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Benchmarking Energy Use Intensity of 33 Office Buildings in Indonesia

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Abstract: The building sector, which is responsible for 40% of global energy usage and 36% of total greenhouse gas emissions, must contribute to net zero emissions by implementing energy-saving techniques and renewable energy sources, thereby reducing climate change. This study identifies buildings in Java and Sumatra, with focus on capital cities, as part of the Green Building Roadmap, aiming to conserve energy and water and reduce CO_2 emissions. The application of statistical analysis methodologies revealed that the mean Energy Use Intensity (EUI) was determined to be 160 kWh/m²/year. In this context, effective benchmarks that were set below 115 kWh/m²/year were indicative of high performance, while benchmarks that exceeded 190 kWh/m²/year were suggestive of significant inefficiency. The main energy users in office buildings were HVAC systems (64.7%), office equipment (15%), lighting systems (8.8%), lifts and escalators (7.0%), and other electrical equipment (about 4.5%). Implementing zero-energy buildings in Indonesia is attractive due to the low average EUI and the potential of photovoltaic energy in tropical countries. The research aims to provide practical reference data for evaluating building energy performance and potentially reducing greenhouse gas emissions.

Keywords: Building Energy Benchmarking; Energy Use Intensity; Greenhouse gas; Indonesia; Office Building

1. Introduction

The building sector must contribute to climate change mitigation, considering that it accounts for 40% of global energy usage and 36% of total greenhouse gas emissions[1]. In 2022, Indonesia's electricity demand reached 299.2 TWh, with the commercial sector accounting for 23.02%[2,3]. Net zero-energy buildings are those that utilize zero energy in a typical year, thereby reducing heat and electrical power demand while meeting their annual energy needs with renewable energy sources[4]. This strategy for decarbonization aims to reduce energy consumption while increasing the use of renewable energy sources. Achieving this objective requires a multifaceted approach, involving the implementation of energy-saving measures and the expansion of renewable energy utilization.

Improving buildings to be more efficient in energy use becomes essential since it can save energy, reduce cost, and potentially reduce GHG emissions. The primary objective of enhancing energy efficiency within a building is to reduce energy consumption for heating, cooling, and lighting systems while maintaining occupant health and comfort. A building with high-performance efficiency considers costs of energy, natural resources, reduction of waste, and higher air quality in the indoor area of the environment[5–8].

Promoting energy efficiency can significantly reduce energy consumption. Stakeholder involvement, unique factors, motivation, policies, and measures like changing people's minds, technology revolution, and environmental regulation are essential for achieving the desired energy savings[9,10].

Indonesia has an objective for achieving net-zero emissions by 2060. The government of Indonesia has building codes and green building performance rules that complement Minimum Energy Performance Standards (MEPS) and require energy labeling for products. Since

2023, buildings with an energy consumption of at least 500 TOE (ton oil equivalent) or 5.8 GWh per year have had to implement an energy management system.

Energy benchmarking is one tool that may be used to increase energy efficiency. The benchmark provides a baseline for energy savings, efficiency, and transparency, facilitating investigations into poor energy performance[11,12]. Benchmarking a building's performance involves comparing present and past energy usage.

Energy performance refers to quantitative outcomes or values associated with energy efficiency, usage, and consumption. An Energy Performance Indicator (EPI) is a quantitative value or indicator of energy performance that the company defines[13]. The aspects that must be taken into account include the climate, building envelope, occupant behaviour and activities, energy and service systems, building operation and maintenance, and the indoor air quality provided[14].

Identifying the level of performance for building energy usage is important to establish a baseline and create a benchmark for energy consumption. It can also be used to assess energy savings and improve energy efficiency.

According to Wang et al. (2012), the utilization of quantitative energy performance assessment tools is of immense benefit, as they facilitate objective comparisons of existing buildings through the application of standard metrics, such as energy use intensity (EUI). These tools have been demonstrated to be compatible with policy frameworks, aid in energy labeling, and provide diagnostic information to facilitate decision-making regarding the sequence of retrofits. The implementation of these measures can be expanded to other institutions as well. However, the efficacy of these systems is contingent upon the availability of accurate data, which may be limited in older or less-monitored buildings. Moreover, the accuracy and usefulness of these models may be hindered by methodological discrepancies, a lack of flexibility for complex or mixed-use structures, and a dependence on static historical data rather than dynamic, real-time situations[14]

Some tools can be used to evaluate an office building's performance. One of them is DesignBuilder software, which can be used for simulation with linear regression analysis, and it was used in Brazil to analyze based on the climate datasets[15]. Another study with this software has been conducted with additional parameters[16,17]. Most studies currently focus on identifying key variables that may have a significant impact on building energy performance, aiming to set benchmarks for office buildings. The energy efficiency benchmarking system for commercial office buildings was also conducted in Kampala with multiple linear regression analysis. The developed model defines the relationship between Energy Use Intensity (EUI), energy efficiency indicator, and significant factors for internal floor area; installed lighting system; Heating, Ventilation, and Air Conditioning (HVAC) system; building occupancy; and computers used within the building area[6,18]. Another study with a similar method to assess energy performance and develop a method of energy performance benchmarking has been conducted based on national data by Kim & Kim[19]. The EUI is expressed as energy per square foot per year. The calculation of the annual energy consumption of a building is determined by dividing the total energy input, measured in kilobtu (kBtu) or gigajoules (GJ), by the building's total gross floor area, which is typically expressed in square feet or square meters[20].

