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Organizational and Energy Efficiency Analysis of Italian Hospitals and Identification of Improving AI Solutions

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ABSTRACT

This study investigates the integration of Artificial Intelligence (AI) to enhance energy efficiency in Italian hospitals, known for their high energy consumption due to continuous operations and stringent environmental controls. Using AI strategies from the Italian Ministry of Economic Development, the research focuses on optimizing hospital energy management. Analyzing data from 996 major hospitals (2016-2023) revealed an average annual energy consumption of 1,062 kTep. Key parameters were benchmarked against European standards, and MATLAB was utilized for hourly consumption analysis to identify inefficiencies. AI optimization, leveraging historical data, aids in predictive maintenance and reduces equipment downtime. The study underscores the complexities of managing energy in aging hospital infrastructures. Despite the critical need for energy efficiency, many opportunities have been missed due to prioritization of medical technologies and urgent structural repairs. AI offers a solution by enhancing energy management through data analysis, predictive maintenance, and real-time adjustments, leading to significant energy savings and operational improvements. Challenges include high initial investment for AI technology and training, technical integration issues, and variable energy consumption patterns. Nonetheless, the benefits of AI in improving energy efficiency and sustainability in hospitals are substantial, presenting a promising avenue for future research and investment. Strategic AI incorporation can significantly boost operational performance and sustainability, benefiting hospitals across Italy and beyond.

Keywords: Artificial Intelligence, Energy Efficiency, Digital Innovation, Healthcare, Digital Health, Sustainability
JEL Classifications: I18, Q40, Q55

1. INTRODUCTION

The Italian Ministry of Economic Development published a preliminary edition of its National AI strategy for public feedback in October 2020 (AgID, 2024). This strategy, built upon policy recommendations from a proposal published in July 2020, aims to establish a framework for the sustainable development of AI technologies across various sectors in Italy. The final version of the AI strategy was presented in the first half of 2021 and is anticipated to provide a comprehensive roadmap for enhancing the development and competitiveness of AI within the country. The draft AI strategy emphasizes the importance of AI in driving innovation and efficiency in several key areas, including hospitals (Marino et al., 2024). Given the significant energy consumption of hospitals due to their need for continuous operation and stringent environmental control requirements, the potential application of AI in enhancing energy efficiency is particularly noteworthy (Mavrotas et al., 2008).

The focus on a strategic perspective regarding the conscious and responsible use of energy carriers is, unfortunately, much of recent years. Considering the mitigation of energy problems (Clarke et al., 2015), including sources of supply (Russo et al., 2021), consumption (García-Sanz-Calcedo, 2014), and distribution (Patil et al., 2021) of energy. A comprehensive perspective covering the economic system (Liu et al., 2022), technological advancements (Wen et al., 2022), and environmental conditions (Alola et al., 2019) of individual states (Yang et al., 2020) and the global context (Smol, 2022).

The recent changes to the global political and social chessboard, have meant that the cost of any energy carrier, suffered major increases and simultaneously increased energy demand by individual countries. In this sense, the only point where we can act effectively and efficiently is to improve global energy efficiency. (Economidou et al., 2022). In Italy, the hospital sector consumes about 35% of the country's total energy (OECD, 2021). Hospital facilities are complex due to their large size, the use of different technologies (Gopalakrishnan and Ganeshkumar, 2013), and the need to provide constant service 24/7 (De Oliveira et al., 2021). Energy is crucial for the functionality of hospital facilities, ensuring a safe, comfortable, and continuous service for patients, employees, and users (Szczygielski et al., 2021; Erdoğan et al., 2020).

However, implementing efficient energy strategies in hospitals is challenging due to the following:

- Outdated buildings that are difficult to maintain and modernize (Yu et al., 2022; Economidou et al., 2020)
- Change management in hospitals (Hospodkova et al., 2021; Pomare et al., 2019)
- Technology implementation bottlenecks (Jebbor et al., 2023; García-Goñi, 2008).

Following the introduction, we will review the literature, describe the methodology, present the research results, discuss the findings, and conclude with our insights. In the next section, we will highlight the literature review.

2. LITERATURE REVIEW

The recent pandemic has significantly underscored the vital role of hospital facilities, both in terms of the organization and delivery of hospital services and the extensive energy services essential to their operation (Yaps et al., 2021; Santiago et al., 2021; Liang et al., 2019; Castán Broto and Kirshner, 2020; Ejemeyovwi, 2019). In Italy, however, investments in energy efficiency have declined due to the economic crisis, as highlighted by the International Energy Agency in its recent report (IEA, 2022). Additionally, the European Union's (EU) response to the current energy crisis lacks the clarity and cohesion demonstrated during other crises, such as the SARS-CoVID-19 pandemic (Fischer et al., 2020). The implementation of support measures by the European government appears fragmented, showing a lack of strong unity among the 27 Member States.

In this challenge related to the economic and energetic crisis, hospital executives (Liang et al., 2019; Weyman-Jones, 2019; Fawcett and Killip, 2019) are navigating a dual strategic path: providing essential hospital services while managing significant energy consumption. As a result, hospital managers are undertaking a complex and demanding process to balance these critical needs.

The European Parliament is calling on the Council and the Commission to ensure its full involvement in the implementation of the Kyoto Protocol. European hospitals (Mossialos and Le Grand, 2019; Johnson et al., 2020) have demonstrated that addressing this challenge requires a combination of adequate regulatory support (Prada et al., 2020) and collaboration among various entities to identify the best projects and share innovative ideas and technologies (Grillone et al., 2020). National experiences, especially in Italy, highlight several barriers to fully realizing energy efficiency potential. These barriers include a market with long payback times for consumers and businesses, difficulty accessing investment capital, and fragmented measures leading to high transaction costs (Saint Akadiri et al., 2019; Pichler et al., 2019; Martino et al., 2019).

