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Review

Shaping the Future of Healthcare: Integrating Ecology and Digital Innovation

Domenico Bevere * and Nicola Faccilongo

Department of Economics, University of Foggia, 71121 Foggia, Italy; nicola.faccilongo@unifg.it
* Correspondence: domenico.bevere@unifg.it

Abstract: The concept of sustainable healthcare is the subject of an increasingly intense, captivating, forward-looking, yet sometimes still overly theoretical debate. The aim of this contribution is to analyze the current scenarios of ecological and digital transition in the healthcare sector, considering its high energy consumption. In particular, we adopt a holistic and convergent vision of the energy mix and its infrastructure, moving beyond the ideological dichotomy of energy sources. Renewable sources, digital innovations, and the circular economy are seen as playing key roles in the future of the energy sector. In this research, a mixed methodology was employed, combining a questionnaire consisting of 31 questions with semi-structured interviews conducted with the top management of a major player in the private healthcare sector located in southern Italy in 2023. Consequently, we examine the main macro-guidelines of technological development, encompassing enabling technologies, new business models, roles, and professional skills. Based on the analyses conducted, we provide some insights to inform governmental policies and industrial strategies in the near future. Digitalization represents an opportunity to enhance the efficiency of healthcare services, reducing waste and ensuring quality. For instance, digital healthcare solutions enable personalized care on a global scale and offer decision support systems that can enhance overall healthcare performance. However, to maximize the benefits of digital transformation, it is essential to integrate new technologies effectively and sustainably into the existing healthcare ecosystem. A promising example is telemedicine, which can help reduce carbon emissions by decreasing healthcare workers' travel.

Keywords: sustainability; healthcare; innovation; disruptive technology

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1. Introduction

In response to growing environmental concerns, the United Nations established the Sustainable Development Goals (SDGs) in 2015 to provide a framework for implementing environmentally oriented policies and monitoring progress [1]. With Agenda 2030 and its 17 SDGs, there has been a paradigm shift from goals for developing countries to sustainable development goals for all nations worldwide. This represents a milestone, as all 193 United Nations member states have agreed for the first time on a set of sustainable development goals to inform their policies.

The healthcare sector plays a significant role in carbon emissions and waste. Non-biological waste, including plastic, paper, and electronic waste, constitutes a significant portion of the waste. It is estimated that plastic production and incineration have generated 850 million tons of greenhouse gases, with the possibility of this number increasing to 2.8 billion tons by 2050 [2]. About 15% of healthcare waste is considered infectious, radioactive, or toxic. In developed countries, each hospital produces an average of 0.5 kg of hazardous waste per day, while in developing countries, this figure drops to 0.2 kg [3]. The healthcare sector is recognized as a major contributor to the climate crisis, identified as the greatest threat to 21st-century health [4]. Recent studies indicate that the healthcare sector contributes from 4% to 5% to total greenhouse gas emissions, with a steadily increasing trend. The impact varies significantly between countries, with Italy contributing 4% and the

United States 7.6% [5]. Overall, each country's healthcare sector releases greenhouse gases directly and indirectly through healthcare delivery and the purchase of products, services, and technologies with a high environmental impact. The main sources of emissions in the healthcare sector include direct emissions from healthcare facilities and associated vehicles, indirect emissions from electricity and steam production, and emissions related to the supply chain through the production, transportation, and disposal of goods and services.

Numerous initiatives and pieces of legislation have been adopted to promote the sustainability agenda, such as the European Green Deal, which aims to make Europe the first continent with zero net climate impact by 2050, and the REACH legislation on the registration, evaluation, authorization, and restriction of chemicals, which has avoided costs resulting from negative health and environmental effects estimated at EUR 100 billion over 25–30 years [6]. Additionally, the European Commission has initiated a project to transform approximately 15,000 European hospitals into zero carbon emission institutions using renewable energy systems [6].

In the healthcare context, the use of chemicals is widespread but also represents a significant threat to the environment and human health [7]. These substances, used both in the production of devices and products and in disinfection and medical treatment procedures, interfere with delicate natural systems and life cycles, posing serious risks. Waste management is another critical challenge for healthcare facilities, with significant economic and environmental implications. The disposal of hazardous or infectious waste is particularly complex, and the widespread use of disposable products, often necessary to meet infection control standards, further exacerbates the situation. Water resources are another area of concern. While some healthcare treatments require significant amounts of water, the discharge of pollutants through wastewater poses a serious environmental and health problem, especially considering the presence of pharmaceuticals in water. Finally, energy is a critical factor. Healthcare facilities consume considerable amounts of energy, especially when considering the entire supply chain. The healthcare sector significantly contributes to greenhouse gas emissions, primarily through the distribution of energy used. In addition, healthcare services have a significant social and economic impact on the Italian labor market. According to OECD data, in 2021, the healthcare personnel employed by the National Health Service (SSN) amounted to 617,293 employees. SSN employees represented 30.6% of the total employment in the social and healthcare sectors in 2021.

The healthcare sector plays a unique role as a connection point between national innovation systems, responsible for driving technological progress to support economic growth and prosperity, and social assistance systems, aimed at improving the quality of life of the population and reducing social disparities. This peculiarity gives relevance to scientific research in the field of healthcare [8], as the advancements generated in the context of healthcare innovation have a tangible impact on the economy and society as a whole [9]. In every organization, the presence of effective leadership is necessary to guide the group towards achieving results, especially in the face of current global challenges. In this regard, leadership, understood as the ability to influence and inspire others to pursue a common vision, is essential for the success of business initiatives. In the context of environmental sustainability, "green leadership" plays a crucial role in promoting the vision of an ecologically sustainable future. This leadership focuses on creating a sustainability-oriented corporate culture, involving employees in adopting ecological practices and pursuing long-term environmental goals. This includes establishing partnerships with external stakeholders and implementing environmental education programs aimed at raising awareness among staff and promoting a positive ecological footprint.

