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# Impact Of Sustainability Programs On Healthcare Facility Design And Operations: Integrating GHG Emission Reduction And Low Carbon Building Strategies (2015-2025)

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***Abstract***
*Healthcare facilities also serve as the biggest contributors to global emission of greenhouse gases (GHG) (4-5%), but also hold a critical potential to lead the way to low-carbon change with facility design and operations. Integration into the care design and management of sustainability programs is a variance in regions although it is increasingly gaining attention. This paper will address how sustainability programs will affect the design and operations of healthcare facilities in the coming five years of 2015 to 2025 with a focus on greenhouse gas reduction and emission low-carbon mitigation strategies. It aims at finding out the interaction between design interventions, operational practices, and leadership structures in order to provide measurable results. They used a qualitative multi-case study design, and five facilities were assessed; in the study, including Humber River Health (Canada), Vivantes Klinikum Neukolln (Germany), Albert Einstein hospital (Brazil), As-Salam and HMG Sehat Al Sharq (Saudi Arabia) and; a multi-hospital study by Dion, Evans and Farrell. There were the institutional reports and published case studies, as well as interview-based evidence as the sources of data. Within-case analysis and cross-case synthesis were carried out thematically. Retrofits, digital automation, and renewable integration resulted in the creation of structural efficiency potential and were designed interventions. Quantifiable savings in energy and costs were always generated through operational programs particularly through HVAC optimization and the use of energy management systems on ISO basis. Leadership has proven to be the overriding facilitator, completeness of approach, funding, and cultural implementation. Alterations in CO2 emission had a quantitative outcome of up to 40% reduction, savings of 1.37 million kWh/year, and less than 2 years' payback in a few cases. The concept of sustainability in healthcare should entail combination of the design, operational, and governance approaches. The results offer practical suggestions to facility managers, policymakers, and architectures as they show that quantifiable cutbacks in emissions and cost-savings can be acquired in both recent and old facilities when leadership, monitoring, and policy merge.*
***Keywords:*** *Sustainable Development, Healthcare Facilities, Greenhouse Gas Emissions, Energy Conservation, Construction Materials, Sustainable healthcare, Low-carbon building strategies, , Hospital design and operations, and Leadership and governance in sustainability*

## INTRODUCTION

One of the most resource-intensive building environment sectors is the healthcare facilities sector. The health sector also contributes to the overall global climate change through about 4.4-5 percent of greenhouse gas (GHG) emissions, and in hospitals, they are the largest emitters of greenhouse gases because of their energy-intensive nature and 24-hour operation [1]. The results of the buildings under this sector contribute to the most significant percentage of emissions that are related to healthcare, which is related to heating, cooling, ventilation, lighting, and specialized equipment. Moreover, there are the indirect emissions of power production that also increase the amount of carbon footprint in the sector. Several healthcare regimes had devised organized sustainability initiatives focused on harmonizing facility activities with international climate roles and country decarbonization targets between 2015 and 2025 [2]. It has been documented that substantial opportunities for emission cutting and effective economies of scale can be achieved once strategic placement of sustainability in the design and operational policies. As an example, hospitals with innovative building envelopes, renewable power installations, and an HVAC technology saving 20-40% and GHG savings of 30-50% more energy and impacts that were lower than in traditional hospitals [3].

A 29 percent energy consumption reduction and a 42 percent decline in GHG were documented in the Humber River Hospital in Canada versus the benchmarks, with similar programs in Germany and Brazil

registering over 40 percent reduction in the Scope 1 and Scope 2 emissions [4]. The findings underscore the duality of healthcare facilities as the major contributors and the major mandate in supporting and educating the use of low-carbon infrastructure [5]. In addition to environmental effects, sustainable healthcare facilities present operational values, such as one example is through reducing energy intensity, which saves money and protects institutions against energy price changes, as well as improving patient settings. The use of digital monitoring functions, modulator construction method, and renewable energy supply provides an additional boost to the fit between clinical achievement and sustainability goals. Such results demonstrate the strategic significance of incorporating sustainability principles in the design of medical institutions, managing them, and governance [6]. All these benefits notwithstanding, the integration of sustainability is still patchy and erratic. Most of the facilities implement solitary actions, including effective lighting or mini renewables, which they do not link to the organization-wide long-term planning [7]. The result of this has been mixed; some of the institutions have reported increased emission reductions of more than 40, whereas others have reported a decrease of less than 10 in spite of the high investments.