Energy benchmarking is the method of determining the energy performance of buildings, and it is typically included in building classification with energy analysis. Enhancing a building's energy efficiency requires energy benchmarking. It may be used to determine if this building uses energy more efficiently than similar buildings. The prior study gathered and analyzed important information on several benchmarking methodologies, weighing their respective merits against their limits.

In general, the efforts to develop energy benchmarking systems are broad and may be classified according to the reliability and quality of the provided data. The current benchmarking approaches are classified into three groups based on their modeling mechanisms: physical simulation, statistical analysis, and hybrid[21]. Benchmarking methods can be categorized into four categories: statistical methodologies, points-based grading systems, simulation methods, hierarchical, and end-use metrics. In Statistical Analysis benchmarking, statistics for a population of similar buildings are used to generate a benchmark against which a building EUI is compared. This method requires large data sets to produce a reasonably sized sample of comparison buildings. Points-Based Rating Systems, including the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Rating System, do not allow comparisons against other buildings; rather, they provide standards and guidelines to measure how efficient and environmentally friendly a facility is and compare it to best-practice standards. A LEED score is made up of credits assigned for satisfying different criteria, including energy efficiency and other environmental factors. Hierarchical and End-Use Metrics refers to the generation of benchmarks that link energy use to climate and functional requirements. This method is useful for accounting for more of the differences in features affecting energy use; however, the type of data required is not readily available. Simulation model-based benchmarking calculates benchmarks based on an idealized model of building performance, such as DOE-2. Models have many uses in benchmarking, and they have the advantage that they can be tweaked to account for a wide range of factors that contribute to variation in energy use. They can also be used to generate targets and compare design alternatives. A

disadvantage to many users is that they are in fact, simulation models, and benchmarks based on models may not be well calibrated to the actual buildings stock data[22].
The statistical approach is a well-established area that offers a competitive alternative for estimating building energy that has received renewed research attention but has not been reviewed. This study attempts to close this knowledge gap[23].
The common method uses statistics, including regression analysis, the average index method of total energy consumption (mean of EUI), the root mean square, the median, and the percentile. One of the methods used is regression analysis. This method is widely used to develop energy standards, explaining the relationship between different independent variables and energy use. A simple linear regression model is used to predict Energy Use Intensity (EUI), which also explains the relationship between building operational characteristics and primary energy consumption. Multiple regression methods are used to predict energy consumption, such as lighting and HVAC systems[18,19].
Chung et al., Jing et al. and Tso et al. conducted a study that presented a benchmarking process for energy efficiency using multiple regression analysis. This analysis establishes a correlation between energy use intensity (EUI) and its contributing factors. To achieve this, the EUI is standardized by taking into account all significant explanatory factors that influence energy consumption[24–26].
This paper aims to provide a benchmark for energy efficiency in commercial buildings, especially office buildings. A study has been conducted using data on energy consumption intensity from commercial buildings in six major cities in Indonesia. Those cities are Jabodetabek (Jakarta, Bogor, Depok, Tangerang, Bekasi), Pekanbaru, Medan, Bandung, Semarang, and Surabaya. The data collection and analyses will be discussed in this paper, as well as the methodology used for benchmarking compared with previous studies from several countries in Southeast Asia such as Singapore, Malaysia and Thailand. Those data were also presented and discussed for further implications in comparing the energy usage of office buildings. Several factors that need to be considered to assess the level of energy consumption for a commercial building are the occupancy, the building's age, and the climate.
Some methods to develop a benchmark of energy consumption within a commercial building have been identified for application in Indonesia. For this purpose, data collection on energy consumption and primary characterization of office buildings was obtained and analyzed.

2. Methodology

The methodology flowchart in this paper is shown in Figure1.

2.1. Data Description

Based on Indonesia's population, Java Island is the most populated island, accounting for 55.9%, followed by Sumatra at 21.7%, Sulawesi at 7.4%, Kalimantan at 6.2%, Bali at 5.6%, and Maluku and Papua at 3.2% [27].
In this study, the buildings are selected in Java and Sumatra. Almost all the capital cities of the Province of Java Island were selected for this study because of the dense population in those cities. In addition, as illustrated in Table 1, the selection of this location aligns with the Green Building Roadmap, a comprehensive strategy issued by the Ministry of Public Works and Public Housing. The six survey locations encompass over 50% of commercial buildings, indicating a significant potential for energy savings, water conservation, and reduced CO_2 emissions[28].
The selected cities on Java Island are Jabodetabek region, which encompasses the provinces of DKI Jakarta, West Java, and Banten, Bandung (West Java), Semarang (Central Java), and Surabaya (East Java). On Sumatra Island, there are two selected cities with dense populations. The selected cities on Sumatra Island are Medan (North Sumatra) and Pekanbaru (Riau).
This study analyzes energy consumption and other related

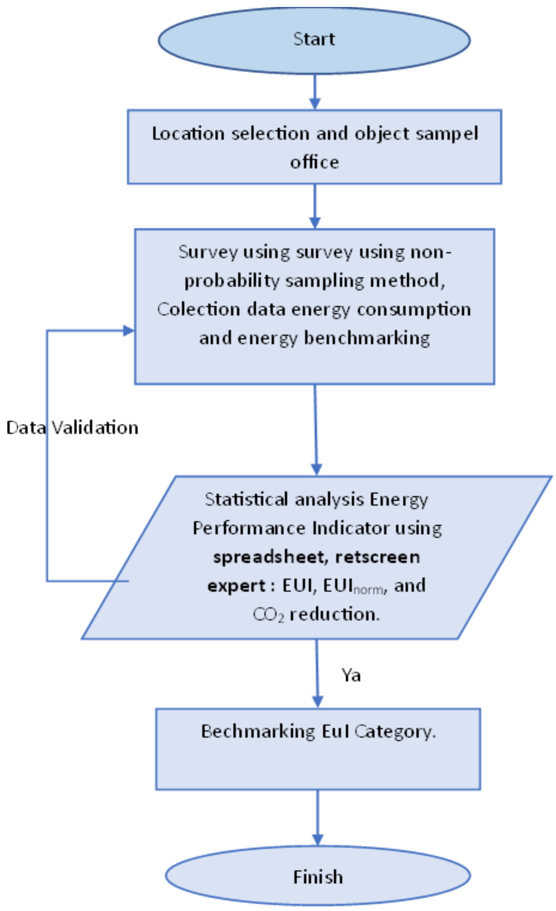

Fig. 1: Flowchart of research methodology

Table 1: Target Area of Commercial Buildings to become Green Buildings [28]

