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Energy Consumption Trends and Determinants in Polish Hospitals: Implications for Energy Efficiency Strategies

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Abstract: In the construction sector, hospitals are the buildings with the highest energy consumption. Due to the high demand for energy, hospitals' energy efficiency is becoming very important. This study aims to examine the trends and factors that determine energy consumption in Polish hospitals from 2010 to 2019, highlighting the impact of hospital size and medical activities on energy efficiency. The analysis was carried out using data from 3061 hospital reports obtained from the e-Health Center, a state budgetary unit established by the Minister of Health. To measure and compare the efficiency of energy usage in hospitals, we developed eight energy usage efficiency indexes based on hospital size and medical activity. The size of the hospitals was described by the number of beds, operation rooms, doctors, nurses, and fixed assets value. Hospital activity was measured by the number of person-days, patients, and operations. Statistical analysis was carried out using StatSoft Statistica software version 13.3. The results show that larger hospitals are more energy efficient across various measures of energy use than smaller hospitals. The findings revealed also several important relationships between energy usage and factors connected with size and hospital activity, such as the number of beds, patients and person-days, medical staff, operations, and fixed asset values, underscoring the necessity for customizing energy efficiency strategies. This research contributes empirical insights that can guide policymakers and hospital administrators in their endeavors to improve energy efficiency and promote sustainability within healthcare facilities.

Keywords: energy efficiency; Polish hospitals; energy usage trends

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1. Introduction

Energy efficiency in healthcare facilities has emerged as a critical concern in recent years, driven by the dual pressures of rising operational costs and the urgent need for environmental sustainability. Hospitals, as significant consumers of energy, play a pivotal role in the overall energy landscape of the healthcare sector [1]. The increasing demand for medical services, fueled by an ageing population and the prevalence of chronic diseases, has intensified the need for hospitals to optimize their energy use [2]. In Poland, the healthcare system has undergone substantial transformations over the past decade, including changes in funding, management practices, and regulatory frameworks [2,3]. These changes have created both challenges and opportunities for improving energy efficiency in hospitals.

The motivation for this study stems from the recognition that energy consumption in hospitals is not merely a matter of operational efficiency. It also has profound implications for environmental sustainability and public health. Hospitals are responsible for a significant portion of greenhouse gas emissions, and as such, their energy consumption patterns can have far-reaching effects on climate change and public health outcomes. By focusing on the trends in energy use efficiency in Polish hospitals from 2010 to 2019, this research aims to examine the factors that determine energy consumption in Polish hospitals, highlighting the impact of hospital size and medical activities on energy consumption patterns.

Understanding this relationship is essential for several reasons. First, it can help hospital administrators and policymakers identify areas for improvement in energy management practices. Second, it can inform the development of targeted interventions to reduce energy consumption and enhance sustainability in healthcare operations. Third, as healthcare systems worldwide grapple with the challenges of climate change and resource scarcity, insights from this study can contribute to the broader discourse on sustainable healthcare practices.

Moreover, the study seeks to address the gap in knowledge regarding the specific factors that influence energy efficiency in Polish hospitals. While there is a growing body of literature on energy consumption in healthcare facilities globally, there is limited empirical evidence focusing on the Polish context. By examining the relationship between hospital size, operational activity, and energy consumption, this research aims to fill this gap and provide a comprehensive understanding of energy efficiency trends in Polish hospitals.

2. Literature Review

The relationship between hospital size and energy consumption has been a subject of interest in various studies [3]. Research has consistently shown that larger hospitals tend to consume more energy than smaller facilities, primarily due to their increased operational complexity and the higher number of services they provide. Larger hospitals often have more extensive infrastructure, including advanced medical equipment, larger staff, and more significant patient volumes, all contributing to higher energy demands [4]. However, economies of scale suggest that larger hospitals may achieve greater energy efficiency per service unit provided, as fixed costs can be spread over a more extensive patient base.

Several studies have explored the determinants of energy efficiency in healthcare settings, identifying key factors related to hospital size and medical activity that affect energy consumption patterns [4–6]. These factors include the number of beds, patients treated, the length of hospital stays (person-days), the number of medical staff, and the value of fixed assets. For instance, hospitals with more operating rooms and advanced medical technologies may experience increased energy consumption due to the demands of operating complex equipment and maintaining comfortable environments for patients and staff. Conversely, hospitals implementing energy-saving technologies and practices may significantly reduce energy use, regardless of size [5].

In addition to operational characteristics, external factors, such as regulatory frameworks, energy prices, and economic conditions, also play a crucial role in shaping hospital energy consumption patterns. For example, energy policy changes or efficiency incentives can motivate hospitals to adopt more sustainable practices. Similarly, fluctuations in energy prices can impact operational budgets, prompting hospitals to seek ways to reduce energy costs. Understanding these external influences is essential for developing effective energy management strategies.

Despite the existing literature on energy consumption in healthcare facilities, there remains a notable gap in empirical research focusing specifically on Polish hospitals. Previous studies have primarily concentrated on Western countries, where healthcare systems and energy policies may differ significantly from those in Poland. As a result, the applicability of findings from these studies to the Polish context is limited. This research aims to address this gap by providing a comprehensive analysis of energy efficiency trends in Polish hospitals, considering the unique characteristics of the Polish healthcare system.

Furthermore, the literature indicates that while many hospitals know the importance of energy efficiency, there is often a lack of systematic approaches to managing energy consumption [6]. Many healthcare facilities operate under tight budgets, which can limit their ability to invest in energy-saving technologies or initiatives. This study highlights the importance of developing tailored energy management strategies that consider Polish hospitals' specific needs and constraints.

In summary, this study's motivation is rooted in recognizing the critical role of energy efficiency in the sustainability of healthcare facilities. By examining the trends in energy use

efficiency in Polish hospitals and the factors that influence these trends, this research aims to provide valuable insights that can inform energy management practices and contribute to the broader discourse on sustainable healthcare. The literature review underscores the need for empirical research in Poland, highlighting hospitals' unique challenges and opportunities in optimizing their energy consumption. Through this study, we hope to contribute to developing effective strategies for enhancing energy efficiency in healthcare, ultimately benefiting both the environment and public health.

3. Materials and Methods

This study aims to see trends and changes in the efficiency of energy use by hospitals in Poland from 2010 to 2019, taking into account their size and medical activity. The research period ends in 2019 because, in 2020, the pandemic conditioned hospital functioning, affecting both the scope and method of their functioning.

The analysis was carried out using data from hospital reports regarding financial data and medical activity for 3061 hospital years. The data were obtained from the e-Health Center, a state budgetary unit established by the Minister of Health. The data utilized in this analysis are submitted electronically using the Health Care Statistics System to the Ministry by hospitals under applicable legal provisions, ensuring that they are accurately described, structured, and devoid of deficiencies. However, due to modifications in legal regulations concerning methodology for encoding and transmitting data to the Ministry in 2011, 2012, and 2014, data for these years were presented in an alternative format and, consequently, were excluded from our analysis.

The use of electricity in subsequent years for individual hospitals was calculated as the quotient of electricity costs and mean year sales price of electricity on the competitive market and is reported in megawatt hours (MWh).

To analyze the trends and changes in the efficiency of energy use by hospital size, we categorized the hospitals according to the number of beds into four groups as follows:

1. hospitals with less than 99 beds;
2. hospitals with beds between 100 and 299;
3. hospitals with beds between 300 and 599;
4. hospitals with more than 600.

