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# Comprehensive Energy Consumption of Elevator Systems Based on Hybrid Approach of Measurement and Calculation in Low- and High-Rise Buildings of Tropical Climate towards Energy Efficiency

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**Abstract:** Rapid population growth and urbanization contribute to an ever-increasing global energy demand, of which the building sector accounts for one-third. The increasing average height and density of buildings escalate the need for vertical transportation, expanding elevator usage and energy needs. This phenomenon accounts for a significant amount of the total building energy use, necessitating a study of elevator system energy consumption. This study aimed to analyze the energy consumption and carbon emissions of elevator systems in low- and high-rise buildings towards energy-efficient estimations. A comprehensive analysis was performed based on a hybrid approach of measurement and calculation using a formula and reference values derived from previous studies. Four buildings were selected and thoroughly studied, representing the low- and high-rise categories. Data were collected based on on-site sampling and observation, as well as information from the building management offices. The mechanical parameters of the elevator system in each building and operational factors in terms of speed, number of trips, load, travel distance, and time were studied. In this analysis, the energy consumption calculation was performed according to International Standard ISO 25745. Annual carbon emissions were calculated in accordance with the USA EPA and IPCC guidelines. The elevator energy efficiency class was determined based on daily energy consumption. It was found from this study that the annual energy consumption of an elevator system is positively correlated to an elevator's daily energy consumption. The annual carbon emissions of the elevator systems are dependent on increasing annual energy consumption, which is also connected to building height indirectly. The low-rise buildings showed better energy efficiency compared to the high-rise buildings due to lower travel distance, less trips, and fewer floors. The annual number of trips, travel distances, and energy consumption had an effect on the energy efficiency of the elevator systems in this study.

**Keywords:** energy consumption; greenhouse gas emissions; energy efficiency; elevator; buildings

## 1. Introduction

World energy consumption is increasing on an annual basis in tandem with high population expansion and urbanization. Many countries across the world contribute to the upward trend. For instance, in 2020, the energy consumptions in Europe, the Commonwealth of Independent States (CIS), North America, Latin America, Asia, the Pacific, Africa, and the Middle East were 1689 Million tonnes of oil equivalent (Mtoe), 1015 Mtoe, 2327 Mtoe, 758 Mtoe, 5955 Mtoe, 152 Mtoe, 809 Mtoe, and 803 Mtoe, respectively [1]. Global energy demand is projected to increase 28 to 30% between 2015 and 2040, from 575 quadrillion British Thermal Unit (Btu) to 736 quadrillion Btu [2,3]. Among various energy sectors, buildings account for a significant percentage of the overall global energy consumption, up to 20.1% to 40% [4–6]. In Malaysia, with a tropical climate, the energy consumption of the building sector contributes up to 48% to 54% of the total electricity usage in the country [5]. Buildings have substantial energy needs throughout their entire life cycles, from the construction phase, operation phase, and maintenance phase, until the demolition phase [7]. In many European countries, residential buildings contribute more to building energy consumption compared to commercial buildings [8–11]. In Malaysia, the energy consumption of commercial buildings outweighs residential buildings [5,12]. Specifically, the nonresidential buildings consume more energy per area (kWh/$m^2$) than the residential buildings [13]. Commercial buildings have an alarmingly high energy consumption. This is contributed to by the increased number of heating, ventilation, and air conditioning (HVAC) systems in commercial office buildings compared to residential buildings in tropical climate countries [14]. Occupant behaviour was also identified as a factor in these buildings' energy consumption [15].

Additionally, when average building height and density increase, vertical transportation demand within the building rises, leading to a surge in elevator usage. As a result, the energy consumption of the building continues to rise significantly with increasing building height [16,17]. According to a previous report by Al-kodmany [18], more than seven billion elevator trips are made every single day in the world. This adds to elevators' high energy consumption, which may account for 2% to 40% of the total building energy consumption. In most cases, the elevator systems in commercial office buildings meet more stringent criteria (e.g., higher rated load, rated speed, and number of cars) than the elevator systems in residential buildings, owing to increased elevator traffic and requirements [19]. Elevator systems with better specifications and more traffic in commercial office buildings consume more energy than elevator systems in residential buildings. This increased traffic in commercial office buildings is a result of tenants' access to entrances and exits and their interfloor travels [20].

The number of elevator cars and their configuration are determined by the number of floors in a building, as well as the population density on each floor [21]. Elevator energy consumption is highly dependent on elevator car and shaft characteristics, motor type, control system, auxiliary system, elevator traffic, and population density in the building [22,23]. Geared and gearless traction roped elevators are both less energy-intensive than conventional elevators and are commonly used in mid-rise and high-rise buildings, respectively. In contrast, hydraulic elevators are more energy-intensive and are typically used in low-rise buildings.

### *1.1. Determination of Elevator Energy Consumption*

There are five common methods used to determine the energy consumption of an elevator system, which are: (i) calculation from first principles [24–26]; (ii) calculation using formulas and reference values derived from previous studies [27,28]; (iii) measurement [29,30]; (iv) a hybrid method of measurement and calculation using formulas and reference values derived from previous studies [31,32]; and (v) modelling and simulation [33–35].

At an early time, Kirchenmayer [25] and White [26] both studied the energy consumption of traction and hydraulic elevators using a method of calculation based on first principles [33]. Both studies reported that the traction-type elevator was a more energy-efficient mode of transport. This method is low-cost and easily implemented. However, this method does not distinguish between elevator load and speed, as well as building usage. Thus, this method is suitable to be used for any investigations that aim to focus on elevator energy efficiency technology instead of elevator energy consumption quantitative analysis. The measurement method refers to direct measurement by installing an energy meter on the elevator system, which provides the most accurate elevator energy consumption value. This method enables continuous monitoring of transient elevator energy consumption parameters, which are current and voltage, according to the desired sampling rate and average time specified. To produce a high-quality outcome, precise and accurate tools should be employed. This method is the most expensive, yet it provides the most precise and immediate findings. It is vital for the validation of alternative methods of determining elevator energy consumption.

The hybrid method comprises measurement and calculation using formulas and reference values derived from previous studies, involving measurement and secondary data for further analysis of calculation and extrapolation. This method entails measuring field measurements of energy consumption at specific parameters, such as speed, load, direction, and traffic load. The energy consumption is estimated for various parameter values using relevant and appropriate equations. For instance, data from measurements of loads of 500 kg and 600 kg can be used to predict the energy consumption of a load of 700 kg. Energy assessment and classification schemes, such as Verein Deutscher Ingenieure (VDI) 4707-1:2009 and the International Organization for Standardization (ISO) 25745-2:2015, are established examples of this method [36–38]. These scientific experiments give standard reference values in a variety forms, including energy models, categorization tables, and elevator energy profiles, to be used in different cases with listed conditions.

This method was used in a study by Hu et al. [39] to compare the effectiveness of variable voltage variable frequency (VVVF) drives in the energy efficiency of typical elevator systems, which are hydraulic and traction, following the VDI 4707 method. Bannister et al. [31] collected data on the system and technology within a specific building, developing empirical correlations of these data to the energy consumption of the elevator in that building in order to anticipate the elevator energy consumption in an office building over 3000 $m^2$. The predictive benchmark equation produced in this study can be used in future studies categorized under the hybrid method comprising measurement and calculation using formulas and reference values derived from previous studies. On the other hand, Tukia et al. [32] studied and compared two approaches to predict annual elevator energy consumption from short-term measurement data. In their study, daily consumption measurement data were used to derive the equations for annual elevator energy projection. In the study, a simpler method that worked based on linear extrapolation of the annual consumption based on measurement data was used. Another method used in the study took into account seasonal influences on elevator usage, making it more accurate but necessitating a greater level of data detail. The latter method's results were shown to be accurate when compared to the actual measurement of annual elevator energy consumption, as well as to the estimated results based on VDI 4707-1:2009 and ISO 25745-2:2015.

According to existing studies in the literature, the estimation and calculation method based on short-time measurement may be used to represent long-time measurement, as both results are similar [40]. The cost is much lower than that of the method of pure measurement but higher than that of the method of calculation. It is less expensive than modelling and simulation, but it requires more time and has a lesser degree of comprehensiveness due to its lower complexity. As such, it is well suited for the preliminary monitoring of a specific elevator in order to develop subsequent improvement. Despite this, the assumptions may deviate from the real case due to spatial and temporal differences. Moreover, it does not cover more detailed and short-time energy consumption estimation that is needed for the development of an efficient elevator control system.

### *1.2. Current Situation, Research Gaps, and the Aim of the Current Study*

The literature reports that energy consumption in buildings accounts for around one-third of overall consumption and contributes an equal share of carbon dioxide emissions [41,42]. To obtain a better grasp of the existing body of information in this field, studies on elevator energy consumption and its association with carbon emissions are beneficial towards effective energy management in buildings. This enables better monitoring of the energy performance of an elevator system and the energy-saving awareness of users, resulting in more targeted solutions for excessive elevator energy consumption. Despite this, there are few studies on elevator system energy consumption, particularly in tropical climate countries, compared to total building energy consumption and other high-energy-consuming systems in buildings, such as mechanical ventilation air-conditioning (MVAC) and lighting, as well as building structure and design [43–49]. For example, in Malaysia's hot and humid environment, the majority of researchers have concentrated on the energy consumption and efficiency of a structure or entire building, the cooling system, and the electrical appliances for thermal comfort [5,45,50–55]. There is a lack of studies examining elevator system energy usage and efficiency in relation to carbon emissions. Furthermore, there are a very limited studies available on this topic that employ the hybrid method comprising measurement and calculation using formulas and reference values derived from previous works.