No	Province	Target Building Area (x 1,000 m^2)	Electricity Consumption in 2022 (GWh/year)
1	Banten	22,626	12,539.23
2	West Java	13,732	7,610.34
3	East Java	9,842	5,454.49
4	Central Java	6,838	3,789.54
5	Jakarta	6,149	3,407.59
6	Bali	4,387	2,431.11
7	North Sumetra	3,263	1,808.45
8	Riau	2,231	1,236.21
9	South Sulawesi	2,207	1,222.87
The other provinces were below 2,000,000 m^2			

data for office buildings in six major cities in Indonesia. Those cities are Jakarta, Pekanbaru, Medan, Bandung, Semarang, and Surabaya. The survey was conducted based on non-probability sampling using quota sampling. Sample data was collected by visiting selected locations and conducting measurements, filling out questionnaires and interviews. The total sample of objects was 50 buildings and the sample objects that met the criteria were 33 buildings.

The data are collected directly from facility operators and consist of the following indicators:

Data on energy consumption in the office building, both total and each sub-sector, namely

Petroleum products, such as LPG and kerosene;

Gas;

Electricity.

All Energy data is reported as the unit of electricity use equivalents (kWh), and Eq. (1) can be used to calculate the overall energy consumption.

$$E_{total} = \sum_i \sum_j E_{ij} \cdot \propto_{ij} \qquad (1)$$

Where E_{total} is total energy consumption in kWh, i for a specific energy type, j for each energy type, and $\alpha_{i,j}$ for the conversion factor for j-type energy of i-type energy. To illustrate, the consumption data for natural gas, in cubic meters, is converted into energy through a multiplication of the natural gas's heating value. All energy unit is converted to kWh[29].

Data and specifications for the highest energy-consuming equipment in the office building,

The number of building occupants or number of employees.

Building information data (building area, number of floors and operating hours).

Additional actions were taken to ensure the accuracy and validity of the data, including conducting statistical analysis by averaging a quality-controlled sample of data. The questionnaire data were validated by checking the installed capacity against energy consumption and confirmed with the facility owner. The valid data will then be tabulated and analyzed using a spreadsheet. This study utilizes Excel software for statistical analysis and the RETScreen Expert software portfolio for the prediction of energy consumption reduction (EUI) with regard to emission reduction.

2.2. Energy Performance Indicator

Energy use in office buildings is generally dominated by electricity, and fuel oil for diesel engines as a power backup. The diesel engine uses high-speed diesel oil as a fuel for generating electricity as backup power in case the electricity supplied by PLN (electricity company) blackouts. To measure the building's overall energy usage, the EUI (Energy Usage Intensity) index, or normalized EUI index, was used. That is most often used in many buildings[30–32]. The quantity of energy consumed in a building is expressed using the EUI term, which serves as an indication of energy performance. EUI is expressed in units of kWh/m2/month or kWh/m2/year. A figure that represents the annual energy consumption (in kWh) per m2 of air-conditioned building space or for the entire building area GFA. The gross floor area (GFA) of a building is the sum of the areas of all its floors. This word includes all of a building's enclosed areas, such as lobbies, hallways, stairwells, and living spaces (excluding the parking area).

$$EUI = \sum \frac{E_{total}}{GFA} \qquad (2)$$

EUI can be used by building owners to compare the energy consumption performance of existing buildings with other buildings. The energy used in this benchmark is electrical energy, fuel oil, and gas in the unit of kWh. Chung et al. established the EUI index, determined its affecting elements based on multiple regression analysis, and generated a benchmark electricity meter for EUI[24].

2.3. Energy Benchmarking

Using the relevant variable that relates to building characteristics, a regression model is developed for the normalization of EUI following data collection. The benchmarking process determined the upper and lower range of EUIs using statistical analyses such as mean, median, and percentiles [24,30].

Regression analysis is a method used to establish benchmarks for energy performance in office buildings. It involves analyzing data on building attributes like climate, occupancy rate, design, and energy consumption from multiple buildings. The main parameter of energy consumption is identified, and a regression equation is developed to predict the building's energy consumption. For instance, if GFA is a parameter affecting energy consumption, the larger the building's area, the greater the predicted energy consumption. However, if data for this parameter is unavailable, the regression equation cannot be calculated.

2.4. Normalization of EUI for other significant factors

A regression model for energy consumption was built using energy use intensity (EUI) adjusted for significant factors such as building characteristics, and Cooling degree days (CDD). Based on a study conducted by Chung et al (2006), the normalized energy utilization index EUI_{norm} is given by[24)]

$$EUI_{norm} = EUI_0 - b_1 x_1^* - \cdots - b_k x_k^* = EUI_0 - \sum_{i=1}^{k} b_i \left(\frac{x_i - \bar{x}_i}{s_i} \right) \tag{3}$$

where EUI_o is the intercept; $b_1,...,b_k$ are the regression coefficients; $x_1^*,...\ x_k^*$; k are the significant factors.