A similar approach was used by Hwang et al. [7]. Categorizing hospitals by size based on the number of beds is a well-established practice in healthcare management. This classification serves as a basic criterion for assessing hospital efficiency, resource allocation, and healthcare delivery. Various studies have established specific thresholds for these categories, which typically include small, medium, and large hospitals based on their bed capacity [8–11]. By categorizing hospitals based on bed numbers, it becomes easier to interpret energy efficiency trends. Moreover, common patterns and successful strategies can be identified, disseminating proven methods across similar-sized healthcare facilities. Additionally, categorizing hospitals by size enables policymakers to develop tailored energy efficiency policies and guidelines.

In order to analyze how the hospital size and its activity changed between 2010 and 2019 and to what extent these variables depended on the size of the hospital in the first stage, we presented the hospital size and activity by four hospital categories. The size of the hospitals was described by the number of beds, operation rooms, doctors, nurses, and fixed assets value. The fixed asset value was converted from PLN to euro at the PLN 4.23 per euro exchange rate. Hospital activity was measured by the number of person-days, patients, and operations. Means and SDs were calculated for all data. Variables were compared using Student's *t*-test. A *p*-value of 0.005 was considered significant. Statistical analysis was carried out using StatSoft Statistica software version 13.3.

To measure and compare the efficiency of energy usage in hospitals, we developed eight energy usage efficiency indexes and analyzed them within the research period by each hospital category. The efficiency indexes in energy consumption were built based on the available data. These were the energy usage per person-days index, the energy usage

per patient index, the energy usage per operations index, the energy usage per doctors index, the energy usage per nurses index, the energy usage per operation rooms index, the energy usage per beds index, and the energy usage per fixed assets values index. The above energy efficiency indexes are critical metrics for evaluating the performance of healthcare facilities. These indexes provide a comprehensive view of how energy is consumed relative to various operational factors, which is essential for identifying areas for improvement in energy management and sustainability practices within healthcare settings. A similar approach to measuring energy efficiency was used by [7,12–14].

We presented the trends in the changes in one table and on 12 figures. The table lists various energy efficiency indexes by four hospital bed size categories: <99, 100–299, 300–599, and >600. The mean and standard deviation (sd) for each index are provided, and *p*-values indicate statistical significance across the different bed size categories. The *p*-value column assesses the statistical significance of the differences between the smallest and largest hospital bed size categories for each index.

Figures present the box-and-whisker plot (box plot) displaying the overall variable of hospitals each year. The key elements of the box plot are the median (line inside the box) and the 25th to 75th percentile range (the box). To make the figures more readable, the figures displaying the variables by hospital groups present a median with a non-outlier range (whiskers).

4. Results

Table 1 presents the size and activity of the hospitals, categorized by the number of beds: "<99", "100–299", "300–599", and ">600". The mean value and standard deviation (SD) are provided for each hospital category for energy usage. Hospital size is measured by the mean regarding the number of doctors, nurses, beds, operation rooms, and fixed asset value. The hospital activity in the table is measured by person-days, number of patients, and operations.

Table 1. Size and activity of the research sample.

Variables	Number of Beds				*p*-Value *					
	<99	100–299	300–599	>600						
	Mean (SD)				1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
Energy usage (MWh)	2113.23 (1730.96)	4633.59 (5179.97)	12,754.16 (8288.30)	30,819.15 (19,890.34)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Hospital size										
Doctors	23 (22)	72 (51)	193 (103)	425 (230)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Nurses	43 (31)	146 (80)	378 (164)	775 (323)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Beds	62 (23)	192 (55)	424 (88)	818 (204)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Operation rooms	1 (1)	3 (2)	7 (4)	15 (7)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Fixes assets (euro)	2,887,301.62 (3,770,481.713)	6,188,238.88 (6,632,482.40)	15,646,958.1 (12,920,831.02)	33,203,062.04 (31,739,225.93)	<0.05	<0.05	NS	NS	NS	NS
Hospital activity										
Person-days	15,626 (7550)	44,985 (16,329)	107,474 (28,343)	213,694 (61,702)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Patients	2081.37 (1620.26)	7677.32 (3647.75)	18,074.45 (6386.79)	35,466.13 (11,541.10)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Operations	689 (1307)	2574 (2542)	7065 (4758)	15,971 (9948)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

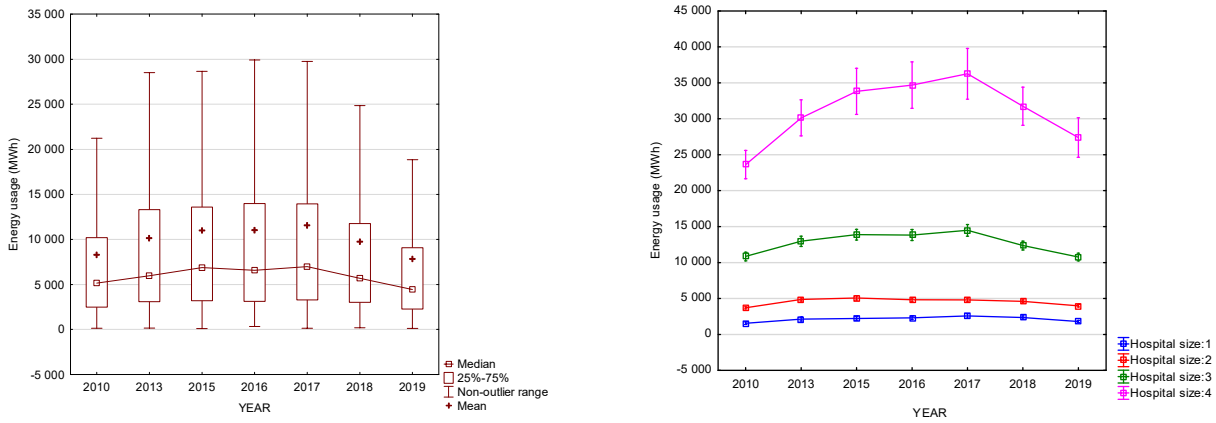
* 1. Hospitals with beds < 99; 2. Hospitals with beds between 100–299; 3. Hospitals with beds between 300–599; 4. Hospitals with beds > 600.

Table 1 shows an increase in mean values for energy usage, number of doctors, nurses, beds, operation rooms, person-days, patients, and operations as the number of beds in a hospital increases. Fixed assets in euros also increase with the number of beds, but have

no significant difference between hospitals with 300–599 beds and those with more than 600 beds.

We presented the trends in changes in energy consumption, hospital size, and activity within four hospital size categories in the five figures.

Figure 1 presents the total energy consumption by hospitals (a) and (b) by size from 2010 to 2019. Figure 1a displays hospitals' overall energy usage (MWh) each year. Figure 1b shows the energy usage (in MWh) by the size of the hospital, with each size category represented by a different color and symbol on the lines.

