ilie, A.; Dumitrescu, R.; Girip, A.; Cublesan, V. Study on Technical and Economical Solutions for Improving Air-Conditioning Efficiency in Building Sector. *Energy Procedia* **2017**, *112*, 537–544. [CrossRef]
82. Wehbi, Z.; Taher, R.; Faraj, J.; Ramadan, M.; Castelain, C.; Khaled, M. A Short Review of Recent Studies on Wastewater Heat Recovery Systems: Types and Applications. *Energy Rep.* **2022**, *8*, 896–907. [CrossRef]
83. Frijns, J.; Hofman, J.; Nederlof, M. The Potential of (Waste)Water as Energy Carrier. *Energy Convers. Manag.* **2013**, *65*, 357–363. [CrossRef]
84. Pomianowski, M.Z.; Johra, H.; Marszal-Pomianowska, A.; Zhang, C. Sustainable and Energy-Efficient Domestic Hot Water Systems: A Review. *Renew. Sustain. Energy Rev.* **2020**, *128*, 109900. [CrossRef]
85. Murr, R.; Khaled, M.; Faraj, J.; Harika, E.; Abdulhay, B. Multi Drain Heat Recovery System—Thermal Modeling, Parametric Analysis, and Case Study. *Energy Build.* **2020**, *228*, 110447. [CrossRef]
86. Wong, L.T.; Mui, K.W.; Guan, Y. Shower Water Heat Recovery in High-Rise Residential Buildings of Hong Kong. *Appl. Energy* **2010**, *87*, 703–709. [CrossRef]
87. McNabola, A.; Shields, K. Efficient Drain Water Heat Recovery in Horizontal Domestic Shower Drains. *Energy Build.* **2013**, *59*, 44–49. [CrossRef]
88. Dong, J.; Zhang, Z.; Yao, Y.; Jiang, Y.; Lei, B. Experimental Performance Evaluation of a Novel Heat Pump Water Heater Assisted with Shower Drain Water. *Appl. Energy* **2015**, *154*, 842–850. [CrossRef]

89. Rismanchi, B.; Zambrano, J.M.; Saxby, B.; Tuck, R.; Stenning, M. Control Strategies in Multi-Zone Air Conditioning Systems. *Energies* **2019**, *12*, 347. [CrossRef]
90. Rasouli, M.; Ge, G.; Simonson, C.J.; Besant, R.W. Uncertainties in Energy and Economic Performance of HVAC Systems and Energy Recovery Ventilators Due to Uncertainties in Building and HVAC Parameters. *Appl. Therm. Eng.* **2013**, *50*, 732–742. [CrossRef]
91. Lee, Y.; Kim, W. Development of an Optimal Start Control Strategy for a Variable Refrigerant Flow (VRF) System. *Energies* **2021**, *14*, 271. [CrossRef]
92. Akbari, K.; Oman, R. Impacts of Heat Recovery Ventilators on Energy Savings and Indoor Radon Level. *Manag. Environ. Qual. Int. J.* **2013**, *24*, 682–694. [CrossRef]
93. Sphaier, L.A.; Worek, W.M. Parametric Analysis of Heat and Mass Transfer Regenerators Using a Generalized Effectiveness-NTU Method. *Int. J. Heat Mass Transf.* **2009**, *52*, 2265–2272. [CrossRef]
94. Sphaier, L.A.; Worek, W.M. Numerical Solution of Periodic Heat and Mass Transfer with Adsorption in Regenerators: Analysis and Optimization. *Numer. Heat Transf. Part A Appl.* **2008**, *53*, 1133–1155. [CrossRef]
95. Hegana, V.P.; Kulkarni, P. Enthalpy Wheel Application for Heat Recovery in Heat Exchanger. *Int. J. Adv. Res. Sci. Eng. IJARSE* **2015**, *8354*, 43–53.