EUI_{norm} may be considered a normalized energy-efficiency indicator by eliminating the influence of deviation in the other significant factors.

The percentile approach is a statistical method that utilizes the percentile value as a benchmark to analyze a building's energy usage. In this particular case study, the 25th and 75th percentiles were selected [24,30,33)].

2.5. Equivalent carbon dioxide (CO_{2e}) estimation

Equivalent carbon dioxide (CO_{2e}) is a measure of global warming caused by specific greenhouse gases, based on an emission factor (f_{CO_2}) that assumes a linear relationship between activity (such as electricity for lighting and cooling) and emissions[24)].

$$CO_2e = E_{total}\ x\ f_{CO_2} \tag{4}$$

In this study, the CO_{2e} of energy used by each building is calculated by multiplying its annual energy consumption by the emission factor. Emission factors can be found from the greenhouse gas emission report issued by the Ministry of Energy and Mineral Resources[34)].

3. Results and Discussion

3.1. Energy consumption breakdown

For office buildings, the energy is sourced from electricity and diesel fuel. The energy mix for office buildings is dominated by electricity reaching 99.79%, while diesel fuel consumption is only 0.21%. Diesel fuel is only used as a backup if the power grid goes out.

Indonesia's weather can be assumed to be similar to that of other Southeast Asian countries, which are hot and humid. In this tropical climate, an office building typically spends more than half of its energy consumption on electricity, with a significant portion allocated to air conditioning (see Table 2). The four main end-users of energy consumption are air conditioning, lighting, office equipment (computers, printers, photocopiers, fax machines, telephones, etc.), and other miscellaneous equipment. This approach was developed by W. L. Lee et al. [35)].

Based on the data from 33 office buildings as the object of this study, the HVAC systems contribute the most dominant of the total energy use (consuming about 64.7%). It is followed by office equipment that is plugged into a power outlet such as computers, photocopiers, televisions, refrigerators, dispensers, and other electrical equipment in the office building (consuming about 15%). The lighting system stands third with a total energy consumption percentage of about 8.8%. The distribution of the energy used for office buildings in Indonesia was similar to the energy used for office buildings in other Southeast Asia countries such as Singapore and Malaysia (see Table 2). Table 2 shows a comparison of the energy breakdown of office buildings in several countries included in this study. HVAC systems are the most energy-intensive components in office buildings, followed by lighting and other equipment. Effective policy, technology, and housekeeping are essential for reducing energy usage and emissions. The comparison of the EUI value of office buildings in this study compared with other countries is shown in Table 3. The EUI of office buildings in this study showed that Indonesia is considerably lower than other Southeast Asian countries with similar climate conditions. The benchmark for a good EUI is subject to variation depending on factors such as building type, location, and operational needs. According to the findings of the study conducted by Diamond et al., the EUI for an office building

Table 2: Electrical energy consumption breakdown of Indonesia compared to other nations

End Use System [%]	Indonesia*	Singapore[36)]	Malaysia[37)]	Hongkong[26)]	Australia[38)]	UK[39)]	China[40)]
HVAC	64.7	70	58	68	39	51.9	45.6
Office Equipment	15.0	-	19	-	22	33.0	22.7
Lighting	8.8	15	20	14	25	15.1	31.7
Vertical Transportation	7.0	10	-	5	4	-	-
Other	4.5	5	3	13	10	-	-

**This Study*

Table 3: Energy Use Intensity (EUI) benchmark in Indonesia compared to ASEAN countries

	Energy Use Intensity [kWh/m²/yrs]						
	Indonesia		**AEA**[43]	Singapore[44]		Malaysia[45]	Thailand[46]
	This Study	JICA[47]		Small	Large		
Office building	160	180	160	268	267	220	219

was determined to be 63 kWh/m^2 per year [41]. Another study, conducted by Kaczmarczyk, obtained a useful energy demand of 35.7 kWh/m^2 per year[42].

3.2. Energy Use Intensity

According to the data distribution, the capital city of the Jakarta area has provided the most data on office buildings. The Gross Floor Area (GFA) of an office building was also reported in the collected data. The obtained data indicate that the median area of an office building was 11,721 m^2, with the smallest office area at about 1,633 m^2 and the most prominent area at 57,767 m^2 (see Figure 2).

Figure 3 presents the normal distribution of electricity consumption and gross floor area of the considered office building. The first step is to analyze the frequency of building electrical energy consumption per area. Thdistribution of energy consumption shows a lognormal behavior.

From the normal distribution, the average energy consumption of the 33 office buildings studied in Indonesia is 160 kWh/m^2/year, with a standard deviation of 78 kWh/m2/year. The median value of energy consumption is 147 kWh/m^2/year. Mostly, the data have energy consumption between 100–200 kWh/m^2/year. However, some buildings have higher energy consumption values (more than 300 kWh/m^2/year) (presented in Figure 2). This contributes to the higher average value of energy use. This energy consumption was for buildings with hybrid cooling systems and fully air-conditioned buildings. Energy usage for both central air conditioning and mixed-mode towers may be determined using the lognormal distribution[48].

3.3. Variable in Energy Use Intensity

Regression analysis was carried out on energy consumption and office building information variables. It affects the energy used, including GFA, climate, and building age. Simple regression analysis was carried out to analyze the change of the dependent variables caused by the changes in a variable.

3.3.1. Gross Floor Area (GFA)

GFA was selected as a key factor for evaluating the energy performance of the office building. It can be seen from the coefficient of determination (R^2 value) of obtained GFA on total energy consumption, whereas it showed a higher effect than other variables (climate and other building characteristics), as seen in Figure 4.