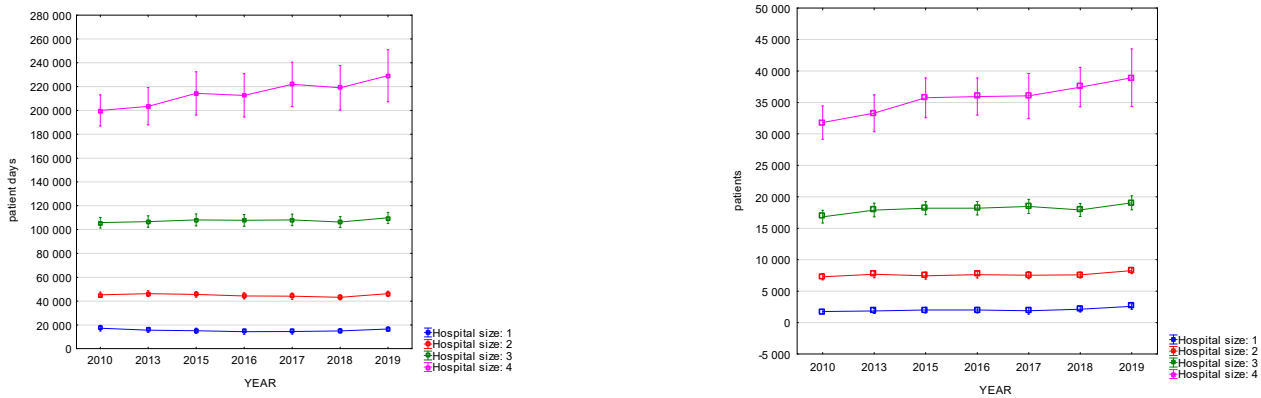


(**a**) (**b**)

Figure 1. Energy consumption in 2010–2019 by hospitals: (**a**) in total; (**b**) by size.

From Figure 1a, we can observe that the median energy usage showed a slightly increasing trend from 2010 to 2018 but dropped in 2019. The mean energy usage fluctuates over the years but generally increases until a drop in 2019. The range of energy usage (indicated by the whiskers) and the interquartile range (the height of the boxes) vary significantly from year to year, suggesting considerable variation in energy usage among hospitals from one year to the next. Figure 1b illustrates that larger hospitals (size 4) consume significantly more energy than smaller ones (sizes 1 to 3), with a peak in energy usage around 2016–2017 before decreasing. Hospitals of size 3 show a gradual increase in energy consumption over the years, with a slight decline in 2019. Hospitals of size 2 exhibit a relatively stable energy consumption. Size 1 hospitals have the lowest energy consumption, with a generally flat trend.

Figure 2 presents the number of person-days (a) and patients (b) by the size of the hospital, with each size category represented by a different color and symbol on the lines.

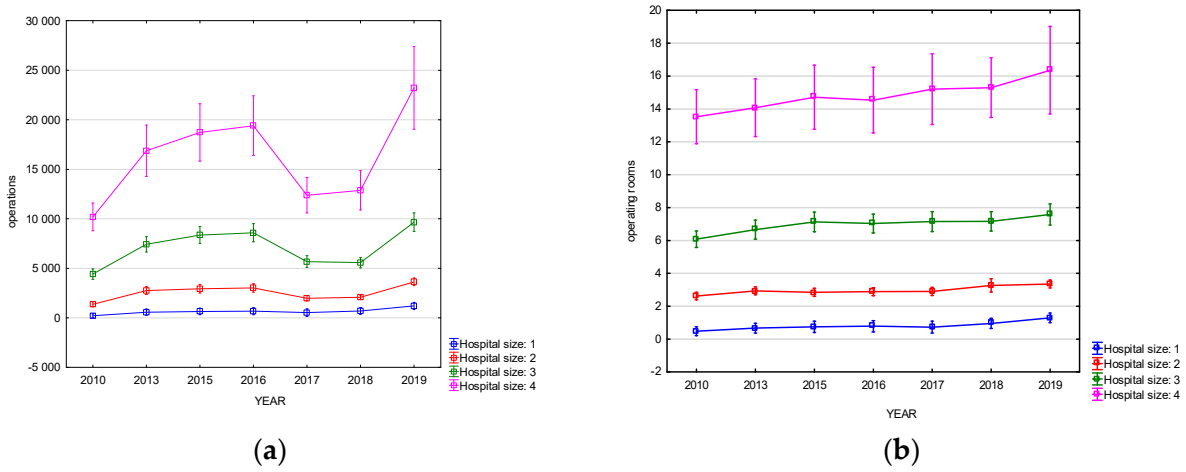


(**a**) (**b**)

Figure 2. The number of person-days (**a**) and patients (**b**) in hospitals by size in 2010–2019.

In Figure 2a, we can observe that larger hospitals (size 4) have significantly more person-days than smaller hospitals (sizes 1 to 3), gradually increasing over the years. Hospitals of size 3 also increase, while sizes 1 and 2 remain relatively constant. Figure 2b demonstrates a similar pattern to graph (a), with the larger hospitals (size 4) treating more patients than the smaller ones. The number of patients treated in size 4 hospitals steadily increases. Hospitals of sizes 2 and 3 exhibit a slight increase in patient numbers, while size 1 hospitals remain relatively flat regarding patient count.

Figure 3a shows the number of hospital operations conducted, while Figure 3b shows the number of operating rooms available.

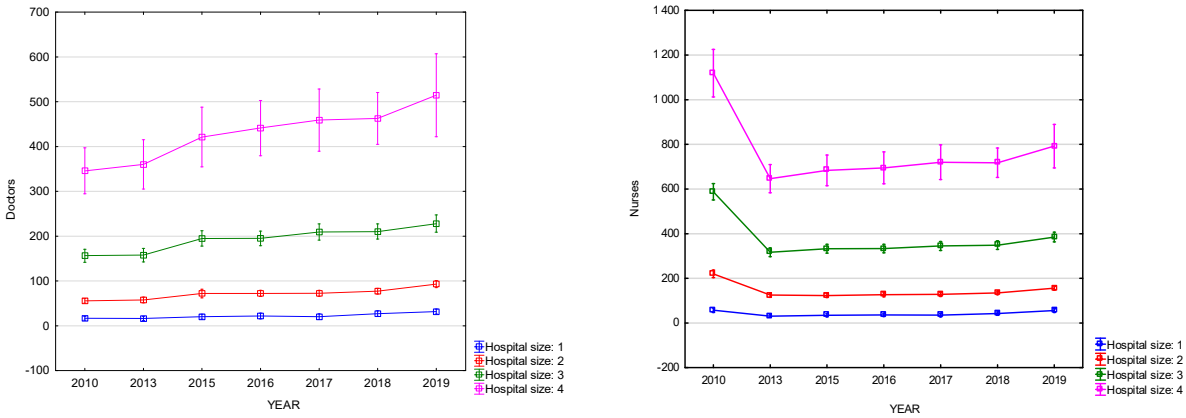


(**a**) (**b**)

Figure 3. The number of operations (**a**) and operating rooms (**b**) in hospitals by size in 2010–2019.

In Figure 3a, the largest hospitals (size 4) exhibit a significant increase in operations from 2010 to 2016, a dip in 2017, and a steep increase from 2018 to 2019. Hospitals size 3 show a gentle increase in operations over the years, peaking in 2016 and stabilizing. Hospital sizes 1 and 2 have relatively fewer operations, with minor fluctuations over the years. Figure 3b illustrates that the largest hospitals (size 4) have the highest number of operating rooms, which remains relatively stable with some variation. Hospital sizes 2 and 3 slightly increase operating rooms over time, while the smallest hospitals (size 1) maintain a consistent number with minor fluctuations.

The data presented in Figure 4a illustrates the longitudinal trends in the number of doctors from 2010 to 2019. In contrast, Figure 4b depicts the corresponding trends in the number of nurses over the same period.