Continuous lapses can be observed in the Scope 3 emission management, i.e., procurement, supply chains, and transportation of patients that often add up to over fifty percent of total emissions. Where the Scope 1 and Scope 2 reductions are large, normally, Scope 3 is still left underreported and under management, effectively limiting the overall effects [8]. The problem of regional disparities also adds to the improvement of progress, and uneven adoption is affected by the policy framework, climate conditions, and available financing capacity. The operational differences are aggravated by operational barriers where facility managers are mostly faced by enormous upfront costs, an abundance of old wisdom on sustainable healthcare design, and the absence of collaboration between architects and engineers, among the operational aspects [9]. The regulatory frameworks are also strictly focused on energy efficiency, disregarding other important dimensions as water, waste, and lifecycle carbon. The requirements bar the ability of the sector to meet the international decarbonization ambitions.

This paper will look into the impacts that the sustainability programs have on the design and operations of healthcare facilities and specifically discuss the type of strategies that can save on the GHG and encourage the development of low-carbon building techniques [10]. The primary query that needs to be addressed is how to ensure that the concept of sustainability can be used by the healthcare facilities in 2015-2025, what amounts of design efficiency should be achieved, and how operational performance increased, and how these interventions may be converted into the savings in carbon that may be measured. By adopting a multicase study format, the study would provide a descriptive and evidence-based vision on how healthcare facilities have been reshaped during this genuine decade of climate action through certain sustainability implementations.

The study contributes to the bodies of academic research and to the practice of sustainable healthcare infrastructure in two aspects. Theoretically, it contributes to the knowledge in terms of analysis of the functioning of the sustainability program when the design interventions, radiations on how the functions operate, and leadership involvement are analyzed simultaneously [11]. Most literature concentrates on either of these areas, focusing, therefore, on architectural performance or functional performance, neglecting the dependence of one aspect on another in terms of how to achieve high performance. Through a multi-case report technique and varying regions and climate conditions, this paper shows how the cooperating challenges of building strategies, management operations, and governance systems result in a quantifiable decrease in the amounts of energy consumption, emissions, and expenses [12]. Combining qualitative insights with longitudinal indicators present in 2015-2025 also becomes an important enhancement of the premise, as it will provide a more detailed idea of how international climate frameworks have been operationalized into institutional practice.

The research adds to the meetings of scholarly studies and to the practice of sustainable healthcare infrastructure in the following two ways. In theory, it adds to the knowledge on the analysis of the operations of the sustainability program once the interventions in the design, the radiations on how the functions will work, and the input of the leadership are studied concurrently. The majority of literature is limited to either of these aspects, with the result that and therefore, designers concerned with architectural performance, or functional performance with regards to high performance dependency, are forced to consider the other [13]. Based on the general method of multi-case reports, and different regions and climatic conditions, the paper

demonstrates how the joint issue of building tactics, managerial workings, and ministerial systems leads to a measured reduction in the quantities of energy use, emissions, and customer costs. The addition of qualitative insights with the longitudinal pointers currently observed in 2015-2025 will also constitute an upgrade of the premise, as it will give a wider image of the ways international climate structures have been translated into the institutional practice.

The research also comes up with practical implications for the healthcare managers, architects, and policymakers. Facilitate level evidence depicts the interventions with the most favorable payoff, such as the integrated energy management systems, the optimization of HVAC, and the adoption of renewable energy. Real-world examples operating in different environments demonstrate how barriers, including large start-up capital, lack of technical expertise, and lack of policy interface, can be conquered using select funding, policy, and the united efforts of leadership. The knowledge of the paper on the basis of practical recommendations based on empirical examples will give decision-makers sufficient space to develop the best strategies of sustainability, which will most effectively fit into the setting and will not undermine the global decarbonization targets. In so doing, it strengthens the bond between scholarly research and practice work in the transition to low-carbon healthcare.