Therefore, considering this research gap, this study was carried out to analyze the energy consumption of elevator systems in low- and high-rise buildings in tropical climates towards energy-efficienct estimation. The study uses a detailed hybrid approach utilizing a combination of measurements and calculation methods. The new contributions of this paper are a contribution towards energy analysis that also takes into account the elevator system type, characteristics, and operating parameters, such as elevator speed, number of trips, loads, travel distance, and time, as well as elevator energy aspects in terms of usage category and elevator powers, in the addition to carbon emissions estimation. The mechanical specifications and operational variables of each building's elevator system were evaluated. In view of demographic trends and the increasing need for convenience, the number of elevator systems is expected to increase. More urbanization in developing countries and a growing awareness of issues of accessibility due to a growing population, particularly in a tropical climate, stimulates the need for more advanced and efficient systems. Thus, this study contributes to the current pool of data to improve the energy efficiency of elevator systems in the building sector, especially in tropical climates.

## 2. Methods

This study covers field data collection and calculations based on a formula and reference values from previous studies, as well as analysis based on the established standards and past studies. The methods of this study are explained in the following subsections.

### *2.1. Characteristics of the Selected Buildings and the Elevator System*

Most of the features of low-rise, mid-rise, and high-rise buildings are the same in different countries, except for a lesser number and a smaller size of windows in tropical climates compared to temperate climates [56]. The most common type of elevator system used in the existing and current buildings in tropical climates is the traction-type elevator [57,58]. Four low- and high-rise buildings with common building characteristics and elevator system specifications were selected in this study to represent the typical low- and high-rise buildings in the Malaysian tropical climate. The characteristics of the four selected buildings were collected from the building management offices.

The building dimensions (in rough form), building floor plan (detailed, exact shape), and function and operating lift of different floors for high-rise residential apartment (HA), low-rise residential apartment (LA), high-rise commercial office (HO), and low-rise commercial office (LO) buildings are shown in Figures 1–4(a–c), respectively. Also, the respective characteristics of the buildings and elevator cars are summarized in Appendices A–D.

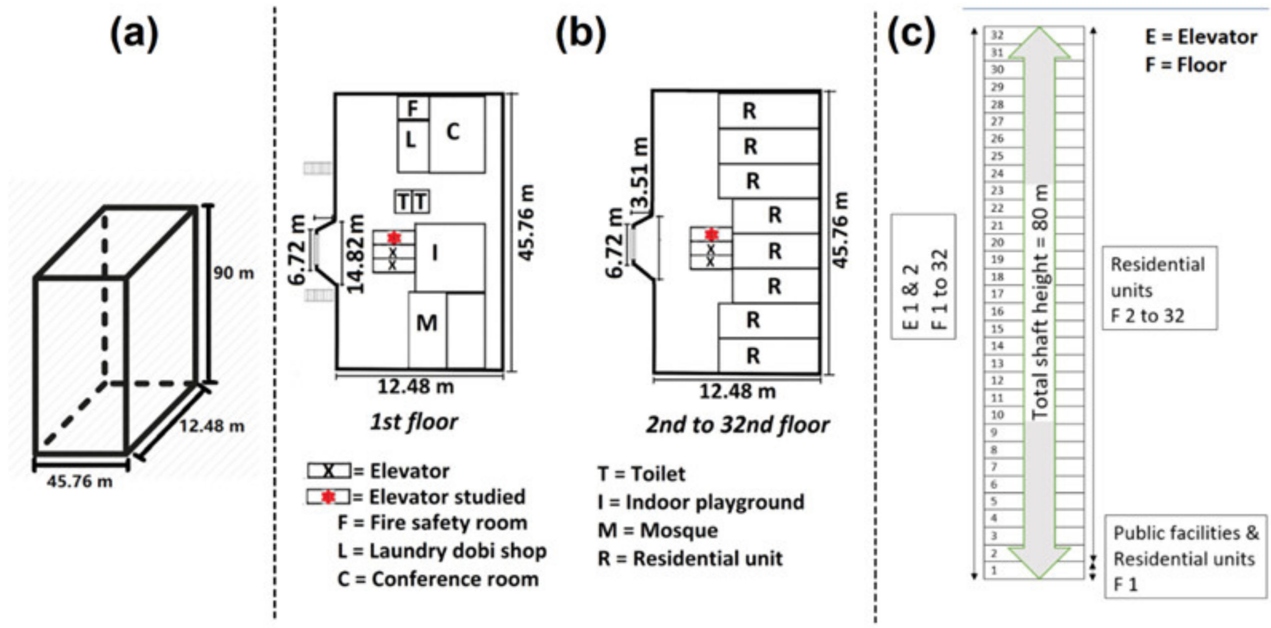


**Figure 1.** HA (**a**) building dimensions, (**b**) building floor plan, and (**c**) function and operating lift of different floors.

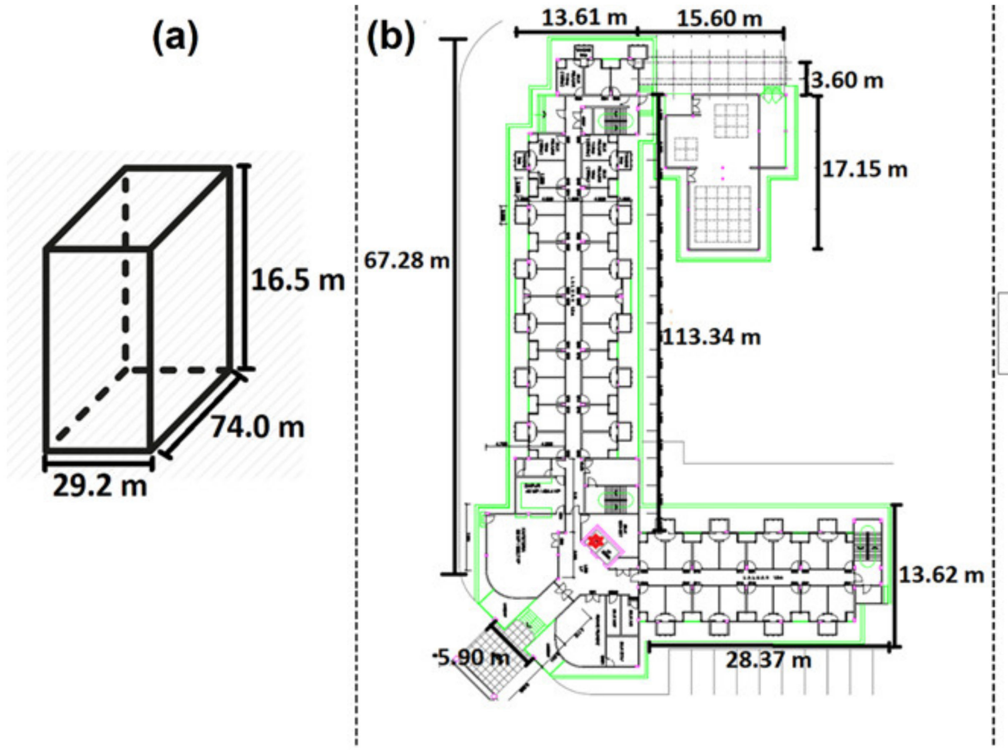


**Figure 2.** LA (**a**) building dimensions, (**b**) building floor plan, and (**c**) function and operating lift of different floors.

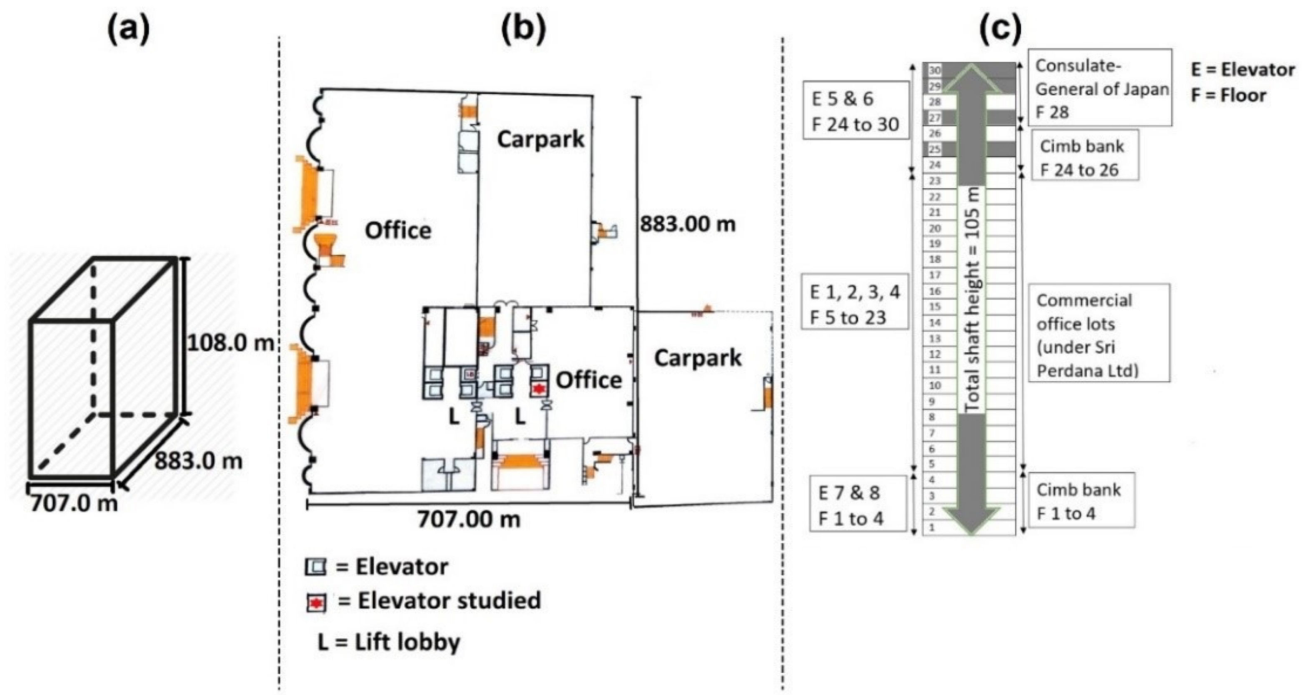


**Figure 3.** HO (**a**) building dimensions, (**b**) building floor plan, and (**c**) function and operating lift of different floors. Shaded floors are vacant during the study.