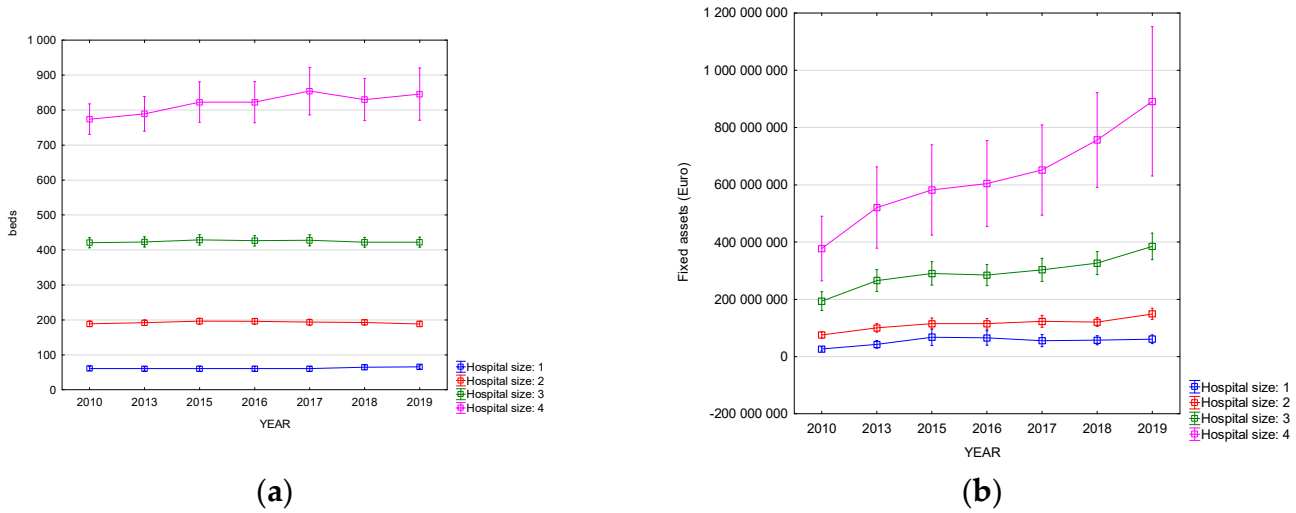
(**a**) (**b**)

Figure 4. The number of doctors (**a**) and nurses (**b**) in hospitals by size in 2010–2019.

Regarding Figure 4a, it is evident that hospitals of size 4 exhibit the highest number of doctors, demonstrating a consistent upward trend, particularly between 2016 and 2019. Although hospitals of sizes 2 and 3 also indicate an increasing trend, the number of doctors in these hospitals remains considerably lower than that of size 4. Conversely, hospitals of size 1 present the lowest number of doctors, maintaining a relatively steady trend with minimal variation.

Turning to Figure 4b, it is noteworthy that the largest hospitals (size 4) experienced a sharp decline in nurses from 2010 to 2013, followed by a gradual recovery and subsequent increase. In contrast, hospitals sizes 2 and 3 initially exhibit a slight decrease in the number of nurses, followed by stabilization. Finally, the smallest hospitals (size 1) demonstrate a consistent number of nurses with minor fluctuations throughout the observed period.

Figure 5a,b displays the number of hospital beds and the value of the fixed assets in hospitals, measured in euros (€).



(**a**) (**b**)

Figure 5. The number of beds (**a**) and fixed assets value (**b**) in hospitals by size in 2010–2019.

In Figure 5a, the largest hospitals (size 4) consistently have the most beds, with slight fluctuations over the years. Hospital sizes 3, 2, and 1 also show relatively stable trends, with fewer beds than size 4. Figure 5b illustrates a clear increasing trend in fixed asset value for all hospital sizes. The largest hospitals (size 4) have a substantial increase in asset value, particularly from 2016 onwards. Hospitals of sizes 3 and 2 show a steady increase, while the smallest hospitals (size 1) have a more modest growth in asset value.

Table 2 shows generally lower means for energy usage per person-day, per patient, per operation, per doctor, per nurse, per operation room, and per bed as the number of beds in a hospital increases.

The energy usage per fixed asset values index shows minimal differences across hospital sizes and no significant difference (indicated as NS) among the categories. The *p*-value column indicates the statistical significance, with "NS" denoting insignificant. The results show that larger hospitals tend to be more energy-efficient across various measures of energy usage than smaller hospitals.

Figure 6 shows the hospital energy consumption per person-day in 2010–2019: (a) total; (b) by number of beds.

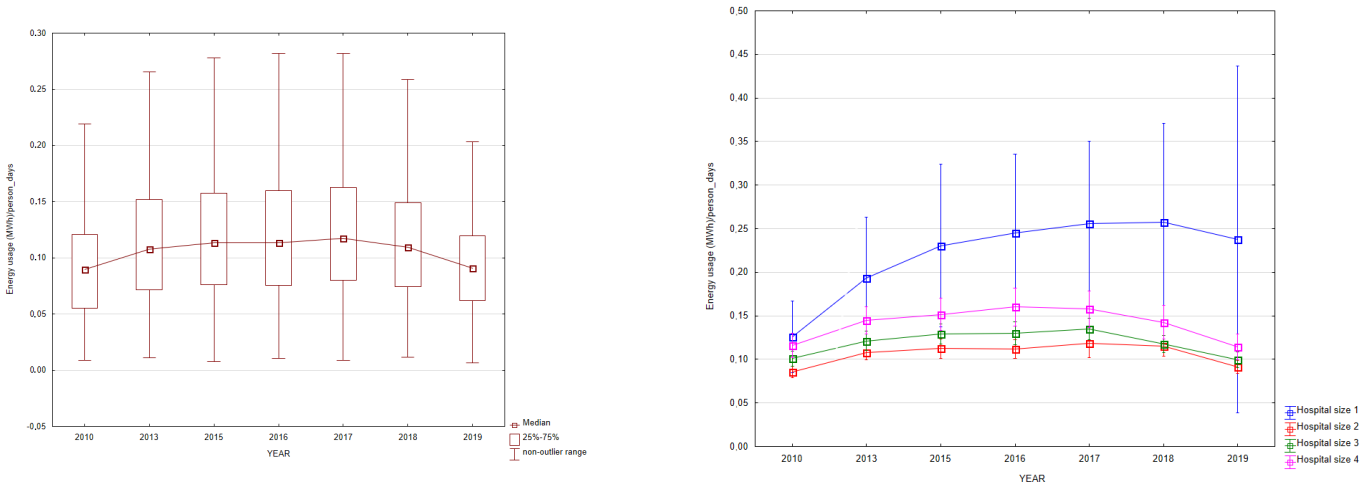
Figure 6a describes the total overall energy consumption per person-days by hospitals, regardless of size or specific category. A slight decreasing trend in the median energy consumption per person-days from 2010 to 2019 can be observed. The IQR also seems to narrow slightly over time, indicating that the energy consumption data may become more consistent across the hospitals sampled. The range of the data seems to vary widely each year, as evidenced by the long whiskers, suggesting significant differences between the highest and lowest energy-consuming hospitals. Figure 6b represents the energy

consumption per person-days for hospitals by size category over the same period. Hospitals of size 1 have the highest energy consumption per person-days and show a sharp increase around 2014, peaking in 2016 and decreasing significantly to 2019. Hospitals of size 2 have a slight upward trend until 2016, then a steady decrease. Hospitals of size 3 remain relatively stable, with a small peak in 2016 and then a decrease. Hospitals in size 4 have the lowest energy consumption, with a slight increase until 2015, then a more pronounced decrease.