The role of individual EU member countries is crucial in establishing effective processes for implementing projects that balance hospital delivery with energy consumption (Marino et al., 2022). Thus, improving the energy performance of Italian hospitals is a strategic priority. Improving energy efficiency in hospitals could have an economic and financial advantage and promote a healthier environment and better conditions for patients and staff. Recent studies (Feng et al., 2020) have thoroughly examined Italian hospital facilities compared to those in Europe (Lal et al., 2021) to assess investment policies and identify effective intervention strategies. These studies include monitoring the structural context and energy consumption of Italian hospitals (Martinez et al., 2022). Thanks to the advent of disruptive technologies (Marino et al., 2023), partly accelerated, due to the pandemic wave of COVID-19, a series of technologies have emerged that have provided rapid responses, streamlining resources - both economic, financial, material and human - and working effectively and efficiently. Artificial Intelligence is being applied across various fields, ranging from the humanistic to the most material. We will investigate the ways in which AI can aid hospitals with managing energy. Specifically, the focus has been on the elements that we have emphasized can be outlined as follows:

Firstly, AI systems can analyze historical energy consumption data to identify patterns and predict future energy needs. By understanding these patterns, hospitals can adjust their energy usage to minimize waste and reduce costs. For instance, studies like those by Kalli and Jonathan (2023) have shown how effective this can be. By harnessing AI, hospitals can make data-driven decisions that optimize energy use, ensuring resources are utilized efficiently (Chintala, 2022; Marino et al., 2023a).

Secondly, AI can predict equipment failures and schedule maintenance activities proactively. This predictive maintenance approach ensures that energy-intensive equipment operates efficiently, reducing unexpected downtime and excessive energy consumption. According to Manchadi et al. (2023), such systems can significantly improve the reliability and efficiency of hospital operations, ensuring that all equipment runs smoothly, and energy is not wasted due to unforeseen breakdowns (Yang et al., 2020).

Thirdly, AI can facilitate the integration of hospitals into smart grids. By optimizing the timing of energy usage and leveraging renewable energy sources, hospitals can reduce their dependence on non-renewable energy and lower their carbon footprint. Research by Omitaomu and Niu (2021) highlights how smart grid integration, supported by AI, can transform energy management in hospitals, making it more sustainable and cost-effective (Dicuonzo et al., 2023).

Additionally, heating, ventilation, and air conditioning (HVAC) systems are significant energy consumers in hospitals. AI can optimize HVAC operations based on real-time data from occupancy sensors, weather forecasts, and indoor environmental conditions. This ensures optimal comfort with minimal energy expenditure. Satrio et al. (2019) have demonstrated that AI-driven HVAC optimization can lead to substantial energy savings while maintaining a comfortable environment for patients and staff.

Lastly, AI-powered Energy Management Systems (EMS) can provide real-time insights and control over energy usage. These systems can dynamically adjust energy settings based on operational needs, ensuring energy efficiency without compromising the quality of care. According to Zhou et al. (2021), such EMS can revolutionize how hospitals manage their energy, making operations more efficient and reducing unnecessary costs.

After analyzing the literature review, we can pose a Research Question that examines the use of AI in Italian hospitals to enhance energy efficiency and compares it to other European countries. The specific research question of our study is: "How can AI help control and manage energy efficiency within Italian hospitals?"

Addressing this research question is essential for several reasons:
- Hospitals are among the most energy-intensive public buildings due to their need for continuous operation
- The complexity of services provided
- The requirement to maintain optimal environmental conditions for patient care and medical procedures.

Understanding how AI can manage this demand effectively can lead to substantial energy savings and operational improvements. AI represents a transformative technology with the potential to revolutionize energy management. By integrating AI, hospitals can transition from traditional energy management practices to more dynamic, data-driven approaches. This shift can help in predicting energy needs, identifying inefficiencies, and optimizing energy use in real-time, thereby enhancing overall efficiency. The implementation of AI can significantly reduce energy costs, which constitute a considerable portion of hospital budgets. AI systems can analyze vast amounts of data from various sources to provide actionable insights, helping hospital administrators make informed decisions that lead to cost savings without compromising the quality of care.

Hospitals, due to their continuous operations, have a substantial carbon footprint. AI-driven energy efficiency measures can contribute to reducing this impact by optimizing the use of resources and integrating renewable energy sources, thus supporting broader environmental sustainability goals. Future research, policy development, and the establishment of optimal energy management practices across diverse industries can be developed for future implications.

By investigating how AI can be utilized to control and manage energy efficiency in Italian hospitals, this research can offer a comprehensive understanding of the benefits and challenges associated with AI implementation. It can highlight the potential of AI to serve as a powerful tool in the pursuit of energy efficiency, thus contributing to the accumulation of knowledge in this critical area.

3. METHODOLOGY

The methodology for integrating artificial intelligence (AI) to enhance energy efficiency in Italian hospitals is grounded in detailed insights gathered from hospital executives through a structured survey with semi-structured interviews, utilizing a Likert scale to standardize responses. This comprehensive approach encompasses both organizational and energy aspects to thoroughly evaluate AI's role in optimizing energy management. These interviews helped contextualize the quantitative data, offering a deeper understanding of the specific barriers and enablers of AI adoption in hospitals. The inclusion of open-ended questions in the survey allowed respondents to provide detailed descriptions of their experiences with AI implementation (see Appendix section). This qualitative data enriched the analysis by highlighting real-world examples of successful AI applications and the perceived impact on energy efficiency.