96. Nóbrega, C.E.L.; Sphaier, L.A. Desiccant-Assisted Humidity Control for Air Refrigeration Cycles. *Int. J. Refrig.* **2013**, *36*, 1183–1190. [CrossRef]
97. Nóbrega, C.E.L.; Sphaier, L.A. Modeling and Simulation of a Desiccant–Brayton Cascade Refrigeration Cycle. *Energy Build.* **2012**, *55*, 575–584. [CrossRef]
98. Sphaier, L.A.; Nóbrega, C.E.L. Parametric Analysis of Components Effectiveness on Desiccant Cooling System Performance. *Energy* **2012**, *38*, 157–166. [CrossRef]
99. Machado, J.V.P.; Pinheiro, I.F.; Sphaier, L.A.; Nóbrega, C.E.L.; Quintans, P.C.; Quintanilha, F.O. Desiccant-Assisted Multistage Air Compression Systems: Performance Improvement and Humidity Control. *Appl. Therm. Eng.* **2024**, *243*, 122572. [CrossRef]
100. Valencia Ochoa, G.; Castillo Santiago, Y.; Duarte Forero, J.; Restrepo, J.B.; Albis Arrieta, A.R. A Comprehensive Comparative Analysis of Energetic and Exergetic Performance of Different Solar-Based Organic Rankine Cycles. *Energies* **2023**, *16*, 2724. [CrossRef]
101. Aridi, R.; Faraj, J.; Ali, S.; Gad El-Rab, M.; Lemenand, T.; Khaled, M. Energy Recovery in Air Conditioning Systems: Comprehensive Review, Classifications, Critical Analysis, and Potential Recommendations. *Energies* **2021**, *14*, 5869. [CrossRef]
102. Vakiloroaya, V.; Samali, B.; Fakhar, A.; Pishghadam, K. A Review of Different Strategies for HVAC Energy Saving. *Energy Convers. Manag.* **2014**, *77*, 738–754. [CrossRef]
103. Yu, Y.; Miao, R.; Miller, L.; Yang, H.; Olson, G. Recent Development and Application of Geothermal Heat Pump Systems in Cold-Climate Regions of the US: A Further Investigation. *Engineering* **2017**, *9*, 625–648. [CrossRef]
104. Clark, J.E.; Mills, A.F.; Buchberg, H. Design and Testing of Thin Adiabatic Desiccant Beds for Solar Air Conditioning Applications. *J. Sol. Energy Eng.* **1981**, *103*, 89–91. [CrossRef]
105. Lavan, Z.; Gidaspow, D.; Onischak, M.; Chaturvedi, S.; Mathiprakasam, B.; Perkari, S. *Development of a Solar Desiccant Dehumidifier*; Solar Energy International Progress: Pergamon, Turkey, 1980; Volume 2, pp. 898–931. Available online: https://www.sciencedirect.com/science/article/abs/pii/B9781483284378500648 (accessed on 12 August 2024).
106. Gunderson, M.E.; Hwang, K.C.; Railing, S.M. *Development of a Solar Desiccant Dehumidifier. Volume 1. Summary. Volume 2. Detailed Technical Information. Technical Progress Report*; AiResearch Mfg. Co.: Los Angeles, CA, USA, 1978.
107. Pesaran, A.A.; Mills, A.F. Moisture Transport in Silica Gel Packed Beds—I. Theoretical Study. *Int. J. Heat Mass Transf.* **1987**, *30*, 1037–1049. [CrossRef]
108. Pesaran, A.A.; Mills, A.F. Moisture Transport in Silica Gel Packed Beds—II. Experimental Study. *Int. J. Heat Mass Transf.* **1987**, *30*, 1051–1060. [CrossRef]
109. Biswas, P.; Kim, S.; Mills, A.F. A Compact Low-Pressure Drop Desiccant Bed for Solar Air Conditioning Applications: Analysis and Design. *J. Sol. Energy Eng.* **1984**, *106*, 153–158. [CrossRef]
110. Air-Conditioning Engineers. *2020 ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Systems and Equipment*; ASHRAE Handbook Committe, Ed.; ASHRAE: Atlanta, GA, USA, 2020; ISBN 9781947192539.