In the healthcare context, leadership is essential to ensuring optimal resource management and the success of healthcare operations [10]. Healthcare management must understand the needs of employees and create a work environment that fosters clinical excellence and environmental sustainability. This involves not only managing energy resources but also promoting an organizational culture focused on social and environmental responsibility. Effective green leadership, accompanied by various innovations, can encour-

age behavioral changes in all hospital users, promoting the creation of a comfortable and safe facility capable of maintaining the balance of the environmental ecosystem [11]. The recent pandemic has highlighted the importance of corporate social responsibility (CSR) strategies, a term coined in the 1950s and expanded in the 1960s. At the heart of the debate was whether companies should go beyond the interests of their shareholders to support societal needs or if such efforts fell outside the responsibilities of businesses. In response to the crisis, many companies have chosen to use the SDGs as a guide to strike a balance between their interests and societal well-being. Specifically, the 17 Sustainable Development Goals (SDGs) provide an ideal framework for CSR plans, as they address current and future global challenges [12]. Indeed, demographic decline, unequal distribution of wealth, ecological issues, and unfair access to resources are just some of the challenges we face. Consequently, the SDGs have become an area of increasing interest, with researchers, institutions, and governments increasingly focusing their attention on the importance of sustainability and social responsibility. In the healthcare sector, ethical principles and the implementation of CSR positively influence innovations in their systems, improve the quality of employees' work, and make them more environmentally friendly, especially when combined with ethical leadership within the company [13]. Additionally, CSR represents a risk management strategy as it protects the company's reputation, keeps stakeholders satisfied, and builds trust among patients [14]. While only the third of the Sustainable Development Goals (SDGs), aimed at ensuring healthy lives and promoting well-being for all ages, is directly relevant to the healthcare sector, it is crucial to acknowledge the indirect relevance of other SDGs to this field. For instance, themes such as hunger, gender equality, access to clean water and sanitation services, clean and accessible energy, promotion of sustainable cities and communities, action to combat climate change, and promotion of peace, justice, and strong institutions encompass a total of 43 indicators that indirectly impact the healthcare sector [15]. Although digital transformation offers potential environmental benefits, it also presents possible ecological risks [7]. This review explores the ecological and digital transition in the healthcare sector, proposing an integrated approach to energy and providing insights for future policies and industrial strategies. It also highlights the potential of digitalization in enhancing efficiency and promoting environmental sustainability in the healthcare sector.

The research objectives were as follows:

- Identify the top management's perception of issues related to environmental sustainability, the use of renewable energy sources, technologies, and intelligent systems, as well as the impact of energy costs on corporate budgets.
- Identify strategic objectives connected to digital and environmental transition.
- Investigate the importance of employee involvement in promoting sustainable practices and adopting solutions for energy efficiency.

2. Theoretical Background

The interplay of current events, such as climate change, the COVID-19 pandemic, and the energy crisis stemming from the Russian invasion of Ukraine, has ushered in a new era in energy resource management, particularly within the healthcare sector. Energy-reliant nations, like those in the EU, are expediting their energy transition efforts and investing in research and innovation to foster sustainable energy technologies [16]. Concurrently, they are implementing energy-conservation policies and enhancing building efficiency through renovation initiatives [17]. Given the aging infrastructure, energy retrofitting has become a global imperative, given that the building sector is a significant contributor to energy consumption and greenhouse gas emissions [18,19]. Recent studies have underscored the absence of a one-size-fits-all solution for building energy retrofitting, prompting the adoption of diverse policies and regulations that evolve continually based on fresh research insights [20]. Notably, energy retrofitting of hospitals, given their energy intensity, is pivotal not only for energy savings but also for enhancing national healthcare services and reducing environmental impact [21,22]. Addressing healthcare needs carries a detrimental

environmental footprint as the healthcare sector stands as one of the principal contributors to environmental pollution. For instance, in the UK, the National Health Service (NHS) emits an annual 18 million tons of CO_2, constituting nearly a quarter of total emissions from the public sector [23]. In the US, total gas emissions from healthcare organizations increased by 6% from 2010 to 2018 [5,24]. Overall, the healthcare sector, encompassing pharmaceutical production, contributes to 4.4% of global greenhouse gas emissions. Moreover, the global market for healthcare waste management is anticipated to rise from USD 6.8 billion in 2020 to USD 9 billion by 2025 [25]. The recent pandemic has further exacerbated this negative impact due to heightened usage of personal protective equipment, diagnostic tools, and vaccines. According to Fadda [26], green healthcare systems are anchored on ten crucial components, including leadership, substitution of harmful chemicals, waste management, energy efficiency, water conservation, transportation strategies, food waste reduction, pharmaceutical pollution reduction, green building utilization, and sustainable procurement practices. Despite numerous studies focusing on hospital environmental performance, it has been emphasized that current approaches are suboptimal, and public policies vary significantly from one region to another, with substantial financial and institutional barriers impeding the execution of substantial energy efficiency projects [27].

Hospitals are increasingly confronted with the sustainability challenge, striving to enhance the breadth of innovations to safeguard ecosystem integrity and optimize natural resource utilization. Carbonari et al. [28], in a study on energy retrofitting of various Italian hospitals, highlighted how energy savings, improved equipment energy efficiency, and renewable energy utilization led to an overall reduction in energy consumption in healthcare facilities ranging from 33 to 79%, with an estimated payback period for energy investments ranging from 9 to 20 years. Various energy efficiency measures based on existing and new technological systems have been proposed as strategies to alleviate high energy demand and energy costs in hospitals [29].

Several studies across different countries have explored the potential role and contribution of hospitals' macroscopic indices to total energy requirements. These countries include Spain [30], Germany [31], China [32], and the USA [33]. In general, the total energy requirement depends on factors such as building size, bed count, employee count, climate and geographic location, in-patient and out-patient numbers, ICU count, and the number of surgeries and tests performed, among others.

2.1. Rethinking Organizational Management: Embracing Sustainability and Innovation

Academic research on sustainability has emerged as a relatively nascent field, gaining prominence primarily over the last two decades. It has become a central focus in organizational discourse, compelling businesses to re-evaluate their contributions to sustainable development. Scholars stress the importance of exploring how organizations can innovate to advance sustainability [34–41]. This entails integrating the economic, environmental, and social dimensions of sustainability into organizational management frameworks, extending this approach to products, processes, services, technologies, structures, and business models. The objective is to create value, ensure organizational longevity, and address stakeholder needs [42].