The energy analysis focused on several key areas:
- The breakdown of electricity consumption.
- The examination of consumption trends over the past 7 years using monthly hospital bills.
- Current consumption patterns.
- The distribution of electricity use.
- Air conditioning requirements.

The survey, conducted between February and December 2023, included responses from executives, 300, at 996 hospitals, ensuring a robust dataset representing various regions of Italy.

Between 2016 and 2023, data from the Ministry of Health was used to calculate the total annual average energy consumption for 996 major hospitals (Ministero della Salute, 2022), estimating an average annual energy consumption of 1,062 kTep. Additionally, the average yearly energy supply costs for Italian hospitals were determined using the same data source (ENEA - RSE, 2014, our elaboration). Key parameters for Italian hospitals were compared with the Eurostat Dataset of European Hospitals in the 27 EU Member States.

The analysis of energy bills from 996 hospitals, focusing on absorption and equivalent hours, revealed varying results. Hourly consumption data was organized and analyzed using MATLAB software to generate meaningful graphs for energy balance. Although this analysis spanned 7 years, only three graphs from 2023 are presented. AI played a crucial role in this process by optimizing energy consumption patterns, predicting energy needs, and identifying inefficiencies. AI systems analyzed historical energy consumption data to identify patterns and forecast future energy demands, enabling hospitals to adjust their energy usage to minimize waste and reduce costs (Goldstein et al., 2020).

The organizational analysis was conducted with Organizational and Energy Managers with interviews, 112, in working groups to understand the current state and challenges of energy efficiency and AI implementation in hospital facilities.

These working groups were performed by analyzing three macro sections:

- The structural characteristics of the facilities.
- The AI implementation for energy efficiency.
- Maintenance activities over the past 6 years.

The Structural Characteristics of the Facilities took in account (a) *"Location and Age of Facility"*, (b) *"Building Modifications";* the section AI Implementation for Energy Efficiency considered (a) *"Current AI Applications"* and (b) *"Challenges in AI Implementation";* last section relating to Maintenance Activities investigated on the (a) *"Maintenance Overview"* and (b) *"Energy Management"*. In addition, the working groups developed proposals related to Future Planning and Suggestions with discussions about *a) "Improvement Areas"* and "*Suggestions for Policy Makers"*.

The 996 hospital facilities (Istat, 2023) were geographically distributed: 220 in the northwest, 155 in the northeast, 214 in central Italy, 262 in the south, and 145 in the islands. Of the total executives contacted, only 5% were unavailable for the proposed organizational and energy analysis meetings. Consequently, the documentation from 996 hospital managers was evaluated for 2016-2023, considering organizational and energy aspects. The 50 unavailable facilities were distributed among the five macro areas as follows: Northwest 11, Northeast 8, Center 9, South 12, and Islands 10.

The working group were performed online with meeting of 40 min, between February and December 2023 (Marino et al., 2022a). The data collected, which highlights 99% of the total, was processed for organizational analysis and created a first dataset on process mapping, a valuable tool for organizational analysis and reviewing the organizational system (Marino et al., 2021; Marino et al., 2022b). The mapped processes were both physical and informational, enabling the identification of operational unit activities linked also AI facilitated predictive maintenance, ensuring energy-intensive equipment operates efficiently, reducing unexpected downtime and excessive energy consumption (Lee et al., 2018).

The combined organizational and energy analysis, linked to AI implementation, is crucial in the management system in hospital organizations, classified as energivory organizations. This approach requires hospital management to undertake a comprehensive analysis and evaluation of the site. Combining quantitative and qualitative methods provides a holistic view of the issue. While quantitative data reveals patterns and trends, qualitative insights explain the underlying reasons for these patterns, offering a richer understanding of the complexities involved. The results significantly influence decisions regarding the organizational structure and the characteristics of the EMS within the hospital. Triangulating data from multiple sources (energy consumption records, survey responses, and interviews) enhances the validity and reliability of the findings. This methodological rigor ensures that the conclusions drawn are well-supported and credible. The assessment of the results, as presented in the next section, is enriched by the interplay between the organizational and energy analyses. AI-powered insights play a vital role in driving these improvements, leading to more sustainable and efficient hospital operations.

4. RESULTS

The average total primary energy consumption for Italian health facilities from 2016 to 2023 was 112.528 kTep, divided into 56.122 kTep of electricity and 56.406 kTep of thermal energy. Analysis of energy bills from 996 hospitals revealed significant insights into energy consumption and costs. Specifically:

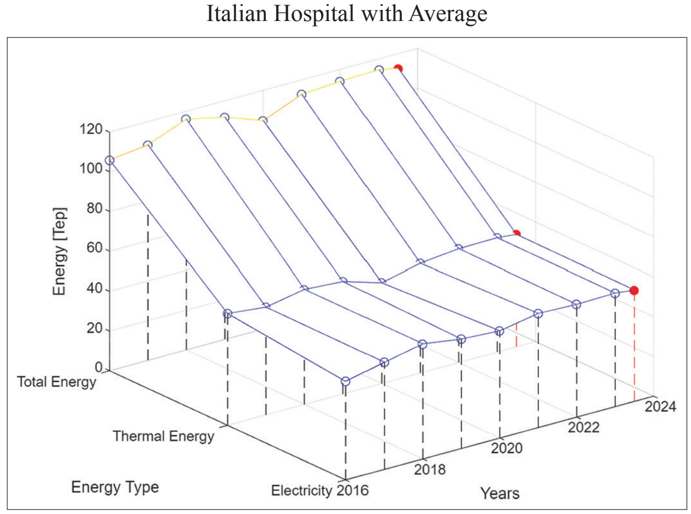
- Energy consumption patterns: Hospitals exhibited a consistent pattern of energy use, with peak consumption occurring during the hottest months due to increased air conditioning demands. Notably, the highest energy measurement was 1165.5 kWh on August 4 at 15:00, with minimum consumption never falling below 360 kWh.
- Cost trends: Energy costs for hospitals have increased significantly over the years, exacerbated by external factors such as the pandemic and geopolitical events affecting energy supply. A comparison between energy consumption and costs highlighted a widening gap in recent years.