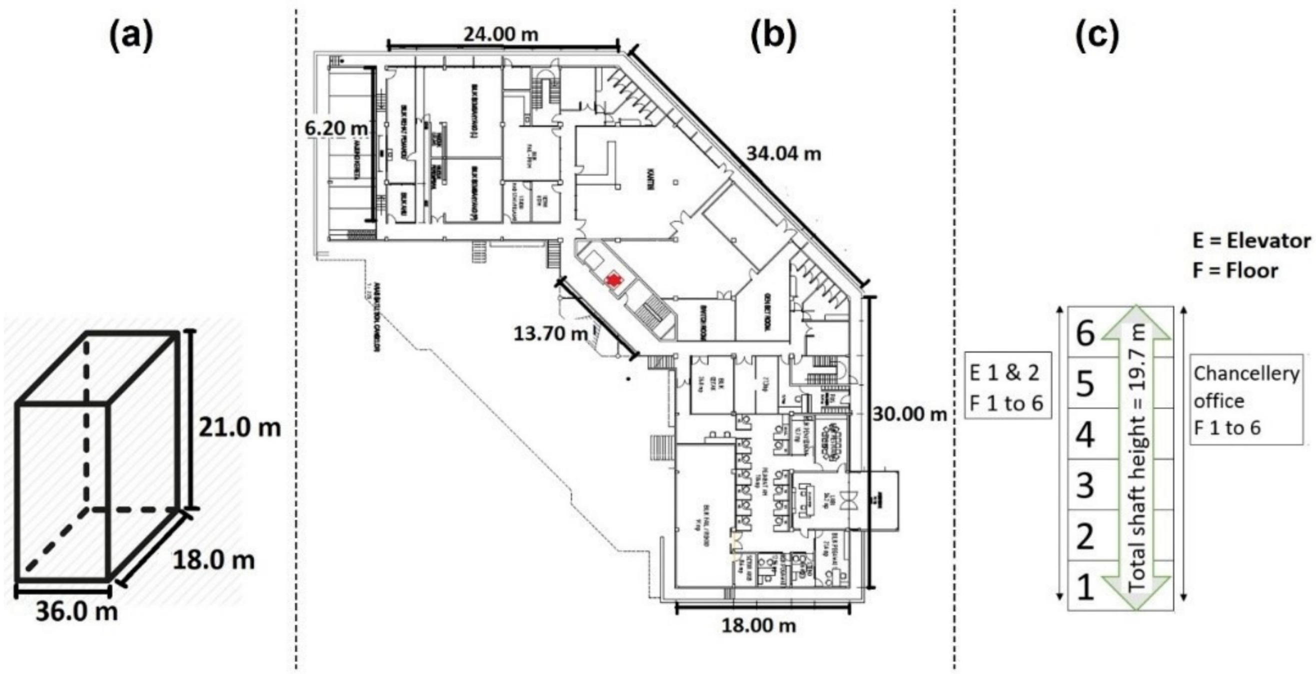


**Figure 4.** LO (**a**) building dimensions, (**b**) building floor plan, and (**c**) function and operating lift of different floors.

### *2.2. Field Data Collection*

Based on this study's conditions, a hybrid approach of measurement and calculation was used to estimate the energy consumption of the elevator systems in the selected buildings. The annual energy consumption of the elevator systems was estimated based on the elevator traffic and operation power following guidelines from ISO 25745 [38]. The elevator traffic was determined based on observation at the elevator site for two weeks to include the variations among weekdays and weekends [35]. The elevator traffic was measured in terms of the number of trips travelled by an elevator, in which a single set of start and stop represented one trip. The average daily number of trips over two weeks was recorded and used for the calculation of each building [36,38]. On the other hand, the operation power was calculated from the data of running power, standby power, and idle power provided by the building management departments and (or) the elevator manufacturer company. The results served to evaluate energy efficiency [20,59].

*2.3. Elevator Energy Consumption Analysis*

The main formulas used in the calculation of the energy consumptions are stated in Equations (3)–(6). Further details of the calculations are shown in [32,36,38,60,61]:

$$E_d = E_r + E_{nr} \tag{1}$$

$$E_r = \frac{(n_d \times 0.5\ t_{av} \times R)}{3600} \tag{2}$$

$$E_{nr} = \frac{t_{nr}}{100}(P_{id}R_{id} + P_{st5}R_{st5} + P_{st30}R_{st30}) \tag{3}$$

$$E_a = E_d + D \tag{4}$$

where, $E_d$, $E_a$, $E_r$, and $E_{nr}$ are the daily energy consumption of the elevator system, the annual energy consumption of the elevator system, the daily running energy of the elevator system, and the daily nonrunning energy of the elevator system in kWh, respectively. Moreover, $n_d$ is the number of trips per day, D is the number of days operated, $t_{av}$ is the average trip time the elevator travelled (s), R is the rated power of the elevator (kW), and $t_{nr}$ is the nonrunning time of the elevator system (s). In all the above equations, $P_{id}$ and $R_{id}$ are the idle power (W) and the time ratio of the idle phase to the nonrunning phase, respectively. $P_{stx}$ and $R_{stx}$ (x = 5, 30) are the first "x" minutes of standby power (W), and the time ratio of the first "x" minutes standby phase to the nonrunning phase, respectively.

*2.4. Elevator Energy Efficiency Analysis*

The efficiency class of daily energy consumption was determined using the equations shown in Table 1 taken from the ISO 25745-2:2015 guidelines [38]. Class A shows the highest energy efficiency, while class G shows the lowest energy efficiency. In the equations in Table 1, the parameters accounted for in the energy efficiency evaluation are as follows: Q is the rated load of the elevator car (kg), $n_d$ is the daily number of trips, $S_{av}$ is the average distance travelled (m), and $t_{nr}$ is the nonrunning time of the elevator system (s).

**Table 1.** Energy efficiency class of elevator systems based on ISO 25745 standards [38]. Reproduced with permission from ISO, ISO 25745-2:2015 guidelines; published by ISO, 2015.

| Energy Efficiency Class | Energy Consumption Per Day (Wh) |
|---|---|
| A | $0.72 \times Q \times n_d \times S_{av}/1000 + (50 \times t_{nr})$ |
| B | $1.08 \times Q \times n_d \times S_{av}/1000 + (100 \times t_{nr})$ |
| C | $1.62 \times Q \times n_d \times S_{av}/1000 + (200 \times t_{nr})$ |
| D | $2.43 \times Q \times n_d \times S_{av}/1000 + (400 \times t_{nr})$ |
| E | $3.65 \times Q \times n_d \times S_{av}/1000 + (800 \times t_{nr})$ |
| F | $5.47 \times Q \times n_d \times S_{av}/1000 + (1600 \times t_{nr})$ |
| G | $5.47 \times Q \times n_d \times S_{av}/1000 + (1600 \times t_{nr})$ |

$S_{av}$ is the average displacement per day.

*2.5. Elevator Carbon Emissions Analysis*

According to the United States Environmental Protection Agency (US EPA) and the Intergovernmental Panel on Climate Change (IPCC) guidelines, carbon emissions were calculated by multiplying the energy consumption with the carbon emission factor [62–64]. Since carbon dioxide is the most significant greenhouse gas (GHG), this study focused only on the carbon dioxide emissions from anthropogenic activities in building sectors [65].

The grid carbon dioxide emissions factor of Malaysia was obtained from the Sustainable Energy Development Authority (SEDA) of Malaysia in accordance with the revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories and 2006 IPCC Guidelines for National Greenhouse Gas Inventories [66–69]. In this study, the carbon emissions of the elevator in each building were calculated using Equation (7), where $E_a$ is the annual energy consumption of the elevator, and 0.639 $tCO_2/MWh$ is the latest grid carbon dioxide emissions factor of Malaysia (updated in 2016) [67].

$$\text{Carbon emissions } (tCO_2) = E_a(MWh) \times 0.639 \left(\frac{tCO_2}{MWh}\right) \quad (5)$$

## 3. Results and Discussion

### *3.1. Energy Consumption and Energy Efficiency of the Elevator Systems*

Table 2 shows the usage, usage category, running power, idle power, standby power 5 min, standby power 30 min, and nonrunning power, as well as daily and annual energy consumption of the elevator systems in the selected buildings based on the present study. In accordance with ISO 25745-2:2015, the elevator usage category was categorized based on the counted number of trips of the elevator and was indicated by an integer from 1 to 6 with increasing usage intensity or frequency.

**Table 2.** Daily usage, usage category, and energy consumption of the elevator systems in the selected buildings.

| Elevator Energy Aspects | High-Rise Building | | Low-Rise Building | |
|---|---|---|---|---|
| | Residential Apartment (HA) | Commercial Office (HO) | Residential Apartment (LA) | Commercial Office (LO) |
| No. of trips per day (trip) | 340 | 504 | 176 | 589 |
| Usage category | 3 | 4 | 2 | 4 |
| Running power, $P_r$ (W) | 13,000 | 13,000 | 4900 | 8500 |
| Idle power, $P_{id}$ (W) | 1334.9 | 1334.9 | 1326.45 | 208 |
| Standby power 5 min, $P_{st5}$ (W) | 252.6 | 252.6 | 190.25 | 120.1 |
| Standby power 30 min, $P_{st30}$ (W) | 161.6 | 161.6 | 128.3 | 81.7 |
| Nonrunning power, $P_{nr}$ (W) | 1749.1 | 1749.1 | 1645 | 409.8 |
| Daily energy consumption (kWh) | 49.81 | 52.52 | 5.35 | 29.68 |
| Annual energy consumption (kWh) | 14485 | 13,617.6 | 1656.48 | 6422.88 |

Based on Figure 5, the present study reported that the annual energy consumption of the elevator systems increased with the daily energy consumption of the elevator systems, as expected. This can be justified by the calculation methods of elevator annual energy consumption in the ISO and VDI standards. In the mentioned methods, the daily elevator traffic is assumed to be consistent throughout the year and is used to calculate the annual energy consumption by multiplication with the operating days of the elevator system throughout the year [37,38]. This is because office and residential buildings are occupied by mostly long-term tenants and operate as usual throughout the entire year.