## LITERATURE REVIEW

### International Sustainability and Low-Carbon Models.

The Paris Agreement (2015), which set the target of limiting the warming to 1.5- 2 degrees C, challenged fast. Decrease in emissions by all industries, including healthcare, of which its proportion is 4.4-5% of all global emissions. Emissions. Organisations such as the Health Care Without Harm and the UNFCCC Race to Zero have empowered hospitals to enter into a net-zero path. Environmental outcomes related to health. An enhanced performance based on Sustainable Development Goals and SDG 3, SDG 7, and SDG, in particular [14]. This adoption is evidenced by country commitments and national engagements, where the UK, Sweden, and Canada require. Emissions by 30-50 percent before 2030, in accordance with the national 2050 net-zero goal. These systems establish standards by which sustainability activities at the facility level are reviewed [15]. To have an interpretation of these ambivalent outcomes, the theoretical concepts that govern the dynamics of evolving sustainability transitions are necessary in complex systems. Sustainability transition theory focuses on the multi-level process of interaction that exists between niche innovations, institutional regimes, and larger socio-technical contexts [16].

### Design and Sustainability of a Healthcare Facility.

The design of the building is one of the major tools to decrease the carbon intensity of medical institutions that have a significant energy burden due to both HVAC systems and medical equipment [17]. Green buildings will incorporate both passive systems (natural ventilation, orientation, and insulation) and active systems, such as high-efficiency HVAC and on-site renewables. The potential is demonstrated through evidence in the Humber River Hospital, Toronto, where, being a fully digital enterprise, the hospital saved 29% of energy consumption and 42% of emission levels against the baseline standards due to being highly envelopeable and building automation [18]. Another additional benefit of renewable integration entails reinforcement of performance where solar photovoltaics, combined heat and power, and geothermal were able to cut off external electricity demand by 20-40% [19]. In healthcare institutions, measures like renewable energy systems or modular buildings are considered a niche domain of innovation that must be supported by the institution and realigned with its culture in terms of scaling [20]. Prefabricated construction and modular construction also increase the sustainability through reducing the amount of waste and facilitating lifecycles which are more efficient and flexible [21]. Nevertheless, it has not been significantly adopted in other related localities, especially the low and middle-income countries, where huge expenses on capital, as well as a lack of experience, particularly hinder green construction skills, hence the necessity to mentally compare the situations in various settings.

### Operational Sustainability Programs

The long-term performance of the healthcare facilities in terms of carbon is centrally organized based on operational practices. Energy watch schemes, waste recycling, water-saving, and staff- and patient-focused behavior-change programs are commonly used programs [22]. It is proven that digital building management and energy monitoring systems save 10-20% of electricity, and the training of staff allows saving money on a

particular basis with gradual but long-term returns [23]. Wastage is also another important issue in the industry: 0.5-1.0 kg of waste is produced per patient daily, and incineration of medical waste contributes to high emissions. At the facilities that have converted to waste segregation, recycling, and material replacement, reports of waste incineration-related reduction are documented by up to 25 percent. Water efficiency, like rainwater collection and low-flow fittings, has environmental incentives and financial outcomes, particularly in water-stricken areas [24]. Operational programs increase the effects of sustainability when implemented alongside design provisions, but there are still obstacles. These are a lack of involvement of staff members, a lack of budget to do the continuous monitoring, and the standardized forms of sustainability reporting, which are not established between institutions of healthcare institutions.

**Past Research in GHG Minimization in Health Care.**

There is an increasing empirical literature to assess the sustainability program results in healthcare facilities, with inconsistent and enlightening findings. In North America and Europe, a number of large hospitals have shown 30 percent or even more cuts in emissions by incorporating energy-efficient HVAC systems into the designs of their buildings, incorporating renewable energy generation, and improving building management technologies in their systems [2]. Even in Germany, Klinikum Neukolln has had a 40 percent reduction in the energy-related emissions after it installed a couple of retrofits that consisted of mixed facilities of renewable installations and insulation upgrades. The same situation was seen in hospitals in Brazil and Canada, which reported lives of over 40% of Scope 1 and Scope 2 emissions, which is in tandem with worldwide optimal methods/practices of carbon reduction [25]. Nevertheless, other facilities experienced minor improvements of less than 10 percent despite immense spending on developing the importance of organizational capacity, regulatory assistance, and working culture in defining the result [26]. The barriers most commonly observed in these studies are: cost and capital are high, access to financing is a problem, lack of skills in sustainable healthcare design, and their governance is fragmented and prevents them from collaborating in both spheres of design and operation. In addition, Scope 3 carbon emissions, that can account for more than half of a facility's carbon footprint in the form of supply chains, purchasing, and the transportation of patients, have not been adequately measured and addressed in the majority of publications.