The size of the building area, as measured with the unit of square has a positive correlation with the EUI value and the building's size. Therefore, for office buildings, it can be concluded that the building area is the main factor in increasing the value of the EUI[49].

3.3.2. Building Characteristics

The building design is a critical aspect that needs to be considered in every construction planning of a building. Old buildings are generally designed without considering the energy aspect. Therefore, many old buildings need an improvement in their energy use which can be conducted

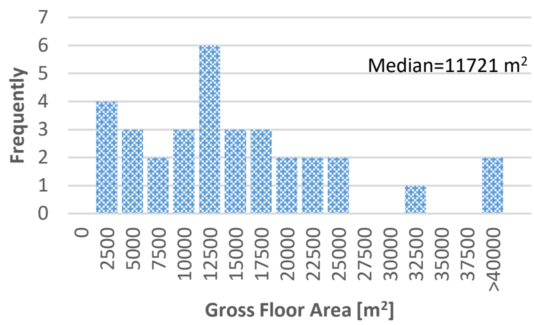

Fig. 2: Distribution of GFA of Office Buildings

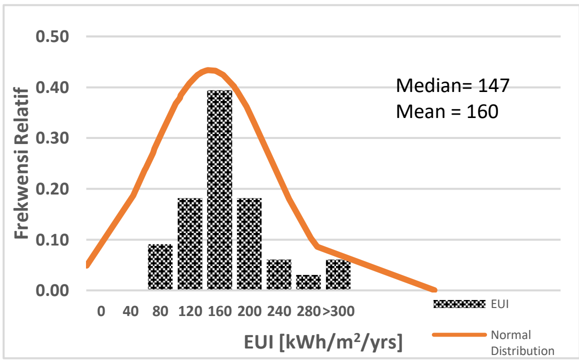

Fig. 3: Distribution of Energy Use Intensity in 6 Cities

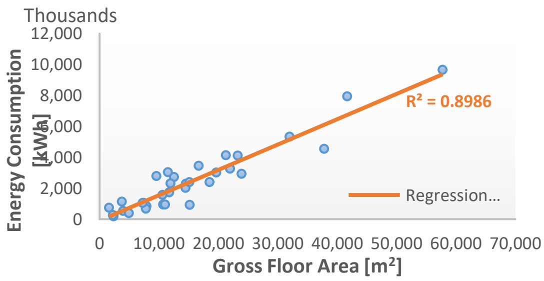

Fig. 4: Coefficient of Determination GFA and Energy Consumption

in addition to the technology of equipment used. With the technology development and increasing public awareness, building design and development in the present day consider the energy aspect. Therefore, the age of the building becomes a factor that needs to be considered as a variable that affects the building's energy consumption.

The coefficient of determination between the age of the building and the EUI value is very small (R2 = 0.0239). A lower R2 value describing the age of office buildings in Indonesia cannot significantly affect the value of the EUI (Figure 5). This is because old buildings have been retrofitted, making their energy use more efficient than in their initial condition. This study's results align with the results of a study conducted by Kontokosta[49].

In addition to building age, other building characteristics that can affect building energy use are operating hours and number of floors.

The building age, operating hours, and number of floors of the building cannot significantly affect the EUI value (Figure 6 and 7). However, these variables will be used to normalize the EUI.

3.3.3. Climate

A simple climate analysis is carried out to characterize the need for heating or cooling space due to climatic factors of the building's location[50]. Indonesia has a tropical climate, and climate factors are needed to correct the building's energy use. In Taiwan's subtropics, energy performance for cooling is benchmarked using envelopment analysis data and the cooling degree hour technique[51]. Through EnergyPlus, research is being done on how climate change may affect different kinds of residential and commercial buildings in all seven climate zones as well as how much energy will be needed in the future in the United States[52]. Global climate change could directly affect the total heating and cooling loads at present and in the future for offices in Japan[16].

Based on previous research on the case study of each area in the subtropical climate, heating degree days and cooling degree days were used for climate correction. These were different since Indonesia is a tropical country (with a climate zone: extremely hot and humid). The heating degree days parameter was irrelevant because the heating energy can be ignored in Indonesian office buildings[53].

Climate data per day from the study of each city were examined and used to calculate Cooling Degree Days (CDD) to see the effect of climate on a building's energy consumption. It was calculated based on the minimum & maximum air temperature and the reference temperature (T_d-T_{ref}), whereas T_{ref} is the base temperature for optimal human comfort. In this study, the reference temperature (T_{ref}) was set at 24°C, which is typical for facility management in Indonesia[54] and reasonable for human comfort. The monthly CDD (CDD_m) is calculated from the daily temperature data for 2018-2019. According to the building location, this CDD data were obtained from NASA data provided in the RETScreen Expert software[55].

$$CDD_m = \sum_{i=1}^{N_d} (T_d - T_{ref}) \quad (5)$$

Where N_d represents the number of days in a month, and T_d (°C) denotes the daily minimum and maximum outdoor air temperature. T_{ref} was set at 24°C.