Figures 1 and 2 illustrate these trends, showing the average energy consumption and rising costs over the period.

In recent years, the gap between energy consumption and associated costs has widened significantly, driven by recent events such as the pandemic and wars affecting energy supply sources. By evaluating parameters across various hospitals in the region, we can identify the widespread difficulties faced by the Italian Health System in managing energy supply and distribution within hospital facilities. The following analysis compares key energy consumption and cost parameters for Italian hospitals with those in the 27 European countries. The examined parameters include:

- Energy consumption per gross surface area (Tep/m²)
- Thermal energy usage relative to square meters and degree days (kWh/m² DD)

Figure 1: Source Ministero della Salute - Energy consumption in Italian Hospital with Average



Source: Own elaboration

- Electricity consumption per square meter (kWh/m²)
- Unit cost of electricity supply (€/kWh)
- Unit cost of methane supply (€/Sm³)
- Unit cost of heat supply from district heating (€/MWh).

Summary of Comparative Analysis are show in Figure 3, and to create a graph that highlights all the numerical values despite differing units of measure, we can use a normalized scale. This approach converts all values into a comparable range, such as 0-1, allowing for better visual comparison:

This comparative analysis illustrates that while Italian hospitals are efficient in energy consumption per surface area and thermal energy use, they face higher costs in electricity and district heating supplies. Addressing these cost disparities could lead to significant financial savings and further improvements in energy efficiency.

Based on the survey responses, the structural characteristics of the hospitals significantly impact energy efficiency:

- Location and age: 32% of energy consumption was concentrated in hospitals located in Central and Southern Italy and the islands. Many hospitals (87%) were over 60 years old, with significant expansions occurring in the 1970s and 1990s.

Figure 2: Source Ministero della Salute - Energy costs of Italian Hospitals with Average Highlighted

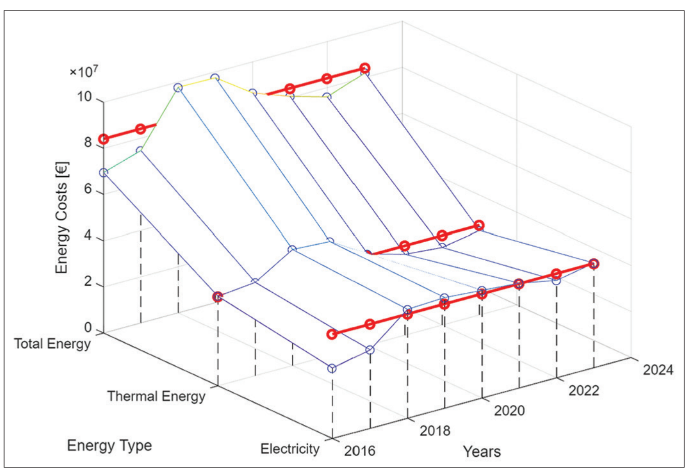


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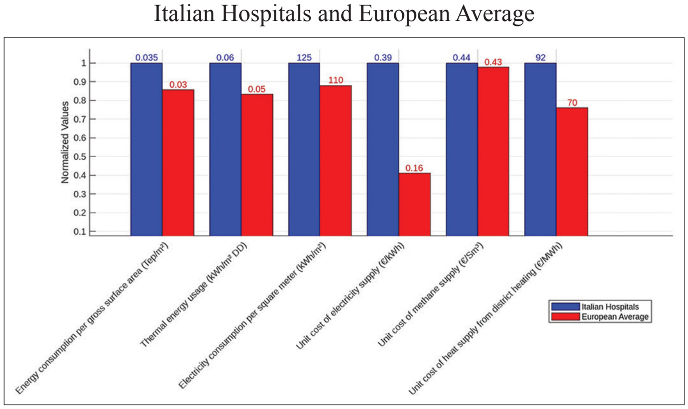
Figure 3: Normalized comparison of energy parameters between Italian Hospitals and European Average



Source: Own elaboration

- Building modifications: The survey indicated that 65% of buildings had undergone expansions in the 1970s, and 70% saw further expansions in the 1990s. These modifications often did not prioritize energy efficiency, contributing to the current challenges.

Energy managers believe that the facility management challenges associated with the age of hospital buildings restrict the use of AI to specific areas, such as operating room management, where AI application projects have been reported. The elaboration of the results of the organizational analysis related to AI implementation highlights the following critical points that hinder improving energy efficiency through AI:

- The building surface to be used for the shelter
- The surface of the laboratory activities
- The management of the facilities.