**Literature Gap Identified**

Even though the empirical and theoretical research has improved, there are still critical research gaps. To start with, the majority of the current research is conducted as a single site or an extensive review of literature that compiles findings rather than considering the contextual differences in influencing the outcome [12]. There is are limited comparative understanding of different regions and climatic conditions, and hence no way of generalizing strategies in order to apply them globally. Second, studies do not apply the same approach to combining building design with operational management since experience in the real world shows them to be crucial to ensure permanent carbon cuts. Third, the temporal aspect has not been analyzed as extensively; a large number of studies failed not only to estimate the development of sustainability programs in the critical decade after the signing of the Paris Agreement (2015-2025) but also to trace the cumulative effects caused by these programs [14]. Lastly, Scope 3 emissions and the general institutional challenges to low-carbon transformation have not been studied to a large extent. Such gaps confirm the use of a multi-case study model that might combine design and operational priorities, replicate the regional diversity, and offer detailed and longitudinal evidence on how hospitals have considered the concept of sustainability in 2015-2025.

## METHODOLOGY

**Research Design**

As a part of the research, a multiple case study research technique is to be employed in the context of the selective qualitative research to quantify the influence that sustainability programs have on the healthcare facility design and operations. The method will be appropriate, as it brings an opportunity to study the way interventions are implemented in various institutional and geographical domains, and results dictated by the options of the management or operations. The construction gives the opportunity not only to investigate technical actions enablement, which involves not only power-efficient buildings and environment-friendly technologies but also organizational mechanisms, including the involvement of staff members and the top management team as well. Comparing a number of cases provides patterns and comparisons and environmental contexts that identify the efficiency of more sustainable initiatives.

**Case study Requirement criteria.**

The diversity and the close richness of information were brought on board through purposive sampling in case selection. Awareness: The five cases reflect North America (Canada), Europe (Germany), Latin America (Brazil), the Middle East (Saudi Arabia), a multi-site report, multiple area study, and consist of new builds, retrofits, and operating programs. The four criteria used in the selection included: (1) carrying out sustainability or low-carbon plans between 2015 and 2025, (2) accessibility of performance measures, i.e., energy consumption, GHG emissions or cost-savings, or certification, (3) recorded key leadership or managerial engagements in planning and execution, and (4) coverage of diverse regional, climatic settings. Table 1 provides an overview of each case by location, type, interventions, period, and data sources, and creates a structured reference to the follow-up within and cross-case analysis.

Table 1 shows an overview of selected case studies

| S.No | Case | Location | Type & Size | Key Interventions (Design & Operations) | Period | Data Sources |
|---|---|---|---|---|---|---|
| 01 | **Humber River Health** | Toronto, Canada | Digital hospital (~650 beds) | Building automation, demand management, and energy conservation planning | 2015–2025 | Institutional reports, audits |
| 02 | **Vivantes Klinikum Neukölln** | Berlin, Germany | Large teaching hospital | Retrofit program, renewable integration, staff engagement | 2010–2025 | Sustainability reports, peer-reviewed study |
| 03 | **Albert Einstein Hospital** | São Paulo, Brazil | ISO 50001-certified hospital | LED replacement, PV panels, ISO 14001/50001 integration, staff training | 2015–2025 | ISO case study, hospital documents |
| 04 | **As-Salam & HMG Sehat Al Sharq** | Saudi Arabia | Private hospitals | Energy-efficient design, sustainability programs aligned with Vision 2030 | 2015–2025 | Published qualitative study, leadership interviews |
| 05 | **Dion, Evans & Farrell Multi-Hospital Study** | Multi-country (MENA + global hospitals) | Multiple hospital sites (varied sizes) | Leadership interviews on sustainability adoption, ISO 50001 pathways, operational barriers/enablers | 2015–2025 | Peer-reviewed qualitative study |