According to the study conducted by H. Borgstein & Lamberts, office buildings in 57 cities in Brazil were

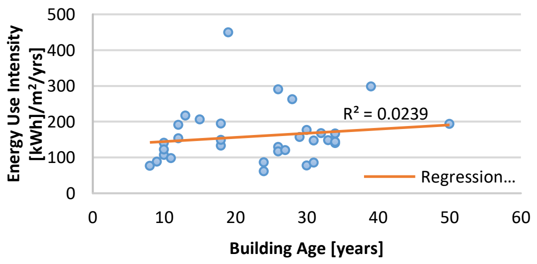

Fig. 5: Distribution Building Age and EUI Value

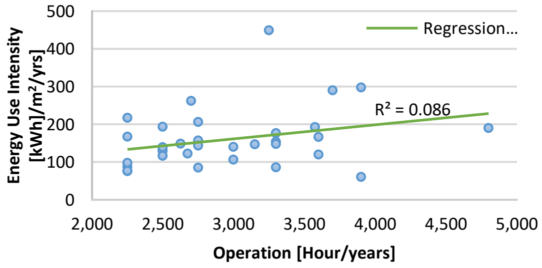

Fig. 6: Distribution Operating hour and EUI Value

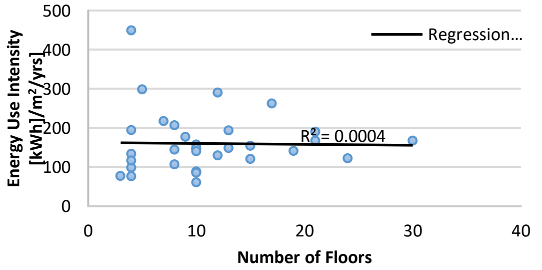

Fig. 7: Distribution Number of Floors and EUI Value

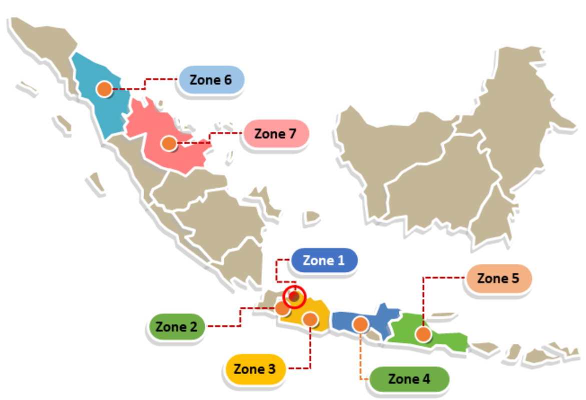

Fig. 8: Sub-climatic Zones in This Study

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grouped by bioclimatic zone[15]. The climate had an influence on energy consumption. The variation within the individual zone was too considerable for this and should be considered an adequate climate correction factor.

Indonesia has only two seasons: the dry and the rainy seasons. Cooling load in Indonesia from CDD starts to increase in April. It is because the dry season in Indonesia occurs from April to September. CDD is also determined by the city's elevation. Figure 10 illustrates that Bandung, situated in Zone 3, has the highest elevation and the lowest CDD value among cities the same latitude.

The effect of seasonal variation, monthly CDD, and Energy Use Intensity were plotted as presented in Figure 9. The 33 office buildings as the object of this study spread across seven cities, then grouped into seven zones based on location with similar cooling degree days (see Figure 8). Based on the previous study, the cooling load in the building will increase in correlation with the increase in CDD[56].

Based on the results of this study, CDD does not have a significant effect on the EUI.

3.3.4. Occupancy

Occupant behavior refers to the interaction of occupants with building systems to attain thermal, visual, and acoustic comfort, as well as control over their interior environment for health considerations. Roulet et al. states that in addition to improving thermal comfort in the living space, improvements in air quality (by introducing fresh air and eliminating air pollution and odor), acoustical conditions (by preventing undesired noise and vibrations), visual or lighting quality (by regulating luminance ratios, reflections, and glare), and aesthetic status[57].

Building energy consumption is influenced by both passive metabolic heat produced by inhabitants (considered in energy modelling software) and active energy usage. Occupants can achieve their desired level of comfort by interacting with control systems and building elements in various ways, such as opening and closing windows, adjusting lighting and solar shading, turning on or off air conditioning, adjusting thermostat temperature, and using hot water and electrical appliances.

In this study, occupancy was not a variable considered for normalizing EUI due to the lack of such data.

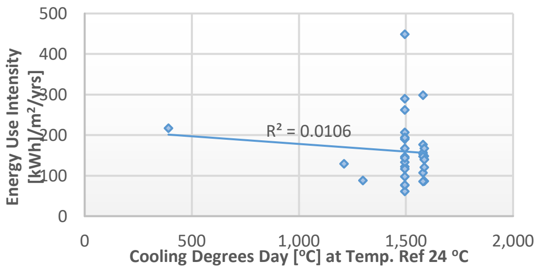


Fig. 9: Distribution Cooling Degree Days and EUI

Table 4: Summary of the parameter correlation with EUI

Parameter	R^2
Gross floor area	0.8986
Building Age	0.0239
Operating Hour	0.086
Number of Floors	0.0004
Climate	0.0106

As presented in Table 4, we found that gross floor area (GFA) significantly impacts energy consumption in office buildings. Building age did not significantly affect energy use. The impact of climate on building energy use should be further investigated by surveying a larger number of buildings, especially those outside of Java. Occupancy rate is another factor influencing energy consumption but was not considered for normalizing EUI due to the lack of data.