The main contributing factors to elevator energy consumption are elevator usage and building height, which affects the total shaft height, and there are positive correlations between each of these variables, which are illustrated in Figure 6. In past and present studies, for similar-height buildings, the annual energy consumption of the elevator system has increased with the annual number of trips for the elevator system [70,71]. However, in the comparison between high-rise and low-rise buildings, the low-rise buildings showed a higher annual number of trips but lower annual energy consumption because the lower building height had a lower total shaft height (full travel distance), leading to a lower total distance travelled throughout the year. This phenomenon is shown in Figure 6, where the low-rise residential apartment and low-rise commercial offices had a high annual number of trips but lower annual energy consumption compared to the high-rise residential apartment and high-rise commercial offices. The high-rise buildings had a higher full travel distance for the elevators and heavier traffic due to a lower number of shared trips and high tenant density. Higher building height with a higher number of floors caused the tenants to be distributed more widely among the different floors, causing a fewer number of trips to be shared by more than one tenant [71]. Moreover, the higher tenant density in the high-rise residential apartment caused a higher difference in the working and school hours of different tenants in the high-rise residential apartment. The high-rise commercial office, which is a multi-tenant office, had lighter traffic compared to the low-rise commercial office, which is a single-tenant office with higher interfloor trips [72]. The low-rise office showed the highest number of trips among all four buildings in the study. This was due to the limitations of the building structure and elevator system of the low-rise office building, which is further elaborated in Section 3.3.

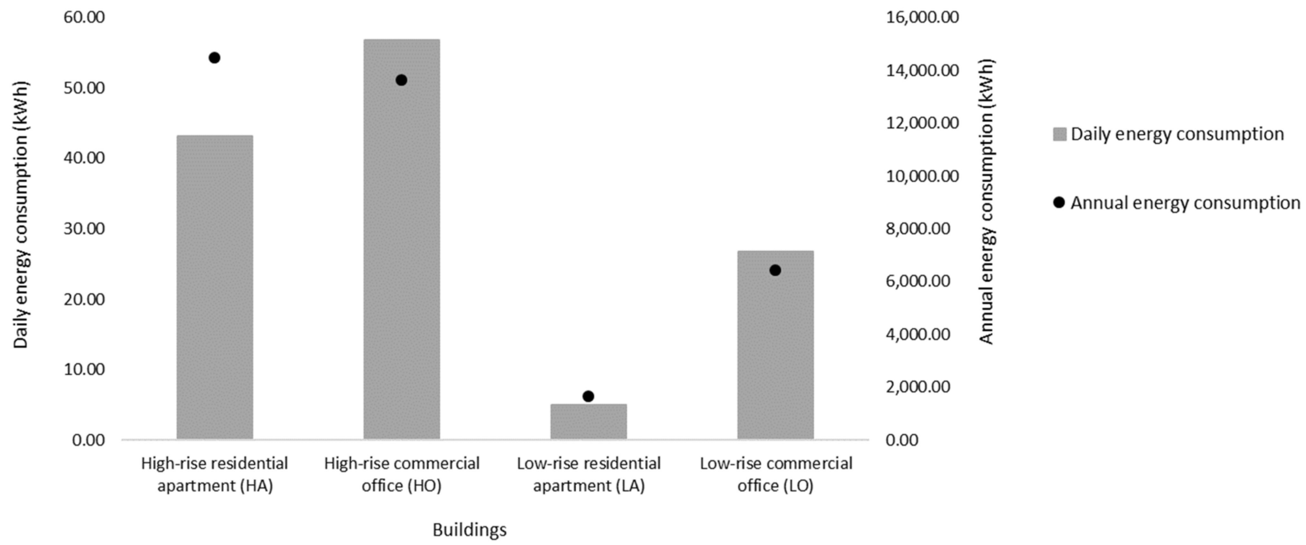


**Figure 5.** Daily energy consumption versus annual energy consumption of the elevator systems in the buildings in the present study.

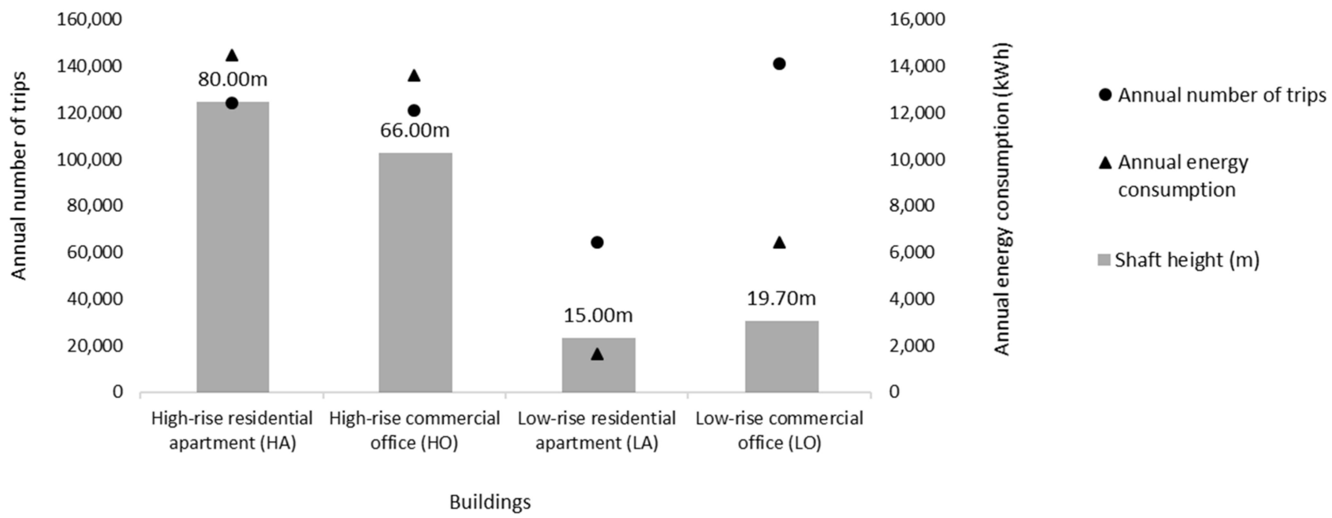


**Figure 6.** Annual number of trips versus annual energy consumption of the elevator system in buildings with different shaft heights based on the present study.

The data from existing studies are collected and shown in Tables 3 and 4. As expected, the elevator energy consumption of the high-rise buildings was higher than that of the low-rise buildings due to their higher full travel distance. Also, building use affected elevator usage and energy consumption. Commercial office buildings recorded a higher elevator energy consumption than residential apartment buildings. This was because the elevator usage of commercial buildings, such as offices, is generally higher than that of residential buildings, such as apartments, due to the higher incoming and outgoing population and activities. Considering the similar number of elevator cars of the elevator systems, the results from this study obey the theoretical results and the trends in past studies' results. Despite this, there are some noteworthy trends shown in Figure 6, in which the annual elevator energy consumption of the high-rise residential apartment building showed a slightly higher value than that of the high-rise commercial office buildings. This was because the high-rise commercial office building has a zoned elevator system with a higher number of cars servicing only specific floors, comprising six cars, compared to the high-rise residential apartment building with only three cars servicing all floors. A higher number of cars distributes the demand for trips travelled, decreasing the energy consumption of each car. Different elevators zones have different home landing or parking floors (resting terminals), enabling more efficient travel among the specific floors. For the cases with the same number of cars in the elevator systems, the low-rise commercial office building had a higher annual elevator energy consumption than the low-rise residential apartment building.

An analysis was conducted based on the elevator annual energy consumptions of past studies and the present study. The past study data are shown in the boxplot with blue markers illustrating the present study (Figure 7). All buildings, except the low-rise office building, had annual energy consumptions of an elevator system within the ranges of typical elevator annual energy consumption. This was due to the limitations of the building structure and elevator system of the low-rise office building, which is further elaborated in Section 3.3.

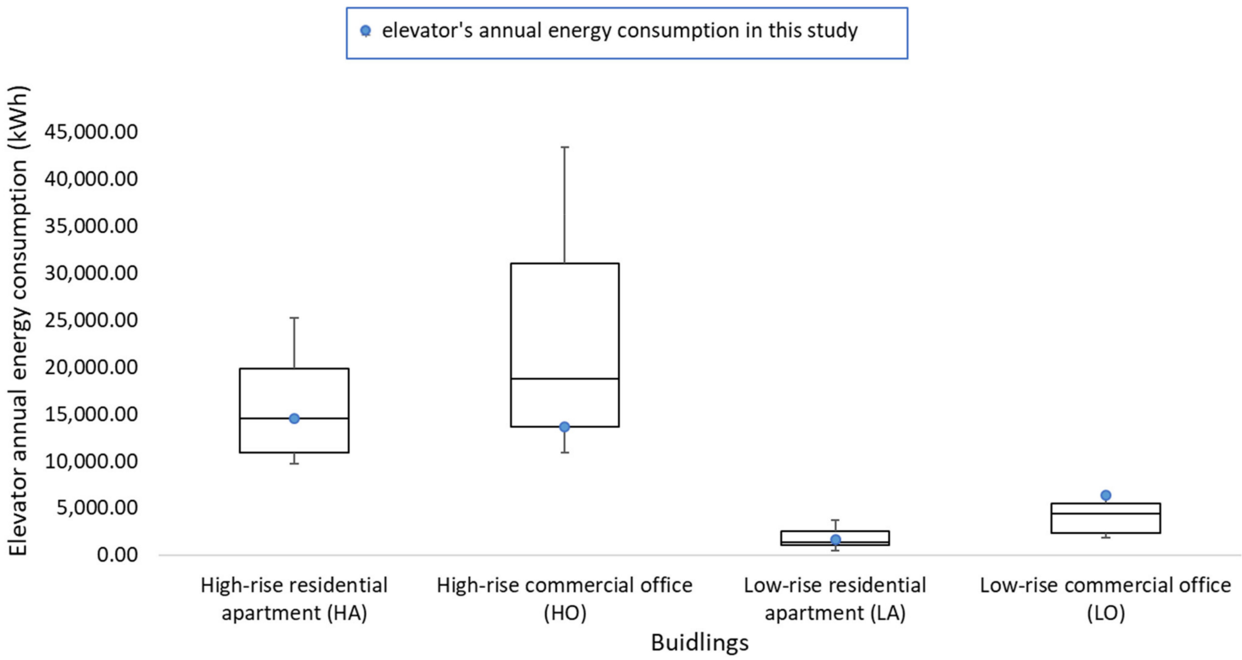


**Figure 7.** Annual energy consumptions of the elevator systems in high-rise and low-rise residential and office buildings based on the present study and past studies.