**Data Sources and Collection**

The research is based on secondary information in terms of institutional reports and published case studies. Humber River Health, Vivantes Klinikum Neukolln, and Albert Einstein Hospital were used in the case of the extraction of detailed performance metrics due to peer-reviewed studies that offered insight into Saudi hospitals and the Dion, Evans, and Farrell multi-hospital case study. Evidence based on interviews was taken as the managerial view in Dion et al., and the records of executive supervision in Albert Einstein. Strategies on the facility level were framed in the context of policy frameworks like the Paris Agreement, the Sustainable Development Goals, and the Vision 2030 in Saudi Arabia. The review of the documents dealt with documents such as technical reports, certification records (LEED, ISO 50001, ISO 14001), conservation plans, and audits. The purposive sampling provided diversity and enriched information since each case will bring a different complex of design interventions, operational programs, and leadership practices to apply to the comparative analysis of the outcomes of sustaining healthcare.

**Data Analysis Approach**

There was a two-stage data analysis. The within-case analysis used the thematic framework proposed by Braun and Clarke through inductive and deductive coding to identify the strategies, operational practices, and leadership styles. Each of them was coded, and then cross-case synthesis was done using the comparative method developed by Yin in identifying leads and lags in the strategies, governance, and outcomes. The

coding shifted to axial coding and theme development, and the main themes in the analysis were design, operations, leadership, barriers, enablers, and performance results. The credibility of findings was increased with the help of triangulation of the information collected during the research of performance metrics and documents, as well as the information offered in the triangulation of interview data conducted with virtual encounters (Ross et al., 2011).

**Ethical Considerations**

In the case of published cases and secondary data, original authors and institutions have been recognized as providers of data. Intrapreferred interviews included in case materials treated, informed consent, anonymity as well and confidentiality were upheld by the original researchers. In case of further expansion of this research, which would conduct primary data collection, consent of the respective institutional ethics board will be taken so that ethical guidelines are met.

**Limitations**

The fact that a small number of cases were used helps to deepen analysis, yet limits us as to generalizability to the broad healthcare sector. The difference in data quality and availability across regions is also problematic; whereas other hospitals offer in-depth quantitative data on their own performance, other hospitals base their reporting on qualitative information or summary statistics. Besides that, successful results are also frequently emphasized in institutional case studies, which opens the risk of reporting bias. These are recognized, and the findings are studied cautiously with an emphasis on analytical generalization as opposed to statistical representativeness.

## RESULTS

**Case Study Overview and Analysis**

**Humber River Health (Canada)**

The 656-bed acute care Humber River Health in Toronto is a first-of-its-kind 100 percent digital hospital, and in its Conservation and Demand Management (CDM) program, the institution integrated sustainability [27]. Lighting, HVAC, and equipment automation systems plus retrofits including LED equipment installations and steam-trap repairs, led to electricity consumption of 1377,352 kWh (41.35 tCO2e), which saved CAD 175,000/ year. The 21,919 m3 of natural gas loss was removed with the use of steam-tap repair, which resulted in the termination of 43 tCO2e and saved CAD 8,300 in a year. Bedside energy intensity was enhanced, which was made possible through board-level governance between digital investments and sustainability objectives [25]. Factors that had impeded this were large capital expenses, legacy integration, and drivers were the digital-first design, effective governance, as well as provincial incentives.

**Vivantes Klinikum Neukolln (Germany)**

The Vivantes Klinikum Neukolln in Berlin had engaged in a 10-year retrofit project, which involved the streamlining of insulation, the building envelope, and renewables. Technical measures, such as staff engagement campaigns, led to a 40 percent reduction of CO2 and minimised electricity and heating demand. Increases of in efficiency price terminated in savings. Making developments was possible through leadership due to the phased nature of investments, except that it was hard to finance at all times, and constant care during retrofits was also a problem. The main enablers included participation of the staff, regulation, and long-term planning in the institution.

**Brazil hospital Albert Einstein (Hospital)**

The first hospital in Brazil certified under the ISO 50001 was Albert Einstein Hospital in Sao Paulo which incorporated energy and environmental management with LEED Gold extensions [18]. The design solutions incorporated LEDs and photovoltaics; the sustainability dashboard and the staff training were applied to consumption. Results resulted in a 16,654 GJ of energy savings (5.66% of the Morumbi unit use), 159.7 tCO 2 reduction, USD 395,896 of cost saved based on a USD 658,000 investment (1.66-year payback), and of water saved 27,600 m3. The use of diesels and gases decreased by 24 percent and 9 percent, respectively, and more than 50 percent of the non-hazardous garbage had been recycled. Governance by the executive members was in line with operational goals. Obstacles were training and capital expenses; sympathizers of these were the ISO recognition and good leadership [28].