Drawing from Hansen et al.'s insights [43], challenges related to sustainability not only drive innovation within businesses but also present opportunities for achieving lasting competitive advantages. This observation underscores the profound link between the adoption of sustainable business practices and the creation of long-term value. The intersection of innovation and sustainability has garnered significant attention from academics and entrepreneurs alike, sparking exploration of novel approaches to translate environmental challenges into substantial business opportunities [37]. Recent studies [44,45] have investigated the nexus between innovation, sustainability, and business performance, underscoring the critical importance of embracing sustainability-focused business strategies to ensure resilience and success in today's competitive landscape.

However, despite advancements in sustainable innovation, there remains ample room for fully integrating sustainability into business decision making and operations. This realization underscores the ongoing need for unwavering commitment from the academic community and industry stakeholders to foster an entrepreneurship culture centered on sustainability and to develop new business models capable of aligning economic, social, and environmental objectives. The ongoing discourse on sustainability in healthcare has evolved beyond environmental concerns to encompass a broader vision that also encompasses the effectiveness and cost efficiency of healthcare services. Initially, efforts were fragmented, focusing on reducing the environmental impact of chemicals and pharmaceuticals, enhancing the energy efficiency of healthcare facilities and raising awareness among medical professionals. However, while significant, these initiatives only addressed a portion of the complexity inherent in the problem. Consequently, contemporary research is shifting towards a more holistic approach to healthcare sustainability, embracing the concept of the circular economy to systematically re-evaluate the sector. This fresh approach proposes innovative models, both in design and economics, that consider the technological, environmental, and social interdependencies of healthcare processes and products. In addition to the economic imperatives of enhancing efficiency and sustainability, an increasing number of hospitals and healthcare organizations are actively committed to minimizing the adverse environmental impact of their activities on patients, staff, and communities. These entities are emerging as trailblazers and exemplary models within the sector, signaling a growing awareness and dedication to promoting eco-friendly and responsible practices [46]. This conceptual evolution necessitates a multidisciplinary examination of organizational dynamics and the socio-economic and ethical implications involved. In this context, Stafford Beer's viable system theory offers a valuable theoretical framework for comprehending the complexity of interactions within the healthcare system and identifying improvement opportunities based on an integrated sustainability perspective. It particularly underscores the importance of considering the dynamic interactions among people, information, and physical resources as fundamental components for achieving the system's common goals. However, this multidisciplinary perspective presents a series of challenges, including managing organizational complexity, balancing economic and ethical considerations, and involving stakeholders in the decision-making process.

2.2. Towards a Sustainable Future: Integrating Innovation in Healthcare Services

Healthcare services aim to meet the health needs of the population, providing care aimed at preserving and improving individual well-being. However, healthcare systems worldwide are currently facing profound changes and challenges that threaten the realization of this mission. One of the main issues is represented by drastic cuts in public spending, which are pushing the healthcare sector towards a process of consolidation. This translates into the merging of hospitals and other healthcare facilities, with the aim of improving efficiency through economies of scale, while simultaneously expanding services and reducing costs. In the current context, new technologies play a fundamental role, optimizing treatment practices and facilitating greater digital interconnectivity between hospitals, clinicians, and patients. The aging population poses an additional challenge for healthcare systems, which are under pressure to respond to the growing demand for care, services, and technologies aimed at preventing and treating non-communicable diseases and chronic conditions associated with aging. Forecasts indicate that by 2050, the number of individuals over 60 years old will double, from 727 million to nearly 1.6 billion (United Nations, 2022). In 2019, non-communicable chronic diseases accounted for 74% of global deaths (WHO Global Health Estimates, 2020), currently representing over 70% of healthcare spending in the United States and the European Union. These challenges have been further exacerbated by the COVID-19 pandemic, which has led to a drastic increase in the number of patients, healthcare worker burnout, and the highlighting of structural deficiencies in the sector, related to staff shortages, supply chain disruptions, equipment shortages, and outdated infrastructure. This trend is conferring an increasingly prominent role on the

healthcare sector in our economies, with its share now amounting to 10% of the GDP and 8% of total employment in the European Union.

Digitization has revolutionized the landscape of healthcare organizations, offering new opportunities to improve the efficiency and sustainability of the system as a whole [47]. However, navigating through complex healthcare systems presents challenges, including equity in access to services and treatment effectiveness. Digital solutions can help overcome these obstacles, enabling more accessible and efficient healthcare while ensuring data security and privacy compliance. Concurrently, sustainability-oriented innovation has emerged as a growing area of interest for organizations and researchers. This approach involves intentional changes in organizations' philosophies and values, as well as in their products and processes, to create social and environmental value in addition to economic returns. Dynamic knowledge of sustainability-oriented innovation projects is increasing and requires an expansion of the field of study, especially in the healthcare sector, which plays a crucial role in the context of research and technological development.

Empirical studies on sustainability-oriented innovation mainly focus on the manufacturing sector, while those related to services are more recent and theoretical [44,48]. However, the healthcare sector, due to its connection with research and development, is emerging as fertile ground for the application of new technologies and sustainable practices, with particular attention to digital platforms and emerging technologies such as biotechnology and nanotechnology. The relationship between the healthcare sector and innovation holds a prominent position in the scientific research landscape, acting as a bridge between national innovation systems and social security systems. This unique position makes it crucial to analyze the impacts of innovation in the healthcare context, as the advancements generated have direct consequences on the economy and society as a whole.

The integration of sustainability principles into organizational discourse represents a significant opportunity for healthcare organizations to align with a sustainable agenda and consequently reap benefits both internally and in the surrounding environment. Scholars have highlighted that sustainability challenges offer a wide range of opportunities for innovation and competitive advantage creation. This is because new socio-environmental regulations drive companies towards greater innovative capacity, while new business opportunities emerge through cost reduction, efficiency improvement, and business diversification.

The interconnection between innovation, sustainability, and business performance has been widely discussed in the literature, emphasizing the importance of an integrated approach to ensure the long-term survival of companies. However, despite the increased attention on sustainability-oriented innovation, there is still a need for further research, especially in the field of administration, to fully understand the dynamics and implications of this emerging approach. Academic research on organizational sustainability and innovation is relatively recent, but it clearly indicates the need to investigate how organizations can integrate sustainability principles into their decision-making and operational processes. The goal is to create long-term value while ensuring stakeholder satisfaction and adherence to the fundamental principles of economic, environmental, and social sustainability.

2.3. Value Constellation in the Healthcare Sector: Roles and Implications for Sustainability

Before delving into the correlations between healthcare and sustainability and their driving factors, it is imperative to gain a comprehensive understanding of the healthcare system to establish a shared comprehension among key stakeholders.