Table 2. Efficiency indexes in energy usage in Polish hospitals.

Energy Efficiency Indexes	Number of Beds				*p*-Value *					
	<99	100–299	300–599	>600						
	Mean (SD)				1 vs. 2	1 vs. 3	1 vs. 4	2 vs. 3	2 vs. 4	3 vs. 4
Energy usage/person-days	1.13 (18.20)	0.107 (0.09)	0.11 (0.06)	0.14 (0.06)	<0.05	NS	NS	<0.05	<0.05	<0.05
Energy usage/patient	4.22 (48.48)	0.65 (0.54)	0.72 (0.42)	0.87 (0.64)	<0.05	<0.05	NS	<0.05	<0.05	<0.05
Energy usage/operations	29.08 (165.17)	8.59 (141.15)	2.67 (3.18)	2.18 (1.24)	NS	<0.05	<0.05	NS	NS	<0.05
Energy usage/doctors	182.982 (291.55)	86.19 (224.54)	73.55 (47.62)	76.98 (37.14)	<0.05	<0.05	<0.05	NS	NS	NS
Energy usage/nurses	76.41 (111.92)	38.08 (37.63)	35.79 (20.23)	40.73 (18.97)	<0.05	<0.05	<0.05	NS	NS	<0.05
Energy usage/operation rooms	1291.76 (913.11)	1480.73 (968.06)	2071.03 (1445.26)	2135.87 (939.12)	<0.05	<0.05	<0.05	<0.05	<0.05	NS
Energy usage/beds	43.62 (60.32)	23.98 (20.80)	29.86 (17.54)	36.15 (16.07)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Energy usage/fixed assets values	0.0017 (0.003)	0.0013 (0.0026)	0.0013 (0.0025)	0.0015 (0.0018)	<0.05	<0.05	NS	NS	NS	NS

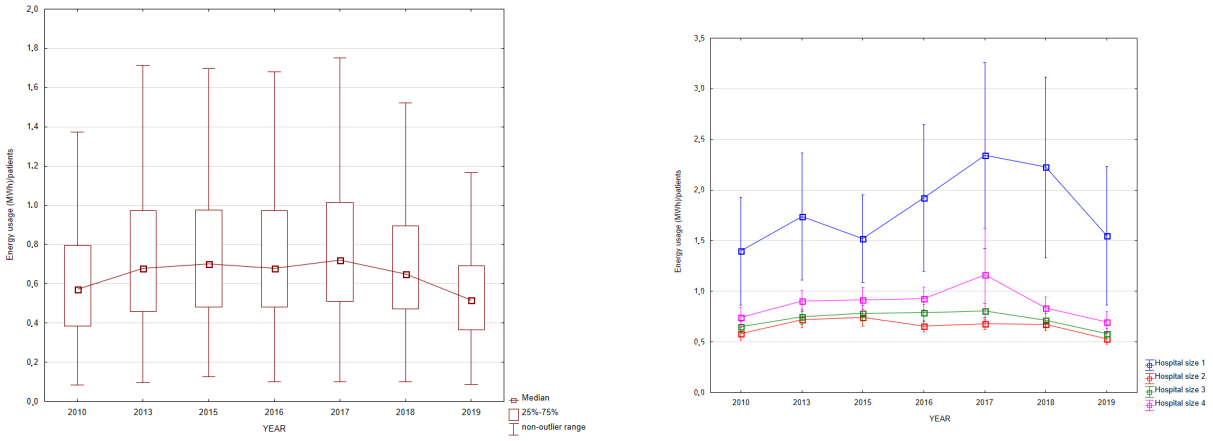
* 1. Hospitals with beds < 99; 2. Hospitals with beds between 100–299; 3. Hospitals with beds between 300–599; 4. Hospitals with beds > 600.



(**a**) (**b**)

Figure 6. Energy consumption per person-day in 2010–2019: (**a**) total; (**b**) by number of beds.

Figure 7a shows the distribution of total energy consumption per patient across Polish hospitals for each year from 2010 to 2019.

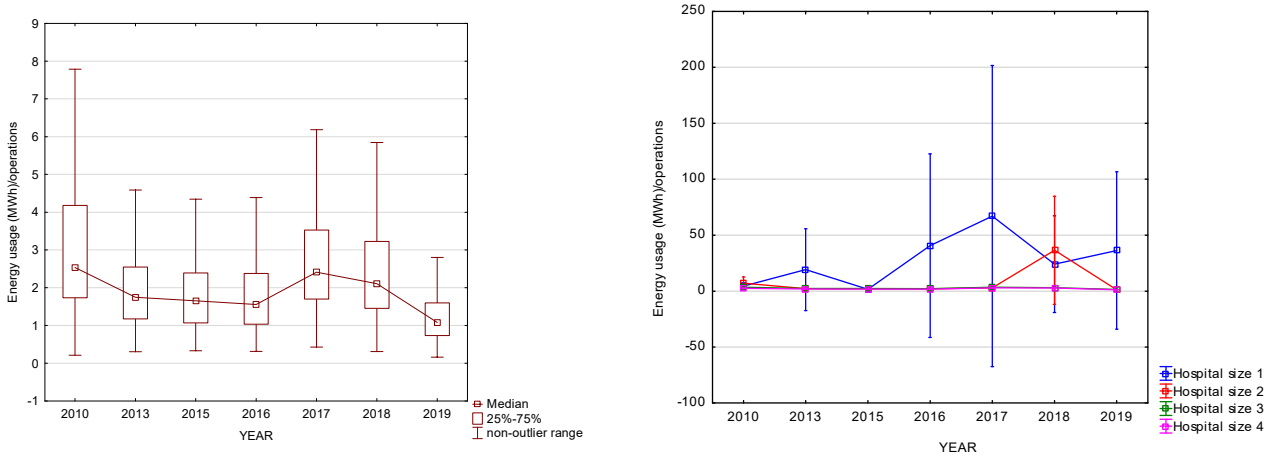


(**a**) (**b**)

Figure 7. Energy consumption per patient by hospitals in 2010–2019: (**a**) hospitals total; (**b**) by number of beds.

Figure 7b shows hospital energy consumption per patient categorized by size. In Figure 7a, the median energy consumption per patient decreases over the years, with some fluctuations. The interquartile range (25–75%) also seems to be narrowing, suggesting a reduction in the variability of energy consumption among hospitals. Figure 7b shows that the smallest hospitals (size 1) have the highest variability in energy consumption per patient, with a notable peak in 2016. In contrast, the largest hospitals (size 4) have a general increasing trend in energy consumption per patient, particularly towards the decade's end. Hospitals of sizes 2 and 3 show more stable trends with less variation.

Figure 8a describes the distribution of energy consumption per hospital bed across Polish hospitals for each year from 2010 to 2019.