**As-Salam & HMG Sehat Al Sharq (Saudi Arabia).**

These hospitals implemented energy-reachable relationships and functionality efficiency programs, in line with the Vision 2030. The leadership made it align with the national objectives, and made sustainability top of the executive agendas [29]. Despite the lack of quantitative data, it was demonstrated that there was an increase in the intensity of energy and awareness among patients and staff. Among the identified barriers were financing and cultural adjustment, with policy incentives and leadership campaigns among the enabling factors, noted during manager interviews.

**Dion, Evans, and Farrell Multi-hospital study (MENA + others)**

This paper served to discuss 8 hospitals by performing 24 executive interviews and managerial interviews. Implementation of ISO 50001 systems decreased electricity consumption to 130-200 kWh/m 2 versus 270-490 kWh/m 2 with the primary target of HVAC systems (56% of all demand) [18]. The systems optimization savings amounted to USD 93,240/year, and the savings in each operating room: USD 9,950/per policy. Sustainability became a cost-controlling and reputation strategy with leadership [30]. Weak regulatory frameworks and limited capital were the barriers, and the enablers consisted of executive sponsorship, ISO integration, and proven financial returns.

**Cross-Case Synthesis**

**Design Interventions and Low-Carbon Strategies**

The cases demonstrate that design interventions are not as situational as they are central. A study by Humber River Health in Canada has demonstrated the size of the potential of digital-first hospitals, with 1.37 million kWh of yearly electricity saved due to automation, LED retrofits, and building optimization. Likewise, combined LEED-certified Gold expansions were implemented in Albert Einstein Hospital in Brazil, together with photovoltaic systems and energy-efficient light sources, which lowered the consumption by 16654 GJ [31]. These two demonstrate that strong returns on the initial integration in design are substantial. Vivantes Klinikum Neukolln in Germany reported an outcome of the progress made through the retrofit pathway of CO2 reduction of 40 percent in lieu of incremental investments of insulation, improving the envelope, and using renewables. Conversely, Saudi hospitals have been pursuing compliance with the codes of Vision 2030, and few strategies have been obtained through the limits of capital and culture [32]. According to the multi-hospital research findings by Dion et al., it indicated that the gains in design can very easily collapse unless it is controlled and funded. TOG of these results demonstrates that new constructions are the most efficient ones, but retrofits become more effective when maintained with a gradual funding system and regulations.

**Operations through Sustainability Programs**

Results were consistent, all of which were largely motivated by operations. One of the results of the Conservation and Demand Management plan formulated by the city of Humber was natural gas conservation of 21,919 m3 through repairing steam-taped [33]. Interesting campaigns by the staff of Vivantes were being complemented with the technical improvements and materializing the process through introducing the new energy-conscious behaviour into everyday life. Einstein has made sustainability institutional by adopting ISO 50001 and ISO 14001 certification, and this has ensured that the management of energy and environmental considerations has been practiced in organizations [34]. The Saudi hospitals mainly used awareness programs due to their prevailing infant level of adoption. The validation was solid, and the energy consumption under the framework energy management dropped by 270-490 kWh/m2 to 130-200 kWh/m2 [11]. In all instances, HVAC systems turned out to be the overwhelming energy burden (~56%), which supports the inevitable necessity of specific intervention to regulate their operation.

**Leadership and Governance**

There was always decisive leadership. Humber had board-level control that made financial priority over CDM programs [14]. Researchers observed that ISO frameworks allow the executive committee at Einstein to match investments according to what was measurable, and at Vivantes, the leaders did not waver in their model, which was a ten-year-long retrofit [12]. Saudi facilities proved that they were in line with national objectives, but the cultural background of Saudis, as well as financial challenges, restricted implementation [18]. Dion et al. validated that executive sponsorship and governance structures stipulated the sustainability programs or abandoned ones [25]. The leadership style also influenced turnover of staff: apparent executive interest was associated with higher cultural uptake, whereas feeble management resulted in scanty uptake.