In the past decade, the healthcare sector has faced mounting pressures stemming from shifts in demand, propelled by epidemiological shifts and increased emphasis on quality and safety, alongside escalating costs linked to the adoption of new technologies. The intricate nature of the healthcare sector is best illuminated through the concept of the "value constellation", as explored by Normann and Ramirez [49]. This concept surpasses the conventional value chain, delineating a "value-creating system" where myriad stakeholders from diverse sectors converge to deliver healthcare, engendering a complex tapestry of services, goods, design, and social value. This gives rise to the formation of

a "healthcare value constellation", wherein healthcare companies, service providers, and patients constitute the principal interconnected elements, each wielding a defined role and influence, including that of sustainability [50]. Public and private healthcare organizations, referred to as healthcare providers, wield a pivotal role in dispensing healthcare services to the populace. Their impact on the sustainability of the system is apparent through the procurement and utilization of products and services for patient care. Furthermore, their procurement role shapes the direction of innovation towards more sustainable practices and guides research endeavors within the sector.

The healthcare industry encompasses a wide array of companies involved in manufacturing medical devices, providing healthcare services, and developing pharmaceuticals, biotechnology, and other supplies for the life sciences sector. These industries rely on established networks of suppliers, comprising both component manufacturers and subcontractors, as well as distributors with whom they maintain steadfast business relationships. While collaborations on innovative fronts, such as sustainability, may arise, these initiatives do not consistently take precedence and may encounter implementation challenges.

Despite their pivotal role in the healthcare system, patients often find themselves in a position of limited influence over sectoral changes, owing to their fragmented nature and lack of purchasing power, particularly in public systems. Despite a shift towards more patient-centered care, marked by the adoption of self-management models, patient involvement remains largely passive within the system. In the healthcare landscape, other actors beyond the primary protagonists come into play through various channels and hierarchical structures. Regional and national authorities wield significant decision-making authority within the intricate value network, shaping policies, strategies, and public investments geared towards fostering sectoral sustainability. The level of autonomy in healthcare service procurement and provision varies significantly depending on the national context, with some countries opting for a centralized procurement approach, while others afford greater autonomy to local healthcare authorities. Overall, regional and national authorities encompass both policymakers, who delineate sectoral policy directives, and public decision makers, who handle technical and administrative matters and execute policies in the healthcare domain. Political advisors, especially at the national level, play a pivotal role, offering counsel on programs and policy initiatives and influencing policy decisions, particularly concerning emerging priorities.

Academic institutions and research centers play a pivotal role in catalyzing innovation and possess extensive expertise in environmental sustainability, which could be leveraged for the healthcare sector coming from other domains. However, presently, their influence within the value network is circumscribed, and their impact hinges primarily on individual collaborations with businesses, suppliers, and other actors in the healthcare system. Entities engaged in waste management, both public and private, are instrumental in ensuring the proper collection and disposal of medical waste. Nevertheless, their contribution to sustainability often goes unnoticed.

Lastly, companies specializing in the provision of technologies and digital solutions play an indispensable role in the digitization process of the healthcare sector, particularly at the local level. They frequently serve as the primary catalysts for developing and implementing digital tools aimed at enhancing the efficiency and accessibility of public healthcare services [51].

2.4. Environmental Impact of Hospitals: Managing CO_2 Emissions

Commencing with the premise that effective management necessitates precise measurement, monitoring energy flows emerges as a critical step for those endeavoring to enhance the efficiency and energy conservation of a building-system complex. Within Italian hospital contexts, this practice holds particular significance, given their substantial energy consumption. According to data from the National Action Plan for Sustainable Energy (PANES), Italian public hospitals consumed a total of 6.4 TWh/year in 2018, equivalent to 2.4% of the national energy consumption. These institutions, characterized by

structural complexity and high consumption rates, demand specific attention to the management of air conditioning and heating systems to address energy challenges. Historically, healthcare facilities have exhibited some reluctance in embracing operational innovations, primarily due to the significant interests at stake, the weighty responsibilities inherent in the services rendered, stringent regulations, and financial constraints impeding investments in institutional changes.

Healthcare facilities confront a mounting challenge in balancing the adoption of advanced technologies with the safeguarding of patient privacy and data security. While many technological solutions promise substantial benefits in terms of efficiency and quality of care, they often entail the risk of exposing patients' sensitive data to vulnerabilities and security threats. In an environment where the security and privacy of health data assume increasing centrality, healthcare facilities are investing in low-risk technological solutions capable of ensuring the protection of patients' sensitive data without compromising innovation and operational efficiency. Moreover, optimizing energy efficiency stands as a critical objective for healthcare facilities, not only to curtail operational costs but also to diminish environmental impact and enhance overall operational sustainability. An effective energy management program can empower healthcare facilities to reduce energy consumption, optimize resource utilization, and enhance operational resilience. Nonetheless, many healthcare facilities find themselves grappling with reactive rather than proactive maintenance approaches. This reactive stance not only results in additional costs owing to unforeseen equipment downtime but also poses risks to patient safety and induces stress among medical staff. To counter this challenge, adopting a preventive maintenance strategy aimed at identifying and rectifying issues before their occurrence becomes imperative, ensuring efficient and uninterrupted equipment operation while safeguarding the well-being of patients and healthcare staff.

Hospitals, with their continuous operation and intricate energy needs, stand as one of the most significant sources of CO_2 emissions into the atmosphere compared to other building types such as residential or commercial ones [52]. This stems from the imperative to maintain a safe and comfortable clinical environment for patients, coupled with the perpetual demand for electricity, heating, and other resources. Addressing climate change mandates management strategies aimed at curbing greenhouse gas emissions into the environment [53]. However, the endeavor is intricate, as hospitals must strike a balance between the imperative to reduce environmental impact and the obligation to ensure safe and efficient patient care.

Moreover, it is crucial to acknowledge that hospitals are subject to a myriad of factors influencing their greenhouse gas emissions, including the year and type of construction, operational modalities, geographical location, and local climate [30]. This variability underscores the indispensability of a tailored approach to reducing the carbon footprint of healthcare facilities. Tackling this challenge necessitates a commitment from authorities and healthcare entities to embrace more sustainable practices [54]. This may encompass the adoption of eco-friendly design and construction techniques, optimization of energy efficiency in facilities, and promotion of a sustainable value chain involving suppliers and business partners [55].