**Table 3.** Characteristics and annual energy consumption of the elevator systems in different heights of residential buildings based on past studies.

| Building Height (m) and Floors | | Parameters | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| | | Elevator Type | Elevator Speed (m/s) | Load (kg) | Elevator Travel Power (kW) | Annual Energy Consumption (kWh) | |
| High-rise | 136.5; 45 | Gearless traction | 3 | 1350 | 39.7 | 26,462.50 | [73] |
| | 230.6; 69 (The Met) | Gearless traction, regenerative, compact machine room, KONE Jump-Lift | 4.0–6.0 | 2000 | N/A | 19,846.50 | [74–76] |
| | 180.0; 63 (Ashok tower) | Gearless traction, regenerative, compact machine room, KONE Mini-Space (old) | 4 | 2000 | N/A | 10,878.00 | [77,78] |
| Mid-rise | 59.0; 16 | Traction, gearless PMSM, non-regenerative | 2.5 | 1500 | 3.8 | 5324.00 | [32] |
| | 50.0; 14 | Gearless traction | 1.5 | 1000 | 13 | 4350.00 | [79] |
| Low-rise | 26.1; 7 | Geared traction | 1.6 | 750 | 7.2 | 4763.30 | [80] |
| | 29.0; 7 | Gearless traction | 1 | 630 | 5.3 | 3969.40 | [80] |
| | 23.7; 6 | Geared traction | 1 | 1000 | 8.5 | 5294.30 | [80] |
| | 14.0; 4 | Geared traction | 1 | 320 | 3.9 | 711.8 | [80] |
| | 14.0; 4 | Geared traction | 1 | 630 | 3.4 | 1126.60 | [80] |
| | 14.6; 4 | Gearless traction | 1 | 630 | 4.8 | 1219.10 | [80] |
| | 17.4; 4 | Gearless traction | 1 | 630 | 5.2 | 1274.90 | [80] |
| | 16.5; 4 | Gearless traction | 1 | 800 | 4.9 | 1408.90 | [80] |
| | 11.2; 3 | Hydraulic | 0.6 | 320 | 9.5 | 2677.30 | [80] |
| | 13.4; 3 | Hydraulic | 0.6 | 500 | 12.6 | 2565.40 | [80] |
| | 12.4; 3 | Hydraulic | 1 | 500 | 4.7 | 1192.30 | [80] |
| | 11.6; 3 | Geared traction | 1 | 630 | 6 | 1481.00 | [80] |
| | 10.2; 2 | Gearless traction | 1.6 | 500 | 7.5 | 2329.40 | [80] |
| | 11.2; 5 | Gearless traction | 0.6 | 320 | travel 8.93 mWh/(m·kg), standby 200W | 2124.3 | [81] |
| | 14.0; 6 | Gearless traction | 1 | 630 | 4 | 950 | [79] |
| | 14.0; 6 | Gearless traction | 1 | 1000 | 6.1 | 953.8 | [79] |
| | 13.0; 6 | Gearless traction | 0.6 | 500 | travel 91 Wh, idle 50 W, standby 31 W | 511 | [36] |

**Table 4.** Characteristics and annual energy consumption of the elevator systems in different heights of office buildings based on past studies.

| Building Height (m) and Floors | | Parameters | | | | | Ref. |
|---|---|---|---|---|---|---|---|
| | | Elevator Type | Elevator Speed (m/s) | Load (kg) | Elevator Travel Power (W) | Annual Energy Consumption (kWh) | |
| High-rise | 192.0; 48 | Traction regenerative, MG-DC gearless | 6.1 | 1360.8 | N/A | 47,815.0 | [82] |
| | 192.0; 48 | Traction regenerative, Quattro-DC gearless | 6.1 | 1360.8 | N/A | 23,725.0 | [82] |
| | 140.0; 35 | Traction regenerative, MG-DC gearless | 5.1 | 1360.8 | N/A | 33,507.0 | [82] |
| | 140.0; 35 | Traction regenerative, Quattro-DC gearless | 5.1 | 1360.8 | N/A | 13,833.5 | [82] |
| Mid-rise | 81.0; 19 (Moorhouse) | Gearless traction, KONE Mini-Space C7 | 4.0 | 2000.0 | N/A | 6900.0 | [83] |
| | 75.0; 21 | Gearless traction | 2.5 | 1600.0 | Travel 170 Wh, idle 500 W, standby 120 W | 12,306.0 | [36] |
| | 72.0; 18 | Traction, VVVF, regenerative | 2–3.0 | 1800.0 | N/A | 20,622.5 | [84] |
| | 76.0; 19 | Traction regenerative, MG-DC gearless | 4.1 | 1360.8 | N/A | 25,367.5 | [82] |
| | 76.0; 19 | Traction regenerative, Quattro-DC gearless | 4.1 | 1360.8 | N/A | 9198.0 | [82] |
| | 73.7; 18 | Gearless traction | 2.5 | 1500.0 | 19.3 | 23,494.3 | [80] |
| | 68.1; 17 | Gearless traction | 2.5 | 1500.0 | 27.1 | 42,705.0 | [80] |
| | 60.9; 15 | Traction inductive AC non-regenerative | 3.1 | 1135.0 | N/A | 38,106.0 | [82] |
| | 60.9; 15 | Traction permanent magnet AC non-regenerative | 3.1 | 1135.0 | N/A | 28,449.0 | [82] |
| | 60.9; 15 | Traction SCR-DC regenerative | 3.1 | 1135.0 | N/A | 27,798.0 | [82] |
| | 60.9; 15 | Traction permanent magnet AC regenerative | 3.1 | 1135.0 | N/A | 14,690.0 | [82] |
| | 51.9; 13 | Gearless traction | 1.6 | 2000.0 | 18.0 | 23,925.8 | [80] |
| | 42.9; 11 | Gearless traction | 2.0 | 3000.0 | 40.0 | 50,008.7 | [80] |

**Table 4.** *Cont.*

| Building Height (m) and Floors | | Elevator Type | Parameters | | | Annual Energy Consumption (kWh) | Ref. |
|---|---|---|---|---|---|---|---|
| | | | Elevator Speed (m/s) | Load (kg) | Elevator Travel Power (W) | | |
| | N/A | Traction | 2.0 | 2000.0 | 19.0 | 17,700.0 | [79] |
| | N/A | Traction | 1.5 | 1000.0 | 13.0 | 4350.0 | [40] |
| Low-rise | 27.5; 9 | Gearless traction | 1.0 | 630.0 | 4.2 | 3531.4 | [80] |
| | 19.6; 8 | Gearless traction | 1.5 | 1000.0 | 21.0 | 4388.9 | [79] |
| | 26.0; 7 (Five boats, Duisburg) | Gearless traction, KONE Mono-Space C5 with energy-efficient options activated | 1.6 | 1000.0 | N/A | 5100.0 | [83] |
| | 18.0; 6 | Non-regenerative geared traction | N/A | N/A | N/A | 5800.0 | [85] |
| | 18.0; 6 | Non-regenerative geared traction | N/A | N/A | N/A | 6902.0 | [85] |
| | 18.0; 6 | Regenerative geared traction | N/A | N/A | N/A | 2441.0 | [85] |
| | 14.6; 4 | Gearless traction | 1.6 | 630.0 | 15.8 | 5010.7 | [80] |
| | 15.6; 4 | Geared traction | 1.0 | 800.0 | 6.7 | 2346.4 | [80] |
| | 11.8; 3 | Geared traction | 1.0 | 630.0 | 6.3 | 1956.0 | [80] |
| | 6.9; 2 | Gearless traction | 1.0 | 630.0 | 4.0 | 1827.9 | [80] |

The efficiency class of the daily energy consumption of an elevator had a positive correlation with the running and nonrunning energy consumption, but it also depended on the load factor, number of trips, and average displacement, as well as on running and nonrunning time [37,60]. Thus, an elevator system with good running and nonrunning energy performances did not necessarily have a good energy efficiency class. Based on the results of the present study, Table 5, the low-rise buildings showed relatively good energy efficiency (A and B) compared to the high-rise buildings (D and B). This can be justified by the lower distance to travel, as well as a smaller number of floors, that caused more passengers to share the same destination floor and pick-up floor, reducing the trip demand of the elevator system. Despite this, the high-rise commercial office recorded the same energy efficiency as the low-rise commercial office. This was due to the zoned elevator system of the high-rise office building and the limitations of the building structure and elevator system of the low-rise office building, as mentioned above. However, running and nonrunning energy consumption were the main factors of energy efficiency.

**Table 5.** Energy efficiency class of the elevator systems based on the present study.

| Buildings | High-Rise Building | | Low-Rise Building | |
|---|---|---|---|---|
| | Residential Apartment (HA) | Commercial Office (HO) | Residential Apartment (LA) | Commercial Office (LO) |
| Efficiency class | D | B | A | B |

## 3.2. Carbon Emissions of the Elevator System

The annual carbon emissions were calculated from multiplication of the annual energy consumption of elevator with the constant grid carbon emission factor of Malaysia. Thus, the annual carbon emissions of the elevator system depended on only the annual energy consumption and increased with annual energy consumption (Figure 8). This was because carbon emissions are produced mainly from electricity generation, which is used to power the elevator operation. These results are supported by previous studies [86,87]. There is a positively correlated trend between growing urbanization and carbon emissions that are generated by the building sector. Carbon emissions depend on building height, which affects elevator usage. It was deduced that there is a positive correlation between energy consumption, building height, and carbon emissions.