**Measures of Quantitative Performance.**

The divergence and the convergence are observed in the comparative review. The most detailed information was presented by Humber and Einstein as CAD 175,000 estimated in savings per annum and a 1.66-year investment payback, respectively. Other water savings that were recorded by Einstein included 27,600 m3, waste recycled over 50 percent, and lowered the use of diesel by 24 percent [27]. Vivantes had a 40 percent cut in CO2, which is hailed as an example of the retrofitted hospital. There were no detailed metrics in Saudi hospitals, but they displayed gradual efficiency improvements and changes of culture [20]. These gaps were closed by Dion et al., who ensured that operational interventions (such as the HVAC setbacks that resulted in USD 9,950 per operating room per year saved) are viable without being detrimental to the financial stability of a hospital [21]. Structured monitoring in cases (Humber, Einstein, Dion et al.) had good evidence on performance, and those without systems could hardly capture impacts.

**Barriers and Enablers**

Humber, Einstein, which has a short payback, Vivantes Co, which provided investments in shifts, and New Saudi facilities, which provided investments according to the state incentives, as the finances are the critical barrier to the justification of investments [3]. The technical problems were the digitisation of Humber and service continuity retrofits in Vivantes. Saudi Arabia was biased to cultural models and offered resistance in the form that the staff did not interact with leadership effectively, despite staff leadership orientation [13]. They were policy and certification frameworks that were always facilitators: in the case of Einstein hospital, external validation was given through the use of the ISO 50001 and the pressure through the German regulations and that set by Saudi Vision 2030 [27]. This engagement of the employees promoted progress, and Vivantes exploited the course initiatives of conduct. Einstein made use of formal training, and Humber associated monitoring with accountability.

**Synthesis of Findings**

The synthesis illustrates these designs that form eminent designs, and operation produces quantifiable returns, and leadership provides a financial and cultural mix. There is a large amount of energy and emissions which is saved and savings costs that can be achieved under any income and policy climate in which monitoring systems and the governor are promoted to work together [19]. The generated evidence reflects that healthcare sustainability is not contained in the concept of technology or capital investment but in how systems are designed and the design is assimilable to their practice and led through purposive institutional and policy systems.

## DISCUSSION

The five-case study analysis confirms the above statement that the three variables, design strategies, operational programs, and leadership, are effective most of all, as far as the sustainability of the healthcare facility is concerned [35]. The two cases had some different benefits, and it can be evaluated resting on their comparison how the low-carbon transitions are viewed and what variations may be considered the key trends and problems that condition the real character of how they may be attained [36]. It was discovered that design interventions are context-specific and simple. The low-carbon infrastructure of the initial stages, as evidenced by the design of Humber River Health and other LEED-certified expansions of Albert Einstein Hospital, showed that in the mid and low-density construction, initial provisions of low-carbon infrastructure were able to provide efficiency, albeit qualitatively and measurably [5, 37]. On the other hand, Vivantes Klinikum Neukolln had also realized similar improvements with gradual retrofits and documented that an old facility can also achieve high results through the aid of long-term planning. Saudi Arabian hospitals were implementing a model of compliance alone, have been battling with funding and culture, and a multi-hospital study conducted by Dion et al. has indicated that improvements in the design are insufficient without governance and operational follow-up. Toshiroguchi et al (2010) all suggest that design only generates capacity, whereas operational and managerial systems ultimately yield benefits [38, 39]. It continuously provides operational programs that are measurable in various situations. The demand management, as Humber River at the demand side and steam-tapping repairs by Einstein at the ISO 50001 integration, show how, at a relatively low price, energy and water efficiency could be ensured, as well as staff engagement campaigns, at Vivantes [34, 40]. This was supported by the Dion et al. study, which showed a decrease of up to 50 percent in the intensity of energy under the condition that structurally designed systems of management