Ultimately, managing carbon emissions in hospitals emerges as a critical imperative in the context of combating climate change. Only through collective commitment and an integrated sustainability approach can healthcare facilities make significant strides in reducing CO_2 emissions and safeguarding the environment. Addressing carbon emissions in hospitals has ascended to a paramount priority in numerous countries, including the UK, where hospitals emit over 18 billion tons of CO_2 annually [23], the United States, and China, as hospital activities substantially contribute to a country's overall carbon footprint, ranging between 3% and 8% [56]. CO_2 emissions stemming from hospital operations result from their continuous and complex functioning, which necessitates high energy consumption and utilization of non-renewable resources such as heating oil and natural gas. An energy audit conducted on tertiary hospitals in Tianjin revealed significant average

annual carbon emissions per square meter, ranging between 131 and 157 kg CO_2/m^2 in Tianjin [32]. These findings underscore the urgency of addressing energy efficiency and reducing CO_2 emissions in healthcare facilities. Furthermore, a literature review on environmental sustainability in hospitals has emphasized the imperative of measuring and managing the environmental performance of hospital facilities [57]. This review underscored the significance of adopting sustainable practices and enhancing energy efficiency to diminish the carbon footprint of the healthcare sector. Specific analyses on energy consumption and carbon dioxide emissions attributable to hospital operations have furnished further evidence of the substantial impact of hospital activities on the environment. These studies advocate for the implementation of targeted strategies to curtail carbon emissions, such as the adoption of more efficient energy technologies and optimization of operational processes. Ultimately, addressing carbon emissions in hospitals is imperative both to mitigate environmental impact and enhance the operational efficiency of healthcare facilities [58]. Scientific evidence gleaned from various studies underscores the urgency of undertaking concrete measures to mitigate the environmental impact of hospital activities and promote sustainable management of energy resources, complemented by the inclusion of highly specialized professional expertise.

3. Methodology

This research followed a mixed methodological approach with questionnaires and internal interviews as a data collection method, administered to 14 top managers of a major private hospital group located in southern Italy in 2023. This hospital group comprises six different facilities and provides healthcare services with over 2000 beds. In the period preceding the research, the hospital group developed a series of both digital and environmental objectives, implementing targeted programs on various issues such as waste management, energy efficiency, and process digitalization. In particular, training programs focused on digital and environmental issues were introduced to raise awareness among hospital staff and enable them to contribute to environmental goals through the adoption of technological innovations. The research design adopted, following the recommendations of important methodological publications in the field of human resource management, aims to minimize the impact of uncontrollable contextual factors on the variables considered in the study context. This methodological approach has been successfully used in various studies that have explored the effects of sustainability-oriented human resource management on employees' perceptions and behaviors.

The survey and interviews were administered by the first author during visits to the hospital facilities between October 2023 and December 2023. The printed questionnaires were distributed to top management and strategic management working at the hospital and participating in a planned and mandatory training program. During each training session, the first author had the opportunity to explain the research objective and the content of the questionnaire and clarify that the data were confidential and analyzed in aggregated form.

4. Results and Discussion

The questionnaire consisted of 31 questions divided into four sections: socio-demographic, energy impacts, staff training, and energy efficiency strategies. Before this study, the author visited the offices of the hospital group to observe the facilities, technologies used, and the state of energy efficiency systems. The questions for the questionnaire and interviews were chosen based on these observations and an extensive review of the literature.

The interviews, on the other hand, were conducted individually, face-to-face, in meeting rooms without the presence of other people and began with an explanation of the purpose of this study.

This interview consisted of 10 questions aimed at discovering and identifying the problems and expectations related to their experiences with energy management strategies in healthcare.

Data from the questionnaire's responses and interviews were translated into English and then coded in Microsoft Excel. Next, a thematic analysis was undertaken to identify the important themes from the participants' responses to the interview. The participants' comments were initially classified into categories of the questionnaire examined: positive aspects, negative aspects, and suggestions for the future improvement of promoting energy efficiency and sustainability in hospitals.

Among the study participants, 11 (78%) were men and 3 (22%) were women (Table 1). The average age of the participants was 47 years, and most of the respondents fell into the age group between 41 and 50 years. In terms of educational background, all interviewees had a bachelor's degree, with 43% in legal subjects, 36% in economic subjects, and only 7% in healthcare subjects. The average work experience was 17.5 years, where five participants (36%) had experience ranging from 6 to 10 years, three participants (22%) from 11 to 15 years, and four participants (28%) with over 26 years of experience.

Table 1. Socio-demographic characteristics of the top managers (N = 14).

Variables	Categories	Frequency (#)	Percentage (%)
Gender	Male	11	78%
	Female	3	22%
Age (Years)	31–40	2	14%
	41–50	8	57%
	51–65	1	7%
	>66	3	22%
Education	Medicine	1	7%
	Economics	5	36%
	Law	6	43%
	Engineering	2	14%
Work Experience (Years)	<5	2	14%
	6–10	5	36%
	11–15	3	22%
	>26	4	28%

During the interview conducted on how sustainability can be implemented as a strategic objective, three key points emerged to focus on: process innovation, change management and new skills, and people-centricity.

Firstly, the importance of process innovation was emphasized, which involves the introduction of sustainable practices and technologies to optimize healthcare operations by reducing environmental impact. In this regard, 70% of the respondents consider it essential for the national health service to operate in a more sustainable manner. Additionally, 60% regard the adoption of technologies and strategies to improve energy efficiency as important, attributing to it the capability to contribute to the overall success of their facility. This could include the adoption of new waste management systems and the implementation of recycling practices and energy consumption reduction, as well as the use of advanced technologies to monitor and improve operational efficiency.

The questions concerning top management's perception of environmental sustainability, the use of renewable energy sources, and the impact of energy costs on corporate budgets are summarized in Table 2.

Secondly, the need for effective change management and the development of new skills to address the challenges associated with transitioning to more sustainable care were discussed. This implies not only training staff on the importance of environmental sustainability but also developing specific skills in the use of digital tools, project management, and economic and environmental sustainability strategies. This strategic training is crucial to ensuring that staff are adequately prepared to address the challenges and opportunities associated with sustainable care.