In the ’70s 65% of the buildings were enlarged with other pavilions and in the early 90s, other pavilions were built in 70% of the buildings studied. In the case of 320 garrisons, there are enlargement interventions that belong to both the 1970s and 1990s. The management of the plants to the location, expansion and installation of new plants, the various thermal plants, refrigeration units and substations of district heating, is varied within the structure, depending also on the different use of the departments over the years. In this field, plant engineering, it emerges from the analysis that in the decision-making process there is an overlap of functions for the same decision of 7.5%, other data, in 65% of cases, the absence of structure dedicated to energy management, even if the figure of the energy manager is present in all the hospital principals. The age of buildings, in 87% of cases exceeds 60 years and maintenance over the last 6 years is around 16%. The energy analysis concerned: the characteristics of the electrical system defined the distribution of electricity consumption within the buildings, dividing the energy absorbed by the various types of users. With this method, it will be easy to compare with other average values available in the literature, with the possibility of finding criticalities in the system. In Figure 3 we report the comparison between consumption and expenditure in the 6 years considered by the 996 hospitals analyzed.

Starting from Figure 1 it can be seen that consumption remains similar, even if compared with expenditure in the six reference years, there is a significant additional cost, as shown in Figure 4, therefore it is possible to suppose a monthly consumption calculated as average in this period but, considering in particular, the analysis of bills, Through the analysis of the distributor measurements and then concludes with the analysis of absorption and equivalent hours shows that energy expenditure in hospitals has increased significantly. After examining the bills of the last 6 years, to improve the comparison and analysis, electricity suppliers were asked for the hourly curves of consumption. This analysis was carried out over 6 years, but only three graphs are reported for the year 2023. It was done by varying the colour bar of the graphs obtained, respectively on full-scale, minimum values (between 0 kWh and 650 kWh) and maximum values (between 650 kWh and the maximum value found, 1165.5 kWh). From the Figures you can make some considerations:

a. The maximum value of energy measured is 1165.5 kWh measured at 15:00 on August 4, while lowering the scale to a minimum, the energy value never falls below 360 kWh.
b. The highest consumptions are measured in conjunction with the periods when there is air conditioning, in the hottest hours of the day.
c. In the night range between 23:00 and 6:00, consumption is much lower, and during the day you can see how, from 16:00/17:00 onwards consumption tends to decrease.
d. The difference between public and working days is clear, almost halving. This shows that electricity consumption is particularly dependent on work activities such as offices and clinics.
e. Almost abnormal behaviour is evident in the first half of January.

The cooling requirement has been calculated in two different ways: Top-down and bottom-up. Top-down, we studied the trend of electricity consumption compared to the average external temperature; the consumption remains almost constant for temperatures below 14-15, while, for higher temperatures, the trend is increasing. This increase is certainly attributable to the conditioning load, which increases with the increase in the external temperature.

It therefore also calculated the standard electricity requirement as the average value of consumption recorded for temperatures <15 μc and subtracted this proportion to days when the temperature is higher.

By carrying out this operation for 6 years the average need for conditioning was obtained at 14.1%.

Bottom-up. From the data of the refrigeration units and of the facilities' split systems, consumption was calculated on an annual basis assuming methods and hours of operation. As in talks with the hospital's technical staff, it was found that the refrigeration units were on average from mid-April to mid-October, in conjunction with the shutdown of the heating systems (except for climatic conditions). The assumption used for the calculation is an average of 12/day of operation for all days of the period (180 days), except for groups currently undergoing restructuring, not yet operational. The power absorbed is assumed to be 30%, estimated from the characteristic absorption curve of the groups, initial absorption, followed by an exponential decrease. The annual consumption is calculated as:

$$\sum_{n=1}^{GF} Pot_{el,n} * 30\% * h_{funz} \left[\frac{kWh}{year} \right]$$

Equation 1 - Formula to calculate annual consumption of energy.

Results are shown in Figure 5.

In the same way, the calculation of the split systems presents in hospital facilities, the average electricity consumption was calculated, assuming 8 h of operation for portable systems and 6 h/day of operation for all the others, for only 122 days of the summer period; the power absorbed was calculated by multiplying by the electrical absorption efficiency η = 97% the electrical power shown on the data sheets of the different models. Annual consumption is shown in Figures 6 and 7.

The joint analysis of the 996 Italian hospitals, highlights, the criticality and potential that are reported in the following paragraph.

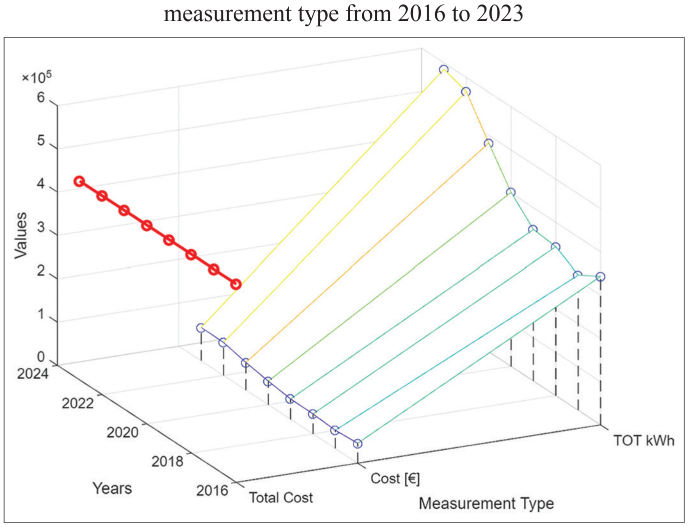
5. DISCUSSION

The results show that the energy efficiency of Italian hospitals is lower than the European average, highlighting structural weaknesses. However, energy efficiency is also a strategic lever for the revitalization of the Italian hospital sector. Hospital construction is heavily involved in these goals, being one of the most energy-intensive sectors due to its multiple functions and the need for 24-h operational services 365 days a year, ensuring:

- Continuity in medical services
- High thermal comfort (in winter and summer) for patients and staff
- Healthy working and hospitalization environments.