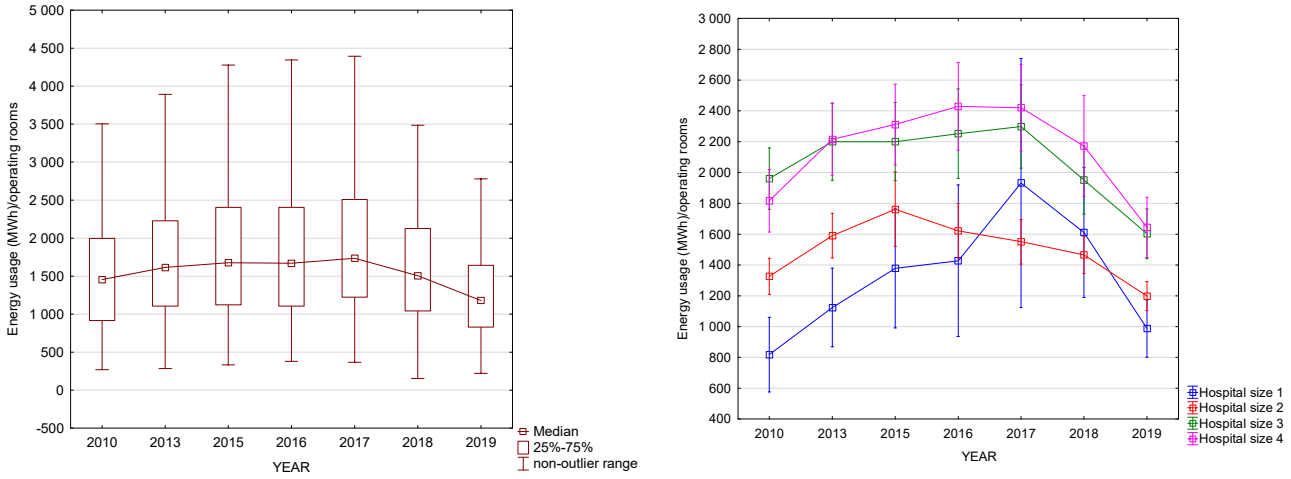


(**a**) (**b**)

Figure 8. Energy consumption per number of beds by hospitals in 2010–2019: (**a**) hospitals total; (**b**) by hospital size.

In Figure 8a, the median energy consumption per hospital bed shows a slight downward trend from 2010 to 2019. There is considerable variability in the data, as evidenced by the length of the whiskers, which indicates that the energy consumption per hospital bed varies significantly from year to year within the dataset. Figure 8b shows that the smallest hospital (size 1) has a highly variable energy consumption per hospital bed, with a notable peak around 2016 and significant fluctuations throughout the period. The other hospitals (sizes 2, 3, and 4) demonstrate less variability, with hospital size 4 showing a general increasing trend from 2010 to 2016 and then a decrease.

Figure 9a depicts the distribution of energy consumption per operating room across all hospitals from 2010 to 2019. In contrast, Figure 9b focuses on the energy consumption per operating room in hospitals categorized by size (ranging from 1 to 4) during the same time frame.

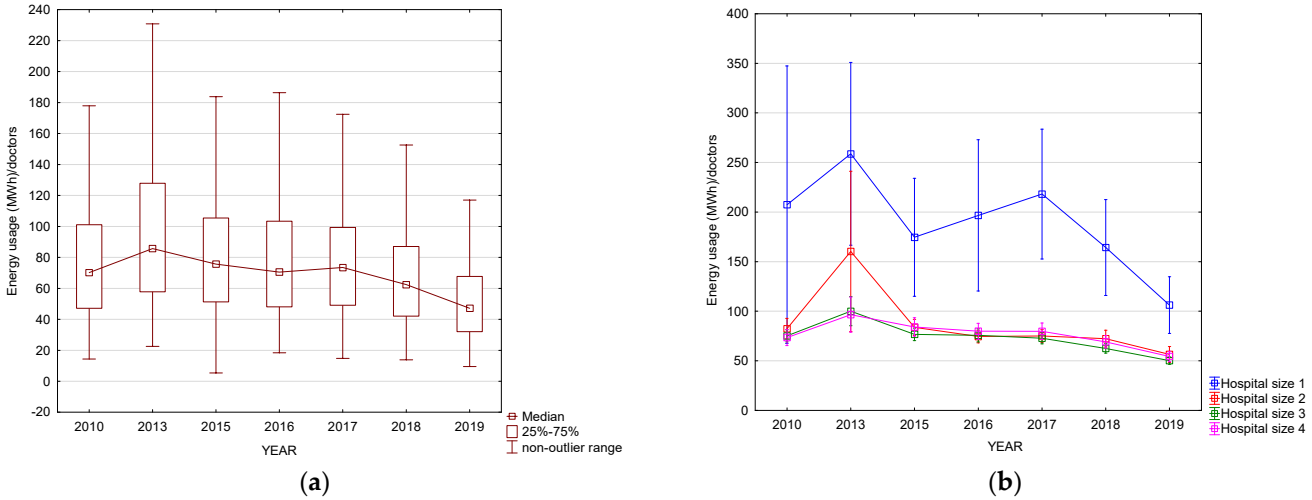


(**a**) (**b**)

Figure 9. Energy consumption per operating room by hospitals in 2010–2019: (**a**) hospitals total; (**b**) by number of beds.

The median energy consumption per operating room, as presented in Figure 9a, exhibits a slight downward trend from 2010 to 2019. The whiskers on the graph indicate a considerable degree of variability within the data, suggesting a wide range of energy consumption per operating room observed across different years. Figure 9b shows that the smallest hospitals (size 1, represented by the blue line) generally experience an increasing trend in energy consumption per operating room, peaking around 2016, followed by a sharp decline towards 2019. Hospitals of sizes 2 and 3 (represented by the red and green lines, respectively) demonstrate an initial increase in energy consumption per operating room until 2016 or 2017, after which a reversal in the trend is observed. Similarly, the largest hospitals (size 4, indicated by the magenta line) experienced a peak in energy consumption per operating room in 2017, followed by a subsequent decrease.

Figure 10a,b present energy consumption per doctor by hospitals in 2010–2019 in total and by number of beds, respectively.

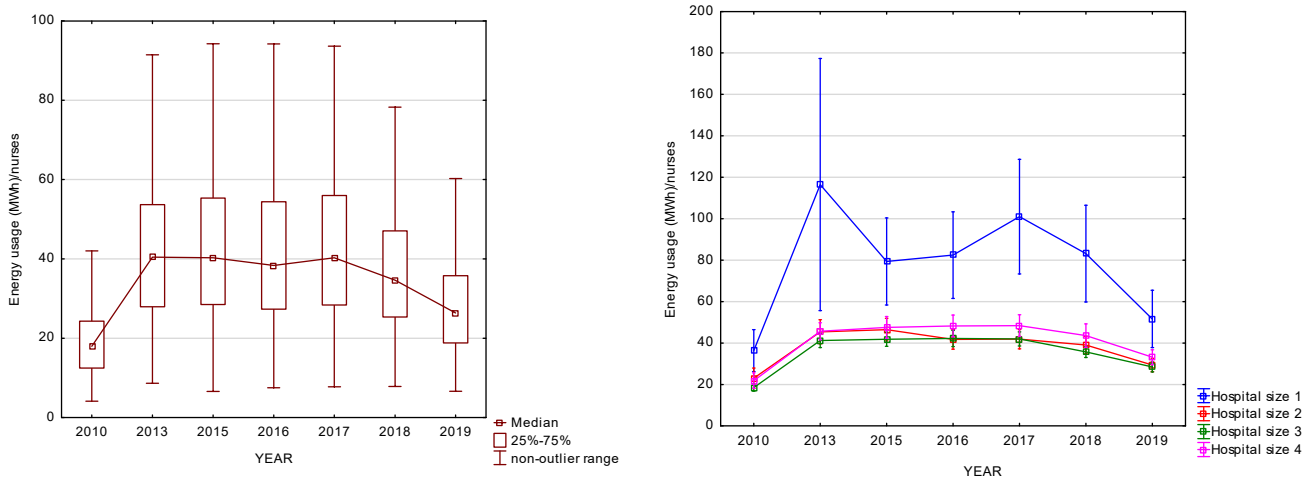


(**a**) (**b**)

Figure 10. Energy consumption per doctor by hospitals in 2010–2019: (**a**) hospitals total; (**b**) by number of beds.