3.4. Normalization of EUI

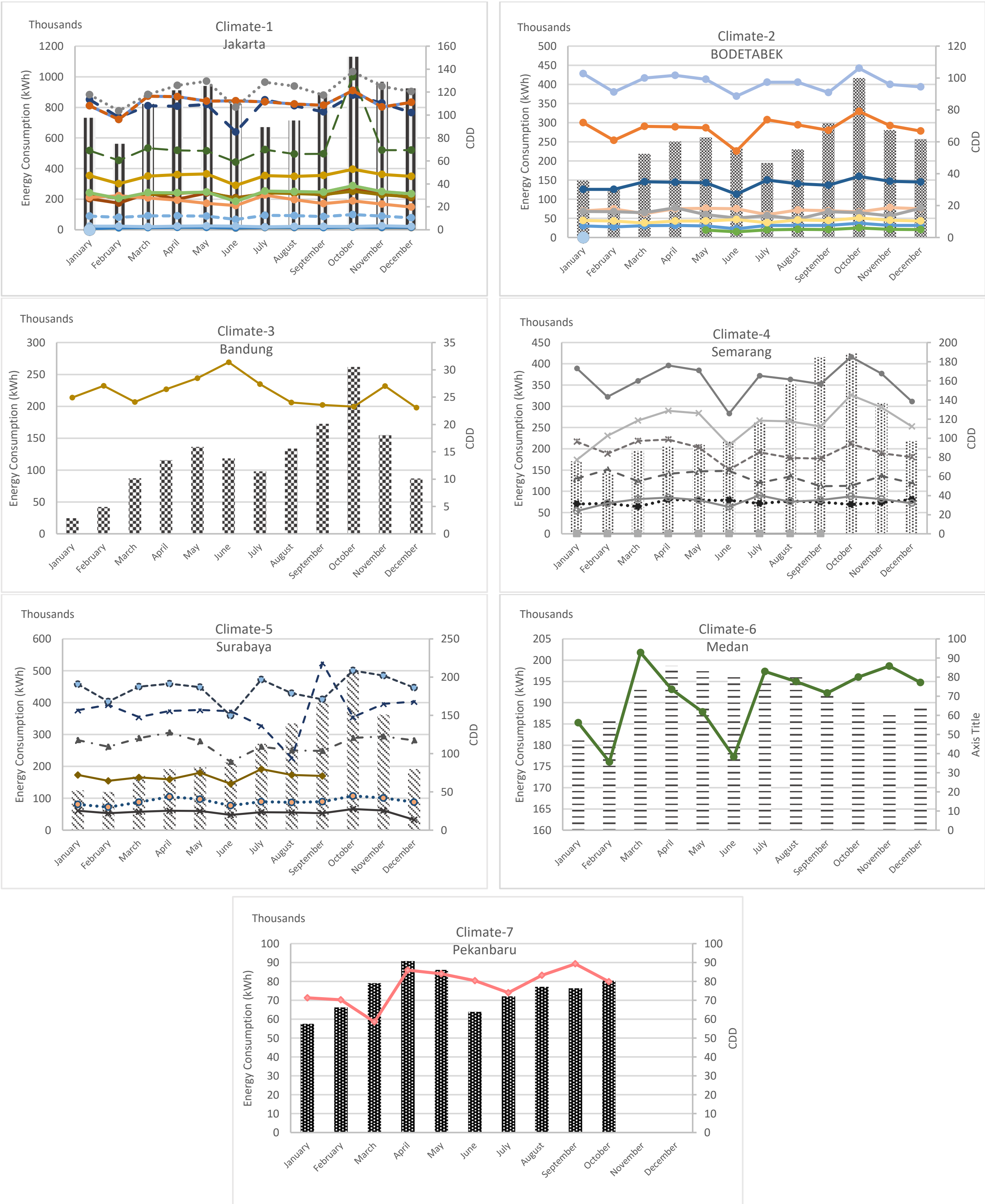
Normalization of the EUI is done to remove the effect of deviations from the explanatory factors (e.g. building characteristics). The variables considered for normalizing EUI include building age (x_1), operating hours (x_2), number of floors (x_3) and CDD (x_4). Considering the above selection criteria, the EUI_{norm} for office buildings is obtained as follows (eq. 3):

$$EUI_{norm} = EUI_0 - 0.4693\,\frac{(Building\ age - 23.36)}{10.35} - 0.0489\,\frac{(Operating\ hour - 2959.85)}{612.47} + 09771\,\frac{(Number\ of\ floors - 11.03)}{6.42} + 0.0920\,\frac{(CDD - 1481.58)}{211.56} \quad (6)$$

Following the previous study, EUInorm was determined using eq. 6 and percentile rank can then be assigned as the benchmark score.

From Figure 11 and Table 5, buildings with an energy consumption per unit area of less than 115 kWh/m2/year are considered the most energy efficient buildings. On the other hand, buildings that consume more than 190 kWh/m2/year are considered the least energy efficient buildings. In the context of building efficiency, there is a growing recognition of the importance of implementing energy management strategies. Such strategies may include conducting energy audits to identify areas for improvement and transitioning to renewable energy sources. These measures are intended to reduce energy consumption, thereby enhancing the overall efficiency of buildings. This is consistent with Government Regulation (PP) Number 33 of 2023, which pertains to energy conservation. The regulatory agency conducts stricter supervision and monitoring of buildings that exceed the upper limit of this range.

Suppose buildings with energy use intensity higher than the median improved their energy efficiency to reach the median value (Figure 12). In that case, total energy use is



Note: The bar graph is the CDD
The line graph shows the energy consumption of each office building

Fig. 10: Monthly Energy Profile vs Cooling Degree Days

estimated to be reduced by 12.04 GWh, equivalent to a reduction in emissions of 10,471 tCO_2/yr.

The relationship between energy savings and CO_2 emissions reductions is not straightforward, as emissions reductions from benchmarking and disclosure requirements may vary across cities due to regional variations in cooling and electricity fuel mix, demand, and time of day. Therefore, the effectiveness and cost-effectiveness of energy efficiency strategies will vary.