Table 2. Assessing the top management perspective on environmental impact.

Statement	Not at All Important	Slightly Important	Important	Fairly Important	Very Important
How important do you think it is to use teleconference services such as video, phone, or internet communications? This would mean that patients could speak with their doctor or other healthcare providers remotely.	0%	10%	20%	20%	50%
How important do you think it is to identify services closer to people's homes (where appropriate) so they don't always have to go to the hospital?	0%	0%	30%	0%	70%
How important do you think it is to improve National Health Service buildings (such as hospitals and medical clinics) so that energy for heating, cooling, ventilation, and lighting is used more effectively?	0%	0%	10%	0%	90%
How important do you think it is for the healthcare and assistance system to operate in a way that supports the environment, such as improving resource efficiency, reducing carbon emissions, and reducing waste?	10%	0%	10%	10%	70%
How impactful do you think the energy cost is in your company?	0%	0%	0%	40%	60%

Finally, the importance of placing people at the center of any sustainable care strategy was highlighted. This involves not only actively engaging staff in sustainability initiatives but also creating a work environment that supports and promotes personal environmental motivation. However, it was noted that this can be particularly challenging in the healthcare sector due to the complexity of medical practices and the often-stressful nature of the work environment. In this regard, the majority of respondents (85.7%) considered it essential to involve staff in promoting sustainable practices and adopting solutions for energy efficiency.

Furthermore, it was highlighted how environmental risks and costs associated with waste disposal can be effectively managed through the adoption of circular business models. In total, 71.4% of the respondents were in favor of adopting circular economy strategies aimed at the environmental sustainability of their facility. These models aim to maximize the use of existing resources while simultaneously reducing material consumption and overall environmental impact. In particular, digital transformation through the Internet of Things (IoT) was identified as a potential lever to enhance the circular economy. Through IoT, digital applications can provide detailed information on the location, conditions, and availability of resources, enabling healthcare organizations to optimize the use of existing resources and reduce waste.

This synergy between digital transformation and the circular economy is seen as a significant opportunity to improve the efficiency and sustainability of healthcare operations. For example, the use of IoT sensors to monitor water and energy consumption can help identify areas of waste and implement corrective measures to reduce consumption. Similarly, the use of digital technologies to track and manage the flow of materials within healthcare facilities can help optimize the waste disposal process and promote recycling and reuse practices.

5. Promoting Energy Efficiency and Sustainability in Hospitals: Guidelines and Recommendations

It is evident that organizational and energy management processes, particularly within the healthcare sector, are confronted with increasingly intricate challenges stemming from the sustainability requirements imposed by the recent economic crisis and subsequent European directives. These directives underscore the necessity of energy restructuring that considers not only the quality standards demanded by citizens but also the budgetary constraints to which the National Health Service must adhere. The analysis conducted in Italy by Marino and Pariso [59] reveals that hospital real estate assets, overseen by hospital directors, often no longer align with current needs. These buildings were erected at a time when there was scant attention to energy regulations and efficiency concerns. Consequently, hospital facilities, instead of being adaptable and flexible, have become obsolete over time. Over the years, no technological innovations have been implemented to address the continuous and escalating utilization of these facilities or to adapt to new regulations and emerging challenges.

There are numerous strategies that hospital facilities can employ to optimize their energy use and embrace a more sustainable approach [60]. These strategies are based on literature review, challenges faced, and best practices developed during the development of energy management in the studied hospitals, cross-case analysis, and author experience:

1. Energy Audits: Conducting detailed energy audits in hospitals is essential to identifying energy waste and inefficiencies. These audits analyze energy consumption, assess the efficiency of systems, and identify areas for improvement. Investing in this type of audit early on can lead to significant energy savings in the long term, improving the efficiency and sustainability of hospital facilities.
2. Building Design and Renovation: A fundamental strategy to improve the energy efficiency of hospitals is to optimize building design and renovate existing structures to reduce energy loss. This can be achieved by using high-quality insulation materials and installing efficient lighting and HVAC (heating, ventilation, and air conditioning) systems. Investing in these improvements not only reduces energy consumption but also enhances the comfort of hospital environments and contributes to environmental sustainability.
3. Lighting Optimization: Implementing energy-efficient lighting solutions. These include adopting technologies such as LED lighting and installing presence sensors. These solutions significantly reduce energy consumption due to lighting while providing effective and comfortable illumination in hospital environments. This investment not only leads to energy savings but also to better lighting quality, thus contributing to the well-being of patients and hospital staff.
4. Equipment Upgrades: replacing obsolete equipment with more energy-efficient models, thus reducing overall energy consumption.
5. Energy Management Systems: implementing energy management systems prioritizing technological investments both to implement the reduction of energy consumption in hospital facilities and interventions aimed at reducing losses and implementing technologies for the exploitation of renewable energy sources.
6. Integration of Renewable Energy: harnessing renewable energy sources such as solar and geothermal energy to reduce dependence on traditional sources and promote sustainability.
7. Staff Training: educating staff on the importance of energy efficiency and involving them in energy-saving initiatives to promote a sustainable culture.
8. HVAC Efficiency: Upgrading existing HVAC systems with more efficient technologies, such as high-efficiency motors and demand-controlled ventilation systems. Additionally, regularly maintaining and optimizing HVAC systems to maximize efficiency.
9. Performance Monitoring: implementing performance monitoring systems to assess the effectiveness of measures implemented and identify further improvement opportunities.

10. Certification: The UNI CEI EN ISO 50001:2018 provide a structured pathway to achieve more efficient energy consumption management, leading to overall environmental conditions improvement. The standard provides detailed guidance on how to establish, implement, and maintain an energy management system, offering hospitals the opportunity to develop energy policies integrated with environmental strategies. This approach not only contributes to optimizing energy use but also to promoting sustainable practices that benefit both the environment and the overall performance of the hospital institution.
11. Reuse: Increasing the useful life of materials and products and combating planned obsolescence, among other medium- and long-range actions. It is important to expand the relevance of the concept, which is often confused and limited to the implementation of small actions to reuse materials that result in objects or products with low added value that are disposable and/or have no real economic or environmental value.

These strategies can help hospitals improve their energy efficiency, reduce operating costs, and contribute to a healthier and more sustainable environment for patients and staff.