The median energy usage per doctor shows a downward trend from 2010 to 2019. The variability, as demonstrated by the length of the boxes and the non-outlier range, is quite significant, especially in the earlier years (2010 to 2015). The median values generally decrease over time, suggesting that energy efficiency per doctor may have improved over these years. Figure 10b shows different trends for hospitals of varying sizes. The most significant variation in energy usage is seen in the hospitals categorized as "size 1", which peaks around 2013 and then shows a declining trend. Energy usage has remained relatively stable for the other hospital sizes over the years, with some fluctuations. Hospitals of sizes 2 and 3 show a slight increase in energy usage in the later years, while size 4 maintains the most consistency with the least variation.

Figure 11a,b depict the energy consumption per nurse distribution for a comprehensive collection of hospitals from 2010 to 2019 and for hospitals segmented by size (1 to 4) during the same period.



(**a**) (**b**)

Figure 11. Energy consumption per nurse by hospitals in 2010–2019: (**a**) hospitals total; (**b**) by number of beds.

Figure 11a shows that the median energy consumption per nurse experienced a gradual decrease from 2010 to 2019, albeit with inevitable fluctuations. Notably, the data exhibits considerable variability, as evidenced by the length of the whiskers, indicating a substantial variance in energy consumption per nurse on a year-to-year basis. Figure 11b portrays the energy consumption per nurse for the smallest hospitals (size 1), which displays notable variability, reaching its peak in 2016 and subsequently witnessing a sharp decline through 2019. Conversely, hospitals of sizes 2, 3, and 4 experienced a peak in energy consumption per nurse around 2016–2017, followed by a subsequent decline.

Figure 12a presents the distribution of energy consumption per fixed asset value for all hospitals combined for each year from 2010 to 2019. Figure 12b shows the energy consumption per fixed asset value for hospitals categorized by size (1 to 4) over the same period. In Figure 12a, the median energy consumption per fixed asset value appears to be declining over the years, with some fluctuations. The variability of the data, as indicated by the whiskers, suggests a significant variance in this ratio from year to year. Figure 12b presents that the smallest hospital (size 1) experiences the most notable variability in energy consumption per fixed asset value, with peaks and troughs throughout the period. The other hospital sizes (2, 3, and 4) also exhibit fluctuations, with a general downward trend in this ratio, particularly after 2016.

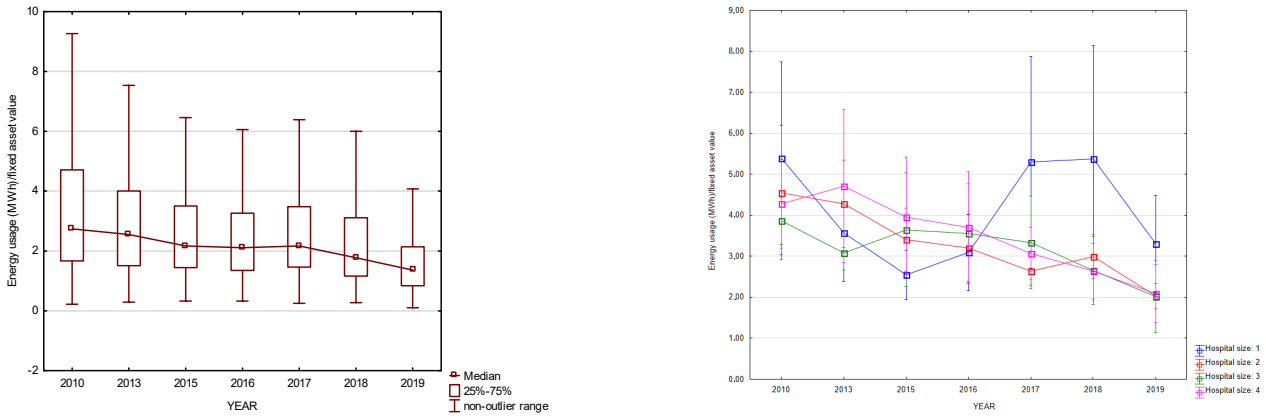


Figure 12. Energy consumption per fixed asset value by hospitals in 2010–2019: (**a**) hospitals total; (**b**) by number of beds.

5. Discussion

This study examined trends and changes in energy use efficiency by hospitals in Poland from 2010 to 2019, highlighting the impact of hospital size and medical activities on energy efficiency. The findings revealed several important relationships between energy usage and factors connected with size and hospital activity, such as the number of beds, patients and person-days, medical staff, operations, and fixed asset values.

5.1. Trends in Energy Use by Hospitals

We observed fluctuations in energy consumption across different years, particularly in larger hospitals, which can be attributed to several interrelated factors, including technological advancements, operational changes, and the implementation of energy-saving measures. One significant reason for these fluctuations can be the rapid pace of technological advancements in energy management systems and medical equipment. Larger hospitals often have more complex operations and a greater variety of energy-consuming devices. As new, more energy-efficient technologies (advanced HVAC systems, LED lighting, and energy-efficient medical devices) are adopted, hospitals may experience reduced energy consumption. Operational changes within hospitals can also significantly impact energy consumption patterns. For example, fluctuations in patient admissions, seasonal variations in occupancy rates, and changes in service offerings can lead to variations in energy use. Larger hospitals, which typically operate 24/7, may experience more pronounced effects from these operational changes. During periods of high patient volume, energy consumption may increase due to the need for additional lighting, heating, cooling, and medical equipment usage.

Conversely, during off-peak times, energy consumption may decrease. However, if the hospital is not optimized for lower occupancy, it may still operate energy-intensive systems at total capacity, leading to inefficiencies. Finally, the complexity of larger hospitals, with their extensive infrastructure and diverse range of services, means that many factors influence energy consumption. Variations in the types of medical procedures performed, the efficiency of different departments, and the operational practices of various units can all contribute to the overall energy consumption patterns observed over the years.

5.2. Trends and Changes in Energy Use Efficiency in Terms of Number of Patients

Analyzing energy consumption per patient, a decreasing trend was observed across all hospitals, suggesting an overall improvement in energy use efficiency per patient. This result is encouraging and suggests effective efforts to promote energy conservation and sustainability in healthcare facilities. However, this trend varied when analyzed by hospital size, with the largest hospitals increasing energy usage per patient over time.

This outcome implies that size alone may not be the sole determining factor for energy consumption efficiency in healthcare facilities. This variation could be attributed to building characteristics, occupancy patterns, and energy-conscious behavior within the hospitals.

Regarding building characteristics, larger hospitals often have more extensive and complex operations, which can result in increased energy consumption per patient [7]. The scale and complexity of operations in larger facilities may also increase patient energy consumption. Moreover, larger hospitals' physical layout and design may require more energy-intensive features such as long corridors, larger common areas, and multiple floors, all of which contribute to increased energy consumption.

Occupancy patterns and energy-conscious behavior can impact energy consumption, highlighting the importance of targeted strategies and technologies to optimize energy efficiency in healthcare facilities [8,15–19]. Different hospitals may have varying levels of patient occupancy throughout the year, which can significantly impact energy usage. Hospitals with fluctuating occupancy levels may experience periods of low utilization, resulting in the inefficient operation of energy-consuming systems. Conversely, hospitals that consistently operate at high occupancy rates may have more efficient energy utilization due to constant demand and optimized scheduling of energy-consuming systems.