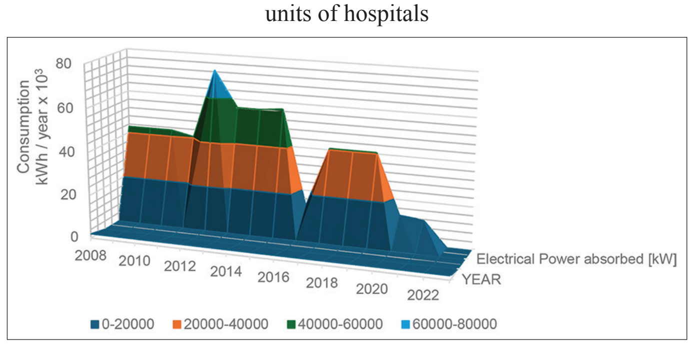
In Italy, research shows that hospitals' assets are often unsuitable for current uses. The buildings were constructed when regulatory constraints were not stringent, and efficiency and energy savings

Figure 4: Comparison of consumption and expenditure electricity measurement type from 2016 to 2023



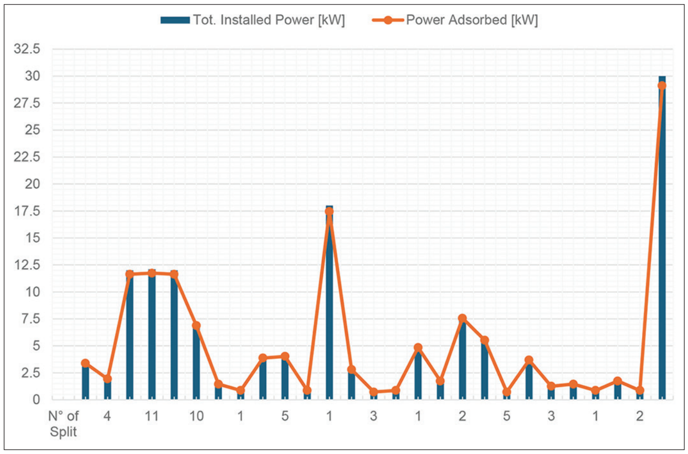
Source: Own elaboration

Figure 5: Annual consumption calculated for the refrigeration units of hospitals



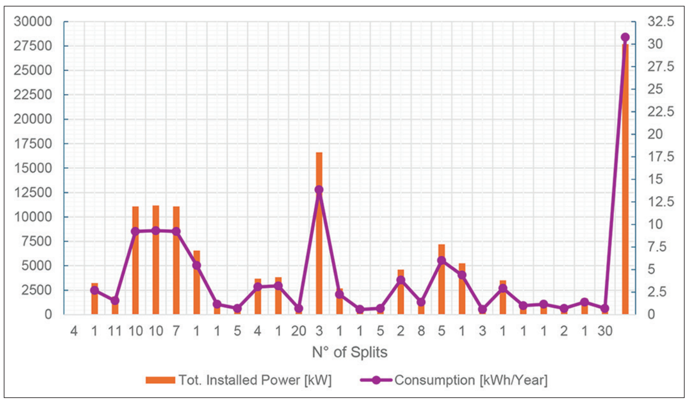
Source: Own elaboration

Figure 6: Installed power versus adsorbed



Source: Own elaboration

Figure 7: Installed power versus consumption



Source: Own elaboration

were not prioritized. Hospital structures should adapt to the continuous evolution of technologies and service organizations but instead fall into obsolescence. Over the years, there have been insufficient technological innovations to address the increasing use of facilities and adaptation to new regulations (Marino et al., 2021a). This issue is evident in an economic context marked by the energy crisis (Vaziri et al., 2020) and the consequent increase in costs. Additionally, there has been a lack of modernization efforts for obsolete hospital complexes, making optimization of energy consumption unlikely and resulting in only partial improvements that do not significantly affect overall consumption. Approximately one-third of the energy consumed in Italy is linked to the health sector, with hospital consumption averaging 3 times higher than the civil residential sector in similar climatic conditions (ENEA, 2022). These buildings, therefore, have a substantial margin for energy savings and economic benefits that can be achieved through prudent management of energy flows and energy efficiency interventions on building-plant systems.

In the total budget of the National Health System, energy supply (thermal and electricity) corresponds to 5% and 2.2% of the budget share, equating to 27% of total expenditure (ENEA 2022a), a significant figure for Italy. By saving a portion of this expenditure through the rationalization of consumption, economic resources can be freed up for the entire public sector. Aside from the construction of new hospital buildings, some actions are possible in the short term. The first action to reduce expenditure is the reorganization of energy efficiency management, eliminating the duplication of decision-making and operations present in the management process. The second action is to establish energy efficiency units and appoint energy managers.

The high potential for energy and economic savings in the health sector is closely tied to the role of the energy manager (Vaziri et al., 2020). This figure, supported by monitoring systems and empirical observation of plants, is essential to determine the energy performance of each hospital, identify and characterize cost centers, and correctly define energy efficiency interventions. A third short-term action involves mandating this structure to carry out priority technological investments, aimed at reducing energy consumption and implementing technologies for the exploitation of renewable energy sources. These three actions can significantly improve the energy efficiency of Italian hospitals.

In this context, artificial intelligence (AI) can play a crucial role. AI algorithms can support decision-making in energy analysis and the implementation of energy-saving strategies (Bellini et al., 2020). By analyzing data collected by monitoring systems, AI can identify inefficient energy consumption patterns and suggest targeted interventions to improve efficiency. Additionally, AI can help optimize the management of energy resources by forecasting energy demand and regulating resource use in real-time, thereby reducing costs and improving the energy sustainability of hospitals.