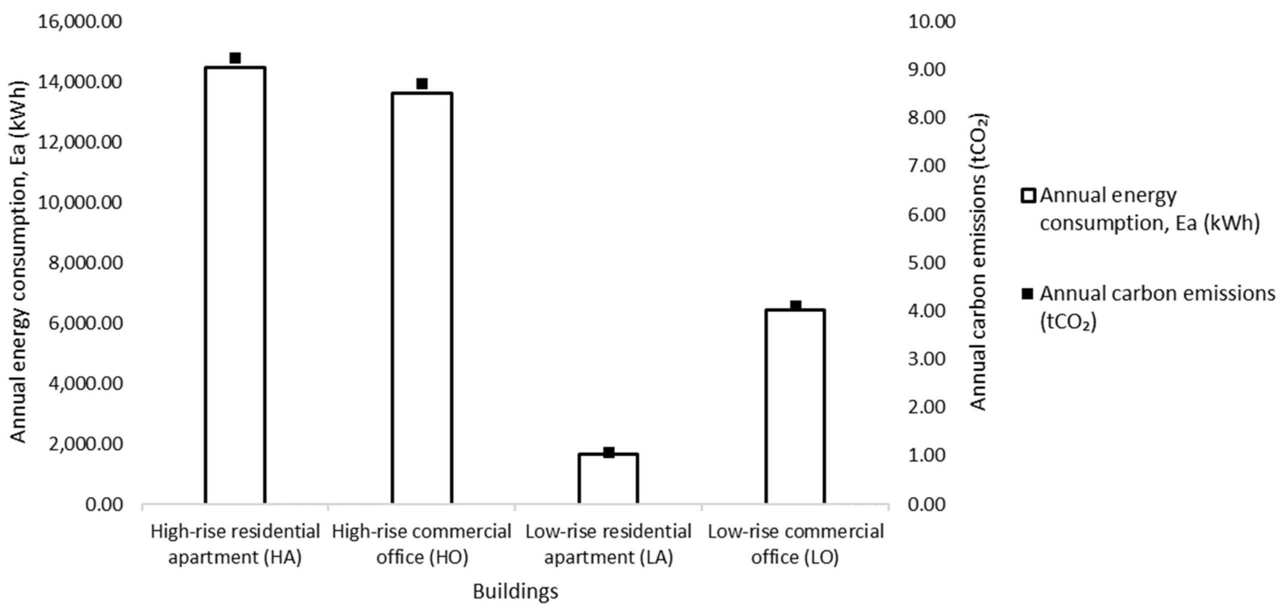


**Figure 8.** Annual energy consumption against the annual carbon emissions of the elevator systems.

In Figure 8, for the cases of the HA, HO, and LO buildings, the black markers indicating annual carbon emissions are further from the bar chart, indicating the annual energy consumption compared to that in the LA building. This can be justified by Equation (7), where elevator energy consumption is the only changing variable, and the emission factor is a fixed variable. Therefore, the only factor to be taken into account was the elevator energy consumption. The small value of elevator energy consumption in the LA building led to the small difference of the value between annual energy consumption and annual carbon emissions, and vice versa, for the HA, HO, and LO buildings. Therefore, the two graphs are more closely plotted for the LA building compared to the HA, HO, and LO buildings.

### *3.3. Limitations of the Studied Elevator Systems in the Buildings and Recommendations*

Based on the present case study, lower efficiency was observed in the cases of high-rise residential apartments and the low-rise commercial office. An analysis of observation was performed by inspecting the elevator system and the building structure and operation. For the high-rise residential apartment, the elevator system did not have a zoned system. All three of the elevator cars travelled for the full shaft distance (covered all thirty-two service floors), making it less energy-efficient and operation-efficient. For the low-rise commercial office, resting terminals were on the ground floor, but its offices were mainly located from the second floor to the sixth floor, and its main entrance and car park were on the second floor. This caused the elevator to travel more from the ground floor resting terminal to the second floor to conduct passengers from the second floor to their destination floor and back to the ground floor resting terminal again. This issue greatly reduced the energy and operation efficiency of the elevator system. The second floor (where the main entrance and car park were located) should be set as the elevator resting terminal in order to avoid the unnecessary travel of the empty elevator car from the terminal to the main entrance and car park floor. Another alternative is the main entrance and car park should be built on the ground floor, which is the resting terminal of the elevator car.

## 4. Conclusions

The annual energy consumption, energy efficiency, and carbon emissions of the elevator systems in the selected low-rise and high-rise buildings in the Malaysian tropical climate were successfully evaluated. From the results, it was concluded that:

- The annual energy consumption of an elevator system had a positive correlation with the average daily energy consumption of the elevator system calculated on a weekly basis, since elevator traffic was relatively consistent weekly throughout the year. Low-rise buildings had a higher ratio of annual number of trips to annual energy consumption. The annual elevator energy consumption of the high-rise residential apartment building showed a slightly higher value than that of the high-rise commercial office buildings with an elevator zoning system;
- A higher number of cars distributing the demand for trips travelled decreased the energy consumption of each car. With the same number of cars in the elevator system, the low-rise commercial office building had a higher annual elevator energy consumption than the low-rise residential apartment building due to the higher incoming and outgoing tenants and passengers, as well as building structure limitations;
- Low-rise buildings showed relatively good energy efficiency compared to high-rise buildings;
- The usage, energy consumption, and carbon emissions had a positive correlation to each other.

The main challenge in this study was the assessment of elevator traffic for the elevator systems in the buildings during peak hours. This caused the risk of under- or over-counting the number of trips. As a result, future studies should look into a more advanced technology to enable a tracking system to replace manual counting, as well as auto-estimates of energy consumption, energy efficiency, and carbon emissions of the elevator systems. Consequently, the building management can have a better management plan to achieve the maximum energy efficiency and minimum emissions. Last but not least, this study contributed to the reference data of elevator energy consumption and carbon emissions to promote more similar, yet improved, versions of studies on different buildings in the future to facilitate energy efficiency and GHG mitigation efforts.

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## Appendix A

**Table A1.** Characteristics of a studied building (high-rise residential apartment).

| | |
|---|---|
| Use | Residential |
| Type | High-rise |
| Height (m) | Approximately 90 |
| Shaft height (m) | 80 |
| Floor-to-floor height (m) | 2.50 |
| Number of blocks | 4 |
| Number of floors | 32 |
| Estimated number of units | 247 per block, 8 per floor |
| Estimated built-up area ($m^2$) | Approximately 65 per unit, and 608.69 per block |
| Estimated total number of occupants (person) | 1976 |
| Number of elevator cars | 3 per block |

**Table A2.** Characteristics of a studied elevator car (high-rise residential apartment).

| | |
|---|---|
| Type; brand | Gearless traction; Northern |
| Car dimension (m) | $1.6 \times 2.4 \times 1.68$ |
| Rated load (kg); capacity | 1150; 17 passengers |
| Rated speed (m/s) | 1.50 |
| Rated power (running power) * (kW) | 13 |
| Full travel distance (m) | 80 |
| Counterbalancing * (%) | 50 |
| Door operation time (open, remained open, close) (s) | 12 |
| Acceleration * ($m/s^2$) | 1.00 (gearless traction type) |
| Jerk * ($m/s^3$) | 1.20 |

* Assumptions based on the typical values of parameters for each type of standard passenger elevator.

## Appendix B

**Table A3.** Characteristics of a studied building (low-rise residential apartment).

| | |
|---|---|
| Use | Residential |
| Type | Low-rise |
| Building height (m) | 16.50 |
| Shaft height (m) | 15 |
| Floor-to-floor height (m) | 2.50 |
| Number of blocks | 1 |
| Number of floors | 6 |
| Estimated number of units | 627 |
| Estimated built-up area ($m^2$) | 1615.1 |
| Estimated total number of occupants (person) | 627 |
| Number of elevator cars | 2 |

**Table A4.** Characteristics of a studied elevator car (low-rise residential apartment).

| | |
|---|---|
| Type; brand | Geared traction; Otis |
| Car dimension (m) | 1.37 × 2.10 × 1.40 |
| Rated load (kg); capacity | 750; 11 |
| Rated speed (m/s) | 0.65 |
| Rated power (running power) * (kW) | 4.90 |
| Full travel distance (m) | 15 |
| Counterbalancing * (%) | 50 |
| Door operation time (open, remained open, close) (s) | 9.13 |
| Acceleration * ($m/s^2$) | 0.80 (geared traction type) |
| Jerk * ($m/s^3$) | 1.20 |

* Similar assumptions to Appendix A.

## Appendix C

**Table A5.** Characteristics of a studied building (high-rise commercial office).

| | |
|---|---|
| Use | Commercial |
| Type | High-rise |
| Height (m) | 108 |
| Shaft height (m) | 66 out of 105 (accounting for only 19 occupied floors out of 28) |
| Floor-to-floor height (m) | 3.50 |
| Number of blocks | 1 |
| Number of floors | 19 out of 30 (accounting for only 19 occupied floors out of 28) |
| Estimated number of units | 94 out of 138 (accounting for only 19 occupied floors out of 28) |
| Estimated built-up area ($m^2$) | Office lot: from 65 to 278.71<br>Total building: 624,281 |
| Estimated total number of occupants (person) | 2070 |
| Number of elevator cars | 4 (for floor 5 to 28), 2 (for floor 1 to 4), 2 (for floor 24 to 28) |

**Table A6.** Characteristics of a studied elevator car (high-rise commercial office).

| | |
|---|---|
| Type; brand | Gearless traction; Northern |
| Car dimension (m) | 1.78 × 2.20 × 1.60 |
| Rated load (kg); capacity | 900; 13 passengers |
| Rated speed (m/s) | 1.60 |
| Rated power (running power) * (kW) | 13 |
| Full travel distance (m) | 66 |
| Counterbalancing * (%) | 50 |
| Door operation time (open, remained open, close) (s) | 4.17 |
| Acceleration * ($m/s^2$) | 1.00 (gearless traction type) |
| Jerk * ($m/s^3$) | 1.2 |

* Similar assumptions to Appendix A.