111. Zhou, X.; Goldsworthy, M.; Sproul, A. Performance Investigation of an Internally Cooled Desiccant Wheel. *Appl. Energy* **2018**, *224*, 382–397. [CrossRef]
112. Shamim, J.A.; Hsu, W.-L.; Paul, S.; Yu, L.; Daiguji, H. A Review of Solid Desiccant Dehumidifiers: Current Status and near-Term Development Goals in the Context of Net Zero Energy Buildings. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110456. [CrossRef]
113. Mohammed, R.H.; Ahmadi, M.; Ma, H.; Bigham, S. Desiccants Enabling Energy-Efficient Buildings: A Review. *Renew. Sustain. Energy Rev.* **2023**, *183*, 113418. [CrossRef]
114. Sultan, M.; El-Sharkawy, I.I.; Miyazaki, T.; Saha, B.B.; Koyama, S. An Overview of Solid Desiccant Dehumidification and Air Conditioning Systems. *Renew. Sustain. Energy Rev.* **2015**, *46*, 16–29. [CrossRef]
115. Radov, M. The Enthalpy Wheel. 2008. Available online: https://vsgc.odu.edu/wp-content/uploads/sites/3/2018/03/2009Environmental_thirdplace.pdf (accessed on 1 April 2024).
116. de Antonellis, S.; Intini, M.; Joppolo, C.M.; Leone, C. Design Optimization of Heat Wheels for Energy Recovery in HVAC Systems. *Energies* **2014**, *7*, 7348–7367. [CrossRef]

117. Mandegari, M.A.; Farzad, S.; Angrisani, G.; Pahlavanzadeh, H. Study of Purge Angle Effects on the Desiccant Wheel Performance. *Energy Convers. Manag.* **2017**, *137*, 12–20. [CrossRef]
118. La, D.; Dai, Y.J.; Li, Y.; Wang, R.Z.; Ge, T.S. Technical Development of Rotary Desiccant Dehumidification and Air Conditioning: A Review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 130–147. [CrossRef]
119. Lawrance, W.; Schreck, T. Rotary Heat Exchangers Save Energy and Prevent a Need for Recirculation Which Contributes to the Decrease the Risk of COVID-19 Transfer. *REHVA J.* **2020**, *5*, 65–68.
120. Men, Y.; Liu, X.; Zhang, T. Experimental and Numerical Analysis on Heat and Moisture Recovery Performance of Enthalpy Wheel with Condensation. *Energy Convers. Manag.* **2021**, *246*, 114683. [CrossRef]
121. Nasif, M.S. *Air-to-Air Fixed Plate Energy Recovery Heat Exchangers for Building's HVAC Systems*; Springer: Singapore, 2019; ISBN 9789811329685.
122. Camargo, J.R.; Ebinuma, C.D.; Silveira, J.L. Experimental Performance of a Direct Evaporative Cooler Operating during Summer in a Brazilian City. *Int. J. Refrig.* **2005**, *28*, 1124–1132. [CrossRef]
123. Melo, F.J.A. Desenvolvimento de um Sistema de Climatização Híbrido: Dessecante e por Compressão de Vapor. Ph.D. Thesis, Universidade Federal da Paraíba, João Pessoa, Brazil, 2019.
124. Singh, R.P.; Das, R.K. Progressive Development and Challenges Faced by Solar Rotary Desiccant-Based Air-Conditioning Systems: A Review. *Processes* **2021**, *9*, 1785. [CrossRef]
125. *BRITA Solar Heating and Cooling of Buildings Guidelines*; BRITA: Palermo, Italy, 2007.
126. Murphy, P. *IEA Solar Heating & Cooling Programme 2004*; Morse Associates, Inc.: Washington, DC, USA, 2005.
127. Ge, T.S.; Dai, Y.J.; Wang, R.Z.; Li, Y. Experimental Investigation on a One-Rotor Two-Stage Rotary Desiccant Cooling System. *Energy* **2008**, *33*, 1807–1815. [CrossRef]
128. Niemann, P.; Schmitz, G. Air Conditioning System with Enthalpy Recovery for Space Heating and Air Humidification: An Experimental and Numerical Investigation. *Energy* **2020**, *213*, 118789. [CrossRef]
129. EPA. *Laboratories for the 21st Century: An Introduction to Low-Energy Design*; EPA: Washington DC, USA, 2008.
130. Masson, S.V.; Qu, M.; Archer, D.H. Performance Modeling of a Solar Thermal System for Cooling and Heating in Carnegie Mellon University's Intelligent Workplace. *Energy Sustain.* **2007**, *47977*, 671–680.
131. *ABNT NBR 16401-3/2008*; Parte 3: Qualidade Do Ar Interior. ABNT: Rio de Janeiro, Brazil, 2008.