These AI potentialities, if reported to our 32% of energy managers interviewed, that are not representative at the national level, highlight the following results.

The implementation of AI in hospitals varied, with several barriers identified:

- Current applications: AI was primarily used in specific areas like operating room management, HVAC systems, and energy usage monitoring. However, the scope of AI application remained limited due to infrastructural constraints.
- Challenges: Key challenges included the age of buildings, lack of dedicated facilities for AI integration, and overlapping decision-making processes. These issues were rated as significant impediments (average Likert scale rating of 4.3).

5.1. Maintenance Activities

Maintenance practices also influenced energy efficiency:

- Frequency and budget allocation: Maintenance activities were generally performed quarterly or as needed, with only 16% of the budget allocated to energy efficiency projects.
- Effectiveness: The effectiveness of maintenance activities in improving energy efficiency received mixed ratings, with an average Likert scale rating of 3.2.

5.2. Cooling Requirements and Energy Management

The cooling requirements were analyzed using both top-down and bottom-up approaches:

- Top-down analysis: This method showed a consistent increase in energy consumption with rising external temperatures. The

average need for cooling was calculated at 14.1% of total consumption.
- Bottom-up analysis: Using data from refrigeration units and split systems, the annual energy consumption was calculated. Figures 4-6 provide detailed comparisons of installed power versus absorbed power and consumption.

5.3. Key Findings and Implications

The combined organizational and energy analyses underscore several critical points:
- Energy management challenges: The absence of dedicated energy management structures in 65% of hospitals, despite the presence of energy managers, was a significant barrier.
- Potential for AI: While AI offers substantial potential for improving energy efficiency, its implementation is hampered by structural and organizational challenges.
- Policy recommendations: Policymakers should prioritize funding for energy-efficient renovations and AI integration, especially in older hospital buildings.

Moreover, the following questions are shown:

The problem of penetration of AI within the hospital is composed of a range of bottlenecks, which can be summarized as follows:
1. Obsolescence of the buildings (year of construction at the latest in 1970 and have been the subject of reorganization over the years, which has distorted the functionality, creating objective problems in logistical and organizational terms).
2. Delay in technological investments and the adaptation of the same structures about the changing needs for energy efficiency.
3. The introduction of AI for energy efficiency management is very fragmented and concerns individual business units and not the system. For example, the Energy Managers we interviewed, using the three macro-areas reported in the methodology, show in that of facility management that AI is most used in some departments, but for example, is completely absent in the operating theatres.

From 2016 to 2023, Italian hospitals consumed an average of 112.528 kTep of primary energy per year, divided into 56.122 kTep of electricity and 56.406 kTep of thermal energy. This energy consumption led to significant costs, with an average annual expenditure of about 82.2 million euros. Using IoT sensors (Internet of Things), real-time data can be collected from various energy systems and hospital infrastructure, we can use this data, such as electricity and heat consumption, energy costs, external and internal temperatures, operating times of various systems (heating, cooling, lighting), and occupancy of different hospital areas, to reduce the total amount of energy cost about 7%, concerning the total amount of the investments (MIMIT, page 71, 2019).

Based on these forecasts, AI can suggest and implement real-time regulation of energy systems. During the summer months, when energy consumption increases due to cooling, AI can dynamically adjust air conditioning system settings based on outside temperature predictions and space occupancy. By dynamically adjusting settings based on real-time data, AI can optimize energy use, particularly in high-demand periods such as summer when cooling requirements surge. This intelligent regulation ensures that energy consumption aligns with external temperature predictions and occupancy levels, minimizing waste. The interplay between organizational and energy analyses, supported by AI, provides valuable insights and actionable strategies for optimizing hospital operations (Kyriakarakos and Dounis, 2020).

However, implementing AI in hospitals is complex, involving structural, operational, technological, financial, and regulatory challenges. Compliance with health and safety regulations is critical to ensure that AI systems do not interfere with medical equipment or patient care protocols. Additionally, privacy and security concerns must be addressed, as AI systems handling sensitive patient data must comply with stringent data protection regulations.

Effective energy management in hospitals requires a strategic approach that includes upgrading infrastructure, establishing clear energy management structures, ensuring data compatibility, and addressing financial and regulatory concerns. Currently, many hospitals lack a dedicated energy management structure, leading to fragmented and less effective maintenance practices (Mischos et al., 2023).

AI can play a pivotal role in overcoming these challenges through comprehensive energy management platforms. These platforms offer centralized dashboards for real-time monitoring and control of energy systems, integration with existing systems via IoT devices, and advanced data aggregation and analysis. This unified view enables immediate detection and response to inefficiencies or system failures, supporting informed, data-driven decision-making.

AI-driven predictive maintenance modules can also revolutionize hospital operations by predicting equipment failures before they occur, thus transitioning from reactive to preventive maintenance. This approach minimizes downtime, reduces maintenance costs, and extends the lifespan of critical infrastructure. Implementing AI-based solutions should begin with a pilot program in a selected hospital facility, followed by a phased rollout to other facilities. Continuous performance monitoring and iterative improvements are essential, as is stakeholder engagement to ensure effective use and management of the AI systems.

6. CONCLUSION

The energy management of hospital facilities is inherently complex due to the substantial energy required to support both health and non-health activities that occur daily across the 996 hospitals analyzed. Operating continuously, 24 h a day, 365 days a year, hospitals exhibit diverse energy consumption profiles. These can be broadly categorized into energy for the comfort and well-being of patients and staff, and energy directly related to medical functions supported by equipment for treatment and diagnosis.