## Appendix D

**Table A7.** Characteristics of a studied building (low-rise commercial office).

| | |
|---|---|
| Use | Office |
| Type | Low-rise |
| Building height (m) | 21 |
| Shaft height (m) | 19.70 |
| Floor-to-floor height (m) | 2.74 |
| Number of blocks | 1 |
| Number of floors | 6 |
| Estimated number of units | 229 |
| Estimated built-up area ($m^2$) | 1148 |
| Estimated total number of occupants (person) | 458 |
| Number of elevator cars | 2 |

**Table A8.** Characteristics of a studied elevator car (low-rise commercial office).

| | |
|---|---|
| Type; brand | Geared traction; Schindler |
| Car dimension (m) | 1.55 × 2.24 × 1.55 |
| Rated load (kg); capacity | 1000; 15 |
| Rated speed (m/s) | 0.70 |
| Rated power (running power) * (kW) | 8.50 |
| Full travel distance (m) | 19.70 |
| Counterbalancing * (%) | 50 |
| Door operation time (open, remained open, close) (s) | 7.39 |
| Acceleration * ($m/s^2$) | 0.80 (geared traction type) |
| Jerk * ($m/s^3$) | 1.20 |

* Similar assumptions to Appendix A.

## References


1. Enerdata. World Energy Consumption Statistics. Available online: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html (accessed on 14 January 2020).
2. International Energy Agency. *World Energy Outlook 2017*; International Energy Agency: Paris, France, 2017; pp. 1–19.
3. U.S. Energy Information Administration (EIA). Emerging Asian Economies Drive the Increase in World Energy Use from 2015 to 2040. Available online: https://www.eia.gov/pressroom/releases/press448.php (accessed on 6 February 2022).
4. U.S. Energy Information Administration. Building Sector Energy Consumption. In *International Energy Outlook 2016*; U.S. Energy Information Administration (EIA): Washington, DC, USA, 2016; pp. 101–112.
5. Hassan, J.S.; Zin, R.M.; Majid, M.Z.A.; Balubaid, S.; Hainin, M.R. Building Energy Consumption in Malaysia: An Overview. *J. Teknol.* **2014**, *70*, 33–38. [CrossRef]
6. Ali, S.B.M.; Hasanuzzaman, M.; Rahim, N.A.; Mamun, M.A.A.; Obaidellah, U.H. Analysis of energy consumption and potential energy savings of an institutional building in Malaysia. *Alexandria Eng. J.* **2021**, *60*, 805–820. [CrossRef]
7. Chel, A.; Kaushik, G. Renewable energy technologies for sustainable development of energy efficient building. *Alexandria Eng. J.* **2018**, *57*, 655–669. [CrossRef]

8. Azari, R. *Life Cycle Energy Consumption of Buildings; Embodied + Operational*; Elsevier Inc.: Amsterdam, The Netherlands, 2019; ISBN 9780128117491.
9. Pérez-Lombard, L.; Ortiz, J.; Pout, C. A review on buildings energy consumption information. *Energy Build.* **2008**, *40*, 394–398. [CrossRef]
10. Department of Energy United States of America. Chapter 5—Increasing Efficiency of Building Systems and Technologies. In *Quadrennial Technology Review an Assessment of Energy Technologies and Research*; Department of Energy United States of America: Washington, DC, USA, 2015.
11. U.S. Energy Information Administration (EIA). *Monthly Energy Review January 2022*; U.S. Energy Information Administration: Washington, DC, USA, 2022; Volume 0035.
12. Aldhshan, S.R.S.; Abdul Maulud, K.N.; Wan Mohd Jaafar, W.S.; Karim, O.A.; Pradhan, B. Energy consumption and spatial assessment of renewable energy penetration and building energy efficiency in malaysia: A review. *Sustainability* **2021**, *13*, 9244. [CrossRef]
13. European Comission. Energy Use in Buildings. Available online: https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-use-buildings_en (accessed on 6 February 2022).
14. U.S. Energy Information Administration (EIA). Electricity Intensity of U.S. Homes and Commercial Buildings Decreases in Coming Decades. Available online: https://www.eia.gov/todayinenergy/detail.php?id=38332 (accessed on 17 April 2019).
15. Chen, S.; Zhang, G.; Xia, X.; Chen, Y.; Setunge, S.; Shi, L. The impacts of occupant behavior on building energy consumption: A review. *Sustain. Energy Technol. Assessments* **2021**, *45*, 101212. [CrossRef]
16. Godoy-Shimizu, D.; Steadman, P.; Hamilton, I.; Donn, M.; Evans, S.; Moreno, G.; Shayesteh, H. Energy use and height in office buildings. *Build. Res. Inf.* **2018**, *46*, 845–863. [CrossRef]
17. Ang, J.H.; Yusup, Y.; Zaki, A.; Salim, S.; Ahmad, M.I. A CFD Study of Flow Around an Elevator Towards Potential Kinetic Energy Harvesting. *J. Adv. Res. Fluid Mech. Therm. Sci. J.* **2019**, *59*, 54–65.
18. Al-kodmany, K. Tall Buildings and Elevators: A Review of Recent Technological Advances. *Buildings* **2015**, *5*, 1070–1104. [CrossRef]
19. Eninter Ascensores. What Determines the Number of Lifts a Building Needs? Available online: http://www.astarlifts.com/en/blog-lifts/lifts-lifts/what-determines-the-number-of-elevators-you-need-a-building (accessed on 17 April 2019).
20. Barney, G.; Al-Sharif, L. *Elevator Traffic Handbook: Theory and Practice*, 2nd ed.; Taylor & Francis: Abingdon-on-Thames, UK, 2016; ISBN 9781138852327.
21. Al-Sharif, L.; Seeley, C. The effect of the building population and the number of floors on the vertical transportation design of low and medium rise buildings. *Build. Serv. Eng. Res. Technol.* **2010**, *31*, 207–220. [CrossRef]
22. Hui, S.C.M.; Yeung, C. Analysis of standby power consumption for lifts and escalators. In Proceedings of the 7th Greater Pearl River Delta Conference on Building Operation and Maintenance—SMART Facilities Operation and Maintenance, Hong Kong, 6 December 2016; pp. 35–47.
23. Zubair, M.U.; Zhang, X. Explicit data-driven prediction model of annual energy consumed by elevators in residential buildings. *J. Build. Eng.* **2020**, *31*, 101278. [CrossRef]
24. Barney, G.C.; Loher, A.G. *Elevator Electric Drives: Concepts and Principles, Controls and Practice*; International Association of Elevator Engineers by Ellis Horwood: New York, NY, USA, 1990; ISBN 0132614626.
25. Kirchenmayer, G. *Energy Consumption of Elevators*; Elevator World, Inc.: Mobile, AL, USA, 1981; p. 48.
26. White, L.E. *Energy Consumption: Hydraulic Elevators and Traction Elevators*; Elevator World, Inc.: Mobile, AL, USA, 1984.
27. Barney, G. Energy Models for Lifts. In Proceedings of the 1st Symposium on Lift and Escalator Technologies, Northampton, UK, 29 September 2011; Volume 1, pp. 25–34.
28. Schroeder, J. Energy consumption and power requirements of elevators. In *Second Century of the Skyscraper*; Springer: Boston, MA, USA, 1988; Volume 34, pp. 621–627. [CrossRef]
29. Daniel, C.; Forth, J.; Arthur, W.; Eric, H.; Douglas, R.; Martin, H. Methods and Apparatus for Retrieving Energy Readings from an Energy Monitoring Device. U.S. Patent 7089089B2, 8 August 2006.
30. Chan, C.Y.B. *Elevator Drive Systems Energy Consumption Study Report—UBC Social Ecological Economic Development Studies (SEEDS)*; University of British Columbia: Vancouver, BC, Canada, 2012; p. 125.
31. Bannister, P.; Bloomfield, C.; Chen, H. Empirical prediction of office building lift energy consumption. In Proceedings of the Proceedings of the Building Simulation 2011, 12th Conference of International Building Performance Simulation Association, Sydney, Australia, 14–16 November 2011; pp. 2635–2642.
32. Tukia, T.; Uimonen, S.; Siikonen, M.L.; Hakala, H.; Donghi, C.; Lehtonen, M. Explicit method to predict annual elevator energy consumption in recurring passenger traffic conditions. *J. Build. Eng.* **2016**, *8*, 179–188. [CrossRef]
33. Al-Sharif, L. Lift Energy Consumption: General Overview (1974–2001). *Elev. World* **2004**, *52*, 61–67.
34. Al-Sharif, L.; Peters, R.; Smith, R. *Elevator Energy Simulation Model*; Elevator World, Inc.: Mobile, AL, USA, 2016.
35. Tukia, T.; Uimonen, S.; Siikonen, M.L.; Donghi, C.; Lehtonen, M. Modeling the aggregated power consumption of elevators—the New York city case study. *Appl. Energy* **2019**, *251*, 113356. [CrossRef]
36. Barney, G.; Lorente, A. Simplified Energy Calculations for Lifts Based on ISO/DIS 25745-2. In Proceedings of the Symposium on Lift and Escalator Technologies, Northampton, UK; The CIBSE Lifts Group: London, UK, 2013; Volume 3, pp. 10–19.