5.3. Trends and Changes in Energy Use Efficiency in Terms of Number of Person-Days

Regarding energy consumption per person-days, the study revealed a downward trend in energy consumption in the latter part of the decade across all hospital sizes. The reduction in energy consumption is likely a result of various energy-saving measures, such as adopting energy-efficient technologies and implementing energy management systems. This indicates potential improvements in energy efficiency in healthcare facilities. However, there was significant variability from year to year and when analyzed by hospital size, suggesting that energy consumption trends are inconsistent across all hospitals. Energy consumption in hospitals is not solely dependent on hospital size. Still, it is also affected by factors such as the complexity of services offered, energy standards, and the efficiency of medical equipment used [20]. The type of management, geographical location, gross domestic product, heating and cooling degree days, and the range of years studied also play a role in determining energy consumption levels in healthcare facilities. HVAC systems have been identified as significant contributors to hospital energy consumption, emphasizing the importance of considering specific operational aspects within hospitals when analyzing energy consumption trends [21,22].

5.4. Trends and Changes in Energy Use Efficiency in Terms of Number of Operating Rooms

The results showed trends in energy consumption per operating room, with larger hospitals tending to perform more operations, having more operating rooms, and higher energy consumption per operating room. This is consistent with previous research showing that as hospitals increase, their resource requirements, including energy, staff, and facilities, also increase [8]. Increasing resource requirements in larger hospitals raises questions about resource allocation, consumption, and efficiency. It is essential to ensure efficiency in hospital operations to provide quality care, optimize resource utilization, and control healthcare costs. Additionally, hospital energy consumption patterns can vary widely within specific spaces, with surgical ORs consuming significantly more energy per square foot than other hospital areas. Sustainable solutions, such as recirculating airflow, can reduce the energy demand of operating rooms [17].

5.5. Trends and Changes in Energy Use Efficiency in Terms of Number of Doctors

The findings of this study also revealed an increase in the number of doctors across all hospital sizes, indicating a rising demand for healthcare professionals to cater to the needs of the increasing number of patients. However, the number of nurses declined, particularly in larger hospitals, before stabilizing or increasing. This decline in the number of nurses can be attributed to increasing patient understanding, which puts a greater strain

on nurses and leads to burnout and job dissatisfaction. Additionally, the emigration of nurses to other countries for better wages and working conditions has contributed to Poland's nurse shortage [23,24]. The study showed that the number of medical staff affects energy use efficiency. The smallest hospitals (size 1) were the least efficient regarding energy consumption per doctor and nurse. The size and scope of the hospital can impact efficiency, with larger hospitals potentially benefiting from economies of scale [18,25–27]. However, there is a point when a hospital becomes too large and may experience diseconomies of scale [8,19].

5.6. Trends and Changes in Energy Use Efficiency in Terms of Fixed Assets Value

Our research revealed that while the number of beds remained relatively stable across all hospital sizes, the value of fixed assets increased over the decade, especially for larger hospitals. This increase in fixed assets may be attributed to investments in advanced medical equipment and infrastructure to support the growing patient population. Other studies have also highlighted investments in advanced medical equipment and hospital technology to enhance patient care and improve treatment outcomes [28–30]. Research has shown that increased fixed asset value leads to improved energy efficiency. The effect of the investments made in Polish hospitals in 2010–2019 was a reduction in energy consumption per fixed asset value by hospitals. The smallest hospitals (size 1) were the least efficient in energy consumption per fixed asset value.

5.7. Implications for Energy Efficiency Strategies

One of the primary implications of this research is the necessity for tailored energy efficiency strategies that reflect hospitals' unique characteristics. Energy efficiency initiatives should be customized, considering factors such as the scale of operations, patient volume, and available resources. By recognizing the diversity among healthcare facilities, stakeholders can implement more effective and targeted energy management practices.

Key factors such as the number of medical personnel, the availability of operating rooms, and overall hospital activity levels significantly impact energy use. Therefore, energy efficiency strategies must integrate these operational considerations to optimize energy consumption effectively. This could involve training staff on energy-saving practices, optimizing scheduling for operating rooms, and implementing energy-efficient technologies in high-use areas. By aligning energy management practices with operational realities, hospitals can improve their energy efficiency while maintaining high standards of patient care.

Policymakers can use the findings to develop regulations and incentives promoting energy efficiency in healthcare facilities. Potential strategies include financial support for adopting energy-efficient technologies, mandates for regular energy audits, and establishing benchmarks for energy performance. By creating a supportive policy environment, governments can encourage hospitals to prioritize energy efficiency, ultimately reducing operational costs and improving environmental outcomes.

The research contributes to the broader discourse on sustainable healthcare practices. Improving energy efficiency in hospitals not only lowers operational costs but also aligns with environmental sustainability objectives. Hospitals can decrease their carbon footprint by reducing energy consumption and contribute to national and global sustainability goals. This dual benefit is a compelling argument for stakeholders, including hospital administrators, policymakers, and investors, to support and invest in energy efficiency initiatives.

6. Conclusions

The study on trends in energy use efficiency by hospitals in Poland from 2010 to 2019 has provided valuable insights into the complex dynamics of energy consumption patterns in healthcare facilities. The research sheds light on the factors influencing hospital energy efficiency and highlights the importance of understanding these trends for cost reduction, environmental sustainability, and overall operational effectiveness.

Several limitations should be acknowledged when evaluating the results. The research focused specifically on hospitals in Poland from 2010–2019, which may limit the generalizability of the findings to other healthcare systems or periods. Countries may have varying healthcare infrastructure, energy policies, and resource allocation practices that could impact energy consumption patterns differently. Future research endeavors may explore a variety of promising directions that extend the insights gained from the present study. One involves expanding the geographic scope of inquiry through comparative studies across diverse countries and regions. This approach would facilitate a nuanced understanding of how differing healthcare systems, energy policies, and economic conditions impact hospital energy consumption and efficiency.

While the study examined factors connected with hospital size, other variables not included in the analysis may influence hospital energy efficiency. For example, patient demographics, technological advancements, or regulatory changes could also shape energy consumption patterns. The study may not have accounted for external factors that could influence hospital energy consumption trends, such as economic conditions, energy prices, or climate variability. These external factors could interact with internal hospital dynamics to shape energy efficiency outcomes.

The study identified trends and relationships between hospital characteristics and energy consumption but did not delve deeply into the underlying mechanisms driving these patterns. Future research endeavors may explore a variety of promising directions that extend the insights gained from the present study. One involves expanding the geographic scope of inquiry through comparative studies across diverse countries and regions. This approach would facilitate a nuanced understanding of how differing healthcare systems, energy policies, and economic conditions impact hospital energy consumption and efficiency. Moreover, longitudinal studies extending beyond the year 2019 are imperative. Such research could elucidate the effects of the COVID-19 pandemic on hospital energy consumption patterns and efficiency strategies, given that the pandemic has profoundly altered healthcare operations.

Another one is the comprehensive analysis of technological innovations. Research efforts could concentrate on emerging technologies—such as smart building systems, renewable energy sources, and energy-efficient medical equipment to enhance hospital energy efficiency. Understanding how these technologies can be integrated into existing infrastructure will be essential for formulating effective energy management strategies.

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