Despite the critical need for energy efficiency, many opportunities for improvements have been overlooked, resulting in outdated and inefficient energy profiles. Traditionally, funding has been directed towards the core functions of hospitals, such as investments in medical technologies for diagnosis and treatment, or urgent structural interventions for safety compliance, rather than comprehensive energy efficiency projects.

To address these inefficiencies, a significant shift in management strategy is required, focusing on securing financial resources for substantial energy efficiency improvements. This shift must encompass both organizational and energy management reforms. In this context, the integration of artificial intelligence (AI) offers a promising solution. AI algorithms can enhance decision-making processes in energy analysis and the implementation of energy-saving strategies. By analyzing data collected through monitoring systems, AI can identify inefficient energy consumption patterns and recommend targeted interventions to enhance efficiency. Furthermore, AI can optimize the management of energy resources by forecasting energy demand and adjusting resource use in real time, leading to cost reductions and improved energy sustainability in hospitals.

Survey results corroborate these findings, highlighting that AI implementation in energy management, though currently limited to specific areas like operating room management and HVAC systems, holds significant potential for broader application. Challenges such as the age of hospital buildings, lack of dedicated facilities, and overlapping decision-making processes were identified as significant barriers. Addressing these challenges can unlock substantial energy savings and increase operational efficiency.

The survey also revealed that maintenance activities, while crucial, often lack a focused approach towards energy efficiency, with only a small fraction of the maintenance budget allocated to this area. Effective maintenance practices, guided by AI insights, can further enhance energy efficiency by ensuring that energy-intensive equipment operates optimally, reducing unexpected downtime and excessive energy consumption.

In conclusion, the strategic incorporation of AI in hospital energy management not only addresses current inefficiencies but also paves the way for a more sustainable and cost-effective hospital system. The combination of data-driven insights and real-time optimization holds the key to unlocking significant energy savings and enhancing the operational performance of hospitals across Italy and beyond. Adopting AI-driven strategies represents an innovative and effective approach to tackling the energy challenges faced by modern hospital facilities, ensuring that they remain sustainable and efficient in the long term.

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APPENDIX

Survey with Semi-Structured Interview Using Likert Scale Methodology

INTRODUCTION

This survey aims to gather detailed insights from hospital executives on energy efficiency and AI implementation in their facilities. The semi-structured interview will include both open-ended questions and Likert scale items to quantify responses.

Section 1: Structural Characteristics of the Facilities

1. Location and age of facility:
   - In which region is your hospital located?
     - Northern Italy
     - Central Italy
     - Southern Italy
     - Islands
   - What is the approximate age of your hospital building?
     - <20 years
     - 20-40 years
     - 40-60 years
     - Over 60 years

2. Building modifications:
   - Has your facility undergone any expansions or major renovations?
     - Yes
     - No
   - If yes, in which decades were the expansions or renovations done? (Select all that apply)
     - 1970s
     - 1980s
     - 1990s
     - 2000s
     - 2010s
     - 2020s
   - How would you rate the impact of these modifications on energy efficiency? (Likert Scale: 1-5, where 1 is very low and 5 is very high)

Section 2: AI Implementation for Energy Efficiency

3. Current AI applications:
   - Are there any AI applications currently in use for energy management in your hospital?
     - Yes
     - No
   - If yes, which areas are AI technologies being applied? (Select all that apply)
     - Operating Room Management
     - HVAC Systems
     - Lighting Systems
     - Energy Usage Monitoring
     - Other (please specify): ___________

4. Challenges in AI implementation:
   - What are the main challenges you face in implementing AI for energy efficiency? (Select all that apply)
     - Age of the building
     - Lack of dedicated facilities
     - Surface area management for different activities
     - Overlapping functions in decision-making
     - Other (please specify): ___________
   - How significant are these challenges to your hospital? (Likert Scale: 1-5, where 1 is not significant and 5 is very significant)

5. Open-ended question:
    - Can you describe any specific instances where AI implementation has improved energy efficiency in your hospital?

Section 3: Maintenance Activities

6. Maintenance overview:
    - How often are maintenance activities performed in your facility?
        - Monthly
        - Quarterly
        - Annually
        - As needed
    - What percentage of the building maintenance budget is allocated to energy efficiency projects?
        - <10%
        - 10-20%
        - 20-30%
        - More than 30%

7. Energy management:
    - Is there a dedicated energy management structure in place at your hospital?
        - Yes
        - No
    - If no, is there an energy manager assigned?
        - Yes
        - No

8. Impact of maintenance on energy efficiency:
    - How would you rate the effectiveness of maintenance activities on improving energy efficiency? (Likert Scale: 1-5, where 1 is very ineffective and 5 is very effective)

9. Open-ended question:
    - Can you provide examples of how maintenance activities have impacted energy efficiency in your hospital?

Section 4: Future Planning and Suggestions

10. Improvement areas:
    - In your opinion, what are the key areas where energy efficiency can be improved in your facility? (Select all that apply)
        - Updating HVAC systems
        - Better insulation
        - Implementing AI-based solutions
        - Regular maintenance and checks
        - Employee training on energy conservation
        - Other (please specify): ___________

11. Suggestions for policy makers:
    - What suggestions do you have for policymakers to support hospitals in improving energy efficiency through AI?

Open-ended Questions

12. General Feedback:
    - Do you have any additional comments or suggestions regarding energy efficiency and AI implementation in hospital facilities?

Likert scale summary: For the Likert scale questions, please use the following scale: 1 - Strongly Disagree 2 - Disagree 3 - Neutral 4 - Agree 5 - Strongly Agree.