Table 5: Normalization of EUI by statistical analysis

Statistical Analysis	EUI_{norm} (kWh/m²/yrs)
Mean of EUI_{norm}	160
Median	147
Minimum	60
Maximum	448
Percentile EUI 25th	115
Percentile EUI 50th	147
Percentile EUI 75th	190

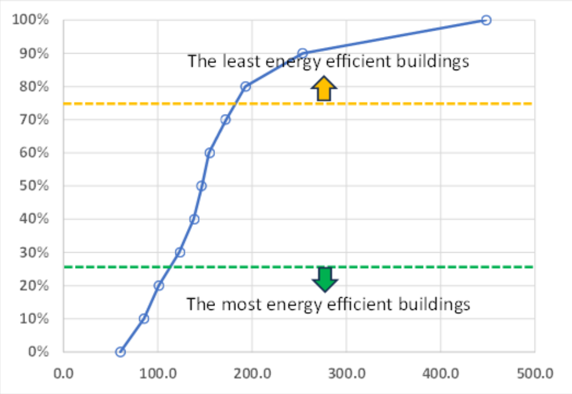


Fig. 11: Benchmarks of EUInorm (Percentile rank)

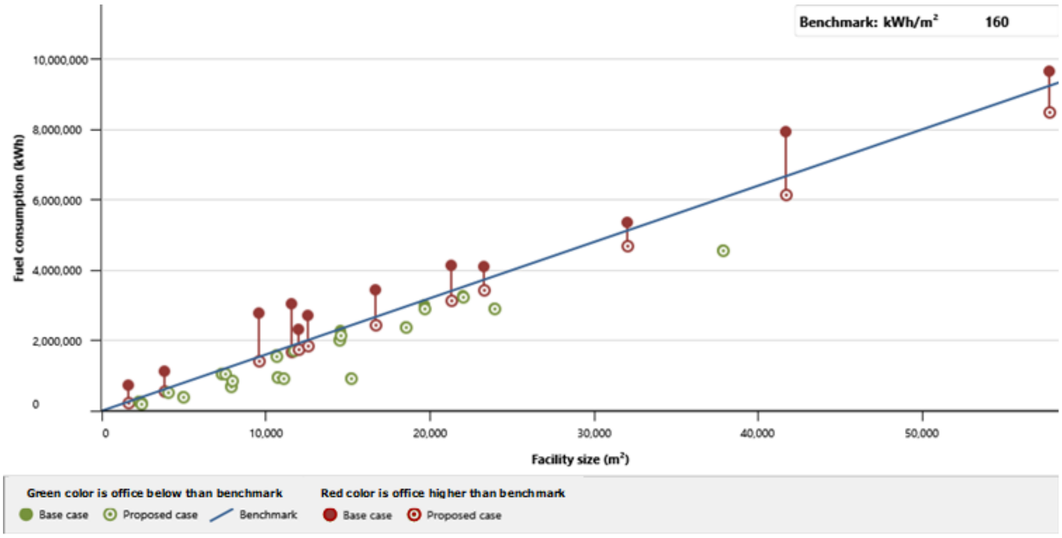


Fig. 12: Benchmark and proposed EUI (reduce EUI value to median)

4. Conclusion

The development of benchmarking of energy consumption in the office building is an important tool for their operations. Benchmarking can help determine how an energy-efficiency goal and strategy can be set for existing buildings and used to examine the design of energy consumption compared to similar types of buildings. The average EUI value obtained for office buildings is 160 kWh/m²/year. The best EUI (most efficient) is below 115 kWh/m²/year, and the worst (most wasteful) is above 190 kWh/m²/year. The implementation of measures designed to improve the efficiency of buildings with high energy use intensity has produced significant results. These measures have resulted in a reduction of total energy consumption by 12.04 GWh and a decrease in emissions by 10,471 tCO_2 per year. HVAC systems consume about 64.7% of total energy (the highest usage), followed by office equipment at about 15%, lighting at about 8.8%, lift & escalators at about 7.0%, and others at about 4.5%.

Considering a benchmark value of Indonesian office buildings with various references, it is evident that the average EUI has moved towards an efficient usage pattern. The energy consumption index also indicates a significant improvement over time. Therefore, updating the EUI data for this building periodically is necessary, and it is suggested once within five years. The range of survey location objects also needs to be expanded to achieve a more representative EUI value of office buildings in Indonesia. Based on the results of a study, the Gross Floor Area (GFA) significantly influences the intensity of energy consumption in office buildings. According to the findings of a study, gross floor area (GFA) has a substantial impact on the intensity of energy use in office buildings. Building age had no significant effect on energy use. The impact of climate on building energy use should be investigated further by surveying a larger number of buildings, particularly those located outside of Java. Another factor that influences energy consumption in buildings is occupancy rate. Further research is needed to determine the relationship between the occupancy rate and the building's energy use. Finally, more comprehensive energy benchmarking in Indonesia is required to compare with other countries such as Singapore, Canada, Europe, the United States, and the UK.

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Nomenclature

MEPS	Minimum Energy Performance Standards
TOE	ton oil equivalent
EPI	Energy Performance Indicator
EUI	Energy Use Intensity (kWh m^{-2} $year^{-1}$)
EUI_{norm}	Normalization of the EUI
E	Energy (kwh)
GFA	Gross floor area (m^2)
CDD	Cooling degree days (°C·days)
CO_{2e}	Equivalent carbon dioxide
f_{CO}	emission factor
R^2	coefficient of determination
T_{ref}	reference temperature (°C)
T_d	daily minimum and maximum outdoor air temperature (°C)
N_d	number of days in a month

Greek symbols

α	conversion factor

Subscripts

i	a specific energy type
j	each energy type

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