37. Association of German Engineers. *VDI 4707 Guideline—Lifts Energy Efficiency*; Association of German Engineers: Düsseldorf, Germany, 2007.
38. *ISO 25745-2:2015 (en)*; Energy Performance of Lifts, Escalators and Moving Walks—Part 2: Energy Calculation and Classification for Lifts (elevators). ISO: Geneva, Switzerland, 2015.
39. Hu, D.M.; Xu, B.; Yang, H.Y. VVVF controlled closed-circuit energy-saving hydraulic lift system. *J. Zhejiang Univ. Sci.* **2008**, *42*, 209.
40. Lehtonen, M.; Tukia, T. Determining and Modeling the Energy Consumption of Elevators. Master's Thesis, Aalto University, Espoo, Finland, 2014.
41. Jing, R.; Wang, M.; Zhang, R.; Li, N.; Zhao, Y. A study on energy performance of 30 commercial office buildings in Hong Kong. *Energy Build.* **2017**, *144*, 117–128. [CrossRef]
42. Mardiana, A.; Riffat, S.B. Building Energy Consumption and Carbon dioxide Emissions: Threat to Climate Change. *J. Earth Sci. Clim. Change* **2015**, *S3*, 1. [CrossRef]
43. Mirrahimi, S.; Mohamed, F.M.; Haw, L.C.; Lukman, N.I.; Fatimah, W.Y.M.; Aflaki, A.; Yusoff, W.F.M.; Aflaki, A.; Mohamed, M.F.; Haw, L.C.; et al. The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1508–1519. [CrossRef]
44. Tahir, M.Z.; Jamaludin, R.; Nasrun, M.; Nawi, M.; Baluch, N. Building energy index (BEI): A study of government office building in Malaysian public university. *J. Eng. Sci. Technol.* **2017**, *12*, 192–201.
45. Akashah, F.W.; Ali, A.S. *Analysis of Energy Trend of Office Building in Malaysia—Case Study in Universiti Pendidikan Sultan Idris (UPSI)*; University of Malaya: Kuala Lumpur, Malaysia, 2017.
46. Sadrzadehrafiei, S.; Mat, K.S.S.; Lim, C. Energy consumption and energy saving in Malaysian office buildings. *Models Methods Appl. Sci.* **2009**, *75*, 152–156.
47. Tee, B.T.; Yahaya, A.Z.; Breesam, Y.F.; Dan, R.M.; Zakaria, M.Z. Energy analysis for lighting and air-conditioning system of an academic building. *J. Teknol.* **2015**, *76*, 5536.
48. Saidur, R. Energy consumption, energy savings, and emission analysis in Malaysian office buildings. *Energy Policy* **2009**, *37*, 4104–4113. [CrossRef]
49. Sadrzadehrafiei, S.; Sopian, K.; Mat, S.; Lim, C.; Hashim, H.S.; Zaharim, A. Enhancing energy efficiency of office buildings in a tropical climate, Malaysia. *Int. J. Energy Environ.* **2012**, *6*, 209–310.
50. Taufiq, B.N.; Masjuki, H.H.; Mahlia, T.M.I.; Amalina, M.A.; Faizul, M.S.; Saidur, R. Exergy analysis of evaporative cooling for reducing energy use in a Malaysian building. *Desalination* **2007**, *209*, 238–243. [CrossRef]
51. Ossen, D.R.; Ahmad, M.H.; Madros, N.H. Impact of solar shading geometry on building energy use in hot humid climates with special reference to Malaysia. In Proceedings of the NSEB2005—SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM, Subang Jaya, Malaysia, 10–11 May 2005; pp. 10–11.
52. Noranai, Z.; Kammalluden, M.N.; Tun, U.; Onn, H. Study of building energy index in Universiti Tun Hussein Onn Malaysia. *Acad. J. Sci.* **2012**, *1*, 429–433.
53. Saidur, R.; Hasanuzzaman, M.; Yogeswaran, S.; Mohammed, H.A.; Hossain, M.S. An end-use energy analysis in a Malaysian public hospital. *Energy* **2010**, *35*, 4780–4785. [CrossRef]
54. Tang, F.E. An Energy Consumption Study for a Malaysian University. *Int. J. Environ. Chem. Ecol. Geol. Geophys. Eng.* **2012**, *6*, 99–105.
55. Saidur, R.; Masjuki, H.H. Energy and associated emission analysis in office buildings. *Int. J. Mech. Mater. Eng.* **2008**, *3*, 90–96.
56. Bureau of Energy Efficiency. *Energy Conservation Building Code (ECBC)—Building Envelope for Hot & Dry Climate 2017*; Bureau of Energy Efficiency: New Delhi, India, 2017; p. 26.
57. Allied Market Research. *Traction Elevator Market by Order Type (Geared Traction Elevators and Gearless Traction Elevators) and Application (Residential and Commercial): Global Opportunity Analysis and Industry Forecast 2021–2030*; Allied Market Research: Portland, OR, USA, 2021.
58. Elevator Wiki. Traction Elevators. *Elevatorpedia* 2019; pp. 1–5. Available online: https://elevation.fandom.com/wiki/Traction_elevators (accessed on 6 February 2022).
59. Menezes, A.C.; Cripps, A.; Buswell, R.A.; Wright, J.; Bouchlaghem, D. Estimating the energy consumption and power demand of small power equipment in office buildings. *Energy Build.* **2014**, *75*, 199–209. [CrossRef]
60. ISO. Energy Performance of Lifts, Escalators and Moving Walks—Part 3: Energy Calculation and Classification of Escalators and Moving Walks. Available online: https://www.iso.org/obp/ui/#iso:std:iso:25745:-3:ed-1:v1:en (accessed on 10 December 2017).
61. Barney, G. Energy efficiency of lifts—Measurement, conformance, modelling, prediction and simulation. 2007. Available online: www.cibseliftsgroup.org/CIBSE/papers/Barney-on-energy%20efficiency%20of%20lifts.pdf (accessed on 6 February 2022).
62. U.S. Environmental Protection Agency. *Indirect Emissions from Purchased Electricity*; Environmental Protection Agency: Washington, DC, USA, 2016.
63. Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2006.
64. Malaysian Green Technology Corporation. *2017 Electricity Baseline for Malaysia*; Malaysian Green Technology Corporation: Selangor, Malaysia, 2017.
65. U.S. Environmental Protection Agency. Overview of Greenhouse Gases. Available online: https://www.epa.gov/ghgemissions/overview-greenhouse-gases (accessed on 6 January 2022).

66. Intergovernmental Panel on Climate Change. Precursors and Indirect Emissions. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2006.
67. Sustainable Energy Development Authority Malaysia (SEDA). Average Carbon Dioxide Emission Factor of Malaysia. Available online: http://www.seda.gov.my/statistics-monitoring/co2-avoidance/ (accessed on 6 January 2022).
68. Intergovernmental Panel on Climate Change. *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*; IPCC: Geneva, Switzerland, 2019.
69. Intergovernmental Panel on Climate Change. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 1996.
70. Patrão, C.; De Almeida, A.; Fong, J.; Ferreira, F. Elevators and Escalators Energy Performance Analysis. In Proceedings of the 2010 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 15–20 August 2010; pp. 53–63.
71. Siikonen, M.; Sorsa, J.; Hakala, H. Impact of Traffic on Annual Elevator Energy Consumption. In Proceedings of the ELEVCON 2010, Lucerne, Switzerland, 2–4 June 2010; Volume 18, pp. 344–352.
72. Hakala, H.; Siikonen, M.-L.; Tyni, T.; Ylinen, J. Energy-efficient elevators for tall buildings. In Proceedings of the Council on Tall Buildings and Urban Habitat, 6th World Congress, Melbourne, Australia, 26 February–1 March 2001; pp. 1–13.
73. Marsong, S. Analysis of Energy Consumption and Behavior of Elevator in a Residential Building. In Proceedings of the 5th International Electrical Engineering Congress, Pattaya, Thailand, 8–10 March 2017.
74. KONE Corporation. *KONE JumpLift*; KONE Corporation: Espoo, Finland, 2017.
75. CTBUH. The Met—The Skyscraper Center. Available online: http://skyscrapercenter.info/building/the-met/1134 (accessed on 7 February 2022).
76. Elevator Wiki Fandom. Kone JumpLift. Available online: https://elevation.fandom.com/wiki/Kone_JumpLift (accessed on 7 February 2022).
77. EMPORIS. Ashok Towers D, Mumbai 261721. Available online: https://www.emporis.com/buildings/261721/ashok-towers-d-mumbai-india (accessed on 19 September 2018).
78. KONE. *KONE MiniSpace*; KONE: Chertsey, UK, 2018.
79. Nipkow, J.; Schalcher, M. Energy consumption and efficiency potentials of lifts. *Hospitals* **2006**, *2*, 3.
80. VDI. *VDI4707 Technical Equipment for Buildings Manual*; VDI: Düsseldorf, Germany, 2008; Volume 5.
81. Zarikas, V.; Papanikolaou, N.; Loupis, M.; Spyropoulos, N. Intelligent Decisions Modeling for Energy Saving in Lifts: An Application for Kleemann Hellas Elevators. *Energy Power Eng.* **2013**, *5*, 31126. [CrossRef]
82. Vollrath, D. *Elevator Drives Energy Consumption & Savings*; Magnetek: New York, NY, USA, 2011; p. 16.
83. KONE Corporation. *KONE C-Series*; KONE Corporation: Espoo, Finland, 2008.
84. Nguyen, H.; Gaudet, E.W. Comparative Evaluation of Line Regenerative and Non-Regenerative Vector Controlled Drives for AC Gearless Elevators. In Proceedings of the Conference Record of the 2000 IEEE Industry Applications Conference, Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No. 00CH37129), Rome, Italy, 8–12 October 2000; pp. 1431–1437.
85. Hackel, S.; Kramer, J.; Li, J.; Lord, M.; Marsicek, G.; Petersen, A.; Schuetter, S.; Sippel, J. *Proven Energy-Saving Technologies for Commercial Properties*; National Renewable Energy Laboratory: Golden, CO, USA, 2015; pp. 36–47.
86. US EPA. Sources of Greenhouse Gas Emissions. Available online: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed on 22 April 2019).
87. Herbert, R.B.; Malmström, M.; Ebenå, G.; Salmon, U.; Ferrow, E.; Fuchs, M. Quantification of abiotic reaction rates in mine tailings: Evaluation of treatment methods for eliminating iron- and sulfur-oxidizing bacteria. *Environ. Sci. Technol.* **2005**, *39*, 770–777. [CrossRef] [PubMed]