5.1. Implementing Energy Management Program in Hospitals

The dynamics of the industrial sector are undergoing a significant evolution towards the adoption of more sustainable policies. However, despite the awareness of the importance of such a transition, many companies find it challenging to implement a truly sustainable approach in their design and management practices. Particularly in the healthcare sector, which includes hospitals, private facilities, and industry professionals, there is increasing pressure to better identify sustainability needs and assess the impacts of activities on different time scales.

In a context where energy conservation assumes a role of growing importance, the designation of a specific energy manager within hospital facilities becomes necessary.

Figure 1 summarizes managers' responses when asked the importance of the figure of the energy manager.

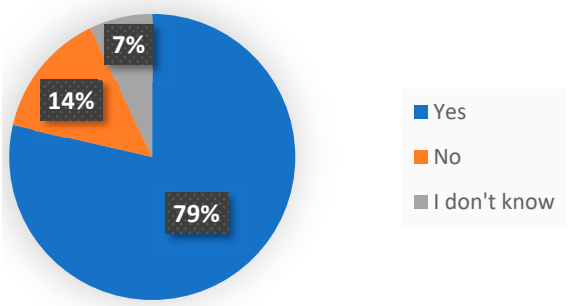

Figure 1. Perceptions of role of energy manager in achieving energy efficiency.

This individual should be tasked with overseeing energy management, assigning it the same level of importance as the management of other costs within the organization. It is essential that energy management has its own financial resources and is considered a key element in the hospital's budget, with a budget set based on a percentage of annual energy costs. The search for the ideal candidate should start from within the organization, aiming to identify a figure already present within the staff and capable of taking on this role. In cases where finding a suitable figure within the organization is not possible, external recruitment would be appropriate. The energy manager should possess multidisciplinary skills, including IT aspects, technical knowledge of hospital building energy systems, familiarity with energy consumption data, and skills in energy data analysis. Active support and a positive approach from hospital management are crucial to ensuring the success of the energy management program. The implementation of such a program can occur in various ways, depending on the specific characteristics of the hospital, but it is

essential to constantly monitor performance and clearly define the responsibilities of each hierarchical level involved.

5.2. Technological Innovations for Energy Efficiency in Hospitals

In the domain of healthcare institutions, technological innovations are emerging as pivotal factors in enhancing environmental, social, and economic performance. It is evident that humanity cannot simply relinquish large-scale energy services to diminish energy consumption. What we require is a gradual and comprehensive transition to innovative energy technologies and paradigms that fulfill our energy requirements without engendering harmful emissions or polluting the environment. This transition not only bolsters energy security by diminishing dependence on external energy sources but also contributes to environmental preservation by curbing air pollution and mitigating risks to human health. For instance, enabling technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics are revolutionizing the energy sector, facilitating greater integration of renewable energies and more efficient management of energy resources.

In total, 92.9% of the respondents expressed awareness that the introduction of telemedicine and remote monitoring can improve the efficiency of healthcare practices in the facility where they work. The same top management was working on the introduction of innovative energy management systems to monitor and reduce energy consumption. Additionally, when asked about the implementation of smart lighting as a lever to contribute to energy savings, 92.9% of respondents were in favor, and 43% considered predictive data analysis and maintenance essential for energy improvement.

Figure 2 summarizes managers' responses when asked about their opinion on the adoption of energy-efficient medical equipment (C), energy storage systems to reduce dependence on traditional sources (B), and the effectiveness of intelligent building management systems in promoting environmental sustainability (A).

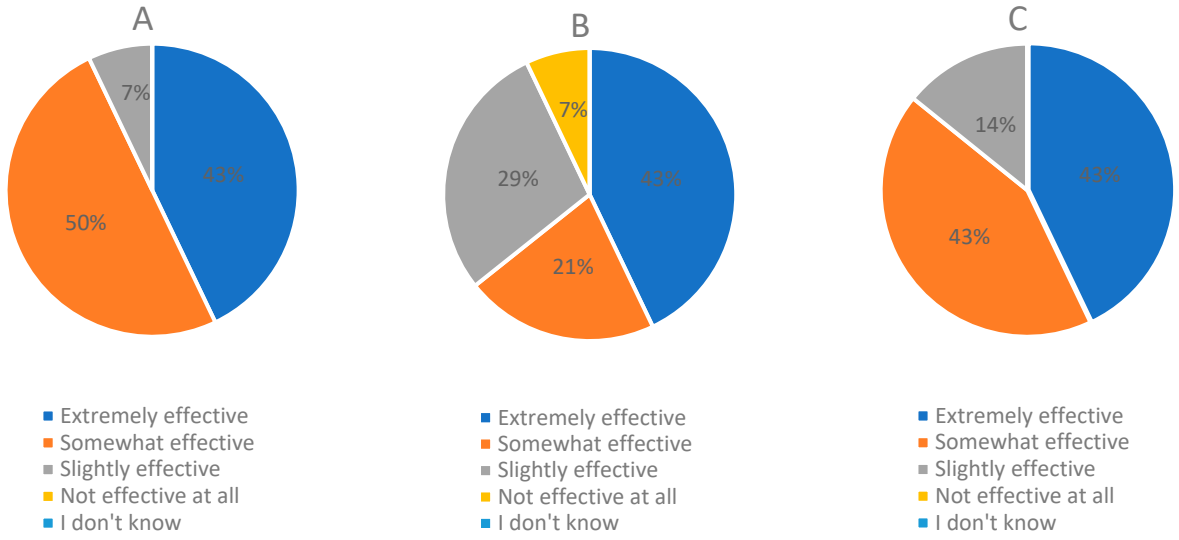

Figure 2. Managers' responses on adoption of energy-efficient medical equipment, energy storage systems, and intelligent building management.

The transition to more sustainable infrastructures and the adoption of technologies such as battery storage and smart grids are radically changing the way we conceive and manage energy. These innovations not only improve the efficiency of the energy system but also offer new opportunities for flexibility and adaptability, enabling more efficient management of energy demand and supply.

A recent study by Rodler et al. (2023) [61] sought to estimate the reduction in carbon footprint for patients using telemedicine. It was found that people using teleconsultations

used their cars less, saving time, money, and CO_2 emissions. Specifically, of the 48 studies meeting inclusion criteria, covering 68,465,481 telemedicine consultations, a saving of 691,825 tons of CO_2 emissions and 3,318,464,047 km of distance traveled was observed. Savings per consultation ranged from 21.9 to 632.17 min and from USD 1.85 to USD 325.

Below are some technological innovations that can improve the energy efficiency of hospitals:

- Telemedicine, AI, and Remote Monitoring: The adoption of telemedicine and remote monitoring represents a significant advancement in optimizing healthcare practices. These technologies allow patients to access virtual consultations and be monitored remotely, eliminating the need for physical visits.
- Intelligent Building Management Systems: these systems integrate advanced sensors, data analytics, and automation to monitor and control a wide range of building systems, including heating, ventilation, and lighting, in real time.
- Building Energy Management Systems (BEMSs): These systems integrate energy data from various sources within the hospital, including heating, ventilation, lighting, and equipment systems, into a centralized platform. They enable real-time monitoring and control of energy consumption, allowing facility managers to identify areas of inefficiency and implement targeted energy-saving measures.
- Energy Storage Systems: These energy storage systems, such as batteries, offer hospitals the ability to store excess energy generated during periods of low demand or from renewable sources. This energy can then be used during peak demand or in the absence of grid power. The adoption of such systems not only reduces dependence on traditional distribution networks, optimizing energy consumption, but also increases the resilience of the hospital's electrical system by providing a backup power source during power outages.
- Intelligent Lighting Systems: These systems use sensors, presence detectors, and advanced controls to optimize lighting levels based on occupancy and available natural light. They automatically adjust light intensity, turning off lights in unoccupied areas and harnessing natural light to reduce energy consumption.
- Energy-Efficient Medical Equipment: Medical equipment is essential for delivering high-quality healthcare in hospitals but often requires significant energy consumption. The adoption of these new generations of devices not only helps reduce overall energy consumption but also offers a range of additional benefits, including maintaining high standards of patient care, long-term cost savings, and reduced environmental footprint.
- Data Analytics and Predictive Maintenance: The introduction of advanced data analytics algorithms represents a revolutionary opportunity for hospitals to improve energy efficiency and optimize maintenance practices. These algorithms allow for detailed examination of hospital energy consumption patterns, equipment performance data, and environmental conditions to identify areas for improvement and energy-saving opportunities.
- Energy-Efficient Water Systems: Water consumption and heating can contribute to energy consumption in hospitals. Implementing energy-efficient water systems, such as low-flow faucets, water recycling, and heat recovery systems, can help hospitals reduce both water consumption and the energy required for water heating.
- Internet of Things (IoT) Applications: The Internet of Things (IoT) offers hospitals a tremendous opportunity to improve energy efficiency and optimize daily operations. Through interconnection and communication among a wide range of devices and systems within the hospital environment, IoT applications enable real-time monitoring and management of energy consumption, ensuring optimal resource utilization and reduced operating costs.
- Circular Economy Systems: This approach focuses on resource optimization, aiming to reduce waste and maximize the value of products and materials within the economy. In practice, it involves adopting strategies that allow products and materials to circulate

for as long as possible, rather than disposing of them after a single use. Among these strategies is dematerialization, replacing physical media with intangible solutions such as software, resulting in reduced consumption of material resources.

By implementing new technologies, hospitals can improve energy efficiency, cut operating costs, and support the environment.

6. Concluding Remarks and Implications

6.1. Conclusions

This research focused on strategies aimed at enhancing energy efficiency and environmental sustainability in hospitals, employing innovative technologies and developing specific guidelines. This approach was grounded in a comprehensive analysis of the scientific literature and the outcomes of a case study conducted across various hospital facilities. The results underscored the significance of energy consumption management, the integration of eco-friendly technologies, staff training, the identification of suitable professional roles, and the upkeep of building infrastructure as fundamental elements for enhancing environmental performance.

Additionally, it was observed that efficient energy management not only benefits hospitals and patients but also aligns the healthcare sector with sustainable development goals. This study captures existing knowledge and identifies future research pathways with the aim of assisting researchers in studying those aspects that have not yet been sufficiently illuminated, while also attempting to highlight the economic impact of energy efficiency policies in healthcare facilities, in light of recent technological innovations. Furthermore, this paper thus sought to contribute groundwork that may lead to a better understanding of how technology innovations respond to the call for new ways of interfacing the healthcare industry in the pursuit of the SDGs.

Finally, the energy costs of healthcare facilities undoubtedly comprise some of the largest and most inelastic costs of the state and private enterprises. In this regard, all the interviewees emphasized the significant impact of energy costs on the company's budget.

Given rapid climate change and limited financial resources, efforts to adopt renewable energy sources and green technologies are necessary in order to contain costs and reduce environmental footprints.

6.2. Policy Implications

Several implications can also be derived from our analysis.

In general, there is a need for public policies more focused on energy efficiency and environmental sustainability. These policies could include tax incentives for eco-friendly technologies, training programs for hospital staff, sustainable building regulations, and funding for research. Environmental monitoring and reporting could be additional tools to assess the impact of measures taken and promote transparency in the healthcare sector.

6.3. Pratical Implications

The findings of this study carry several practical implications. Hospital management must prioritize allocating resources and efforts towards enhancing energy efficiency and promoting environmental sustainability within the facility. This entails conducting thorough analyses of data and scientific evidence to inform strategic decision making and the implementation of measures aimed at actively managing the hospital's energy consumption. Moreover, optimizing the building design, especially its thermal envelope, has been recognized as pivotal for achieving significant energy savings. Additionally, it is strongly recommended to deploy an efficient LED-technology lighting system, monitored by a control unit that adjusts for factors such as temperature, humidity, and lighting levels in each room or section [62].

This study underscores the indispensable role of top management leadership in healthcare institutions for effectively instigating green healthcare initiatives. The unwavering commitment of top management to green healthcare can serve as a catalyst, motivating

active participation from employees in supportive endeavors, as well as in relevant education and training programs. This, in turn, facilitates the successful execution of green healthcare operations.

While acknowledging the existence of competing priorities for healthcare organizations in a resource-constrained world, hospital leaders must cultivate a "sustainable conscience" to optimize the efficiency of available resources for the betterment of human health. Furthermore, ensuring proper maintenance of building infrastructure is essential to maximizing energy efficiency. Lastly, management should regard energy efficiency and environmental sustainability as fundamental components contributing to the attainment of sustainable development goals.

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