were used [41]. Most notably, the HVAC was universally discovered to be the primary energy consumer, which validates the existence of desirable interventions concerning the area. These findings are according to the larger literature that terms operational optimization as the most scalable and cost-effective channel towards GHG minimization in healthcare plants [4]. The most critical issues that led to the notable differences between sustained success and incremental development were leadership and governance. High-quality executive supervision in Canada, Brazil, and Germany led to quantifiable outcomes in reduction, savings, and global accreditation [42]. The Saudi hospitals, on the other hand, emphasized the failure of the projects that were mainly policy compliance-led led with a lack of institutional buy-in through their executive sponsorship and leadership participation. Dion et al. also revealed that the incorporation of sustainability in organizational culture was impossible without leadership engagement and executive sponsorship [9]. The testimony strengthens the fact that technical measures cannot suffice, and unless the sustainability programs are surrounded by the leadership attained through accountability, monitoring, and prioritization of financial needs, sustainability programs would remain vulnerable. Other barriers and enablers are also significant based on comparative synthesis [43]. Financial costs were an obstacle in both front most cases and especially in middle-income settings. Cases like Einstein and Humber, however, proved that well-established monitoring models and definitive payback can be reinvested in and scaled up the program [44]. Examples of external enablers were policy structures, either being ISO certified, through national energy conservation programs, or the Saudi Arabian Vision 2030 [10]. Another facilitating factor was staff engagement, which Vivantes demonstrated can intensify technical retrofits. In general, the results substantiate the idea that when sustainability is integrated on several levels, the healthcare facilities can record substantial energy consumption, emissions, and cost cuts [45]. The overlap of cases demonstrates that results are most robust in a situation when design offers potential, operations efficiency, and leadership maintains focus [33]. Simultaneously, the comparisons of the situation in the high- and middle-income areas indicate that the model of financing, the support of the policy, and cultural adaptation are the critical problems on the way to universal improvement.

## CONCLUSION

This paper has explored how sustainability programs affect the design and operation of healthcare facilities using a multiple case study to cover five different situations, which are Humber River Health in Canada, Vivantes Klinikum Neukolln in Germany, Albert Einstein Hospital in Brazil, As-Salam and HMG Sehat Al Sharq in Saudi Arabia, and the Dion et al. multi-hospital leadership study. The research collected the environmental and financial performance through thematic and cross-case analysis so as to identify how design strategies, operational programs, and leadership practices come together to contribute to environmental and financial performance. The findings demonstrate the structural capacity of efficiency resulting in design interventions, scalable instantaneous and long-term benefits in operation measures, and integration based in leadership is essential to incorporate it through governance, financing, and culture. Integrated facilities with all the three dimensions performed better. The quantitative indicators ensured the realization of significant improvements: Humber managed to save over 1.3 million kWh of energy per year, Einstein was able to cut down on 16,654 GJ, and a 1.66-year payback, and Violettes saved at least 40 percent of CO2 with the assistance of retrofits. The Saudi hospitals showed a gradual advancement in line with the vision 2030, and the Dion et al. research supported the importance of leadership in promoting the energy management standard within the systems of the hospital. The cases bring out three lessons that are recurrent. To start with, energy management systems as well as specific programs, that is, HVAC optimization provided the high financial profit, as well as quantifiable emission measures. Moreover, the competence of leadership, in terms of executive sponsorship, in the form of certifications of the ISO, or the national frameworks, is important to maintain the progress moving. Besides, strong monitoring and reporting systems endure warranted and certified accomplishments and attract future making up of capital. The findings confirm that the medical field has achieved sustainability not through separate solutions but a mix of technology, process, and structure solutions. The evidence, as applied to practitioners in high- and middle-income settings, entails the fact that new and existing facilities can be rearranged to regain significant losses of efficiency in case both the design, operations, and leadership are arranged in a superior manner. Their results to the policymakers and institutional leaders consolidate the elements of regulatory frameworks, monetary motivation, and

certification programmes as low-carbon healthcare enablers programmes in the long term. Overall, in this research, sustainable healthcare is demonstrated to be possible with the assistance of purposeful design choices, created operation programs, and focused management.

**Recommendations**

The leaders of the facilities need to develop the integrated systems of energy and environmental management having clear monitoring, reporting, and accountability. Those high consumption areas that require optimization where the high levels of optimization provide great savings on cost and air emissions should have priority. To mitigate on capital barriers, policymakers need to tighten the regulatory elements and offer monetary prods to encourage certification schemes including ISO 50001 and LEED to enhance perpetual enhancement. Where intermediate incomes are between 3,500 and 10,000 dollars, mid-income schemes that combine public and privates funding can boost retrofits and uptake of renewables faster. Sustainability should be part of the strategic plans and budgets of the hospital, with the continuity should be supported by the executive [28]. Technical measures should be included with staff training and behavioral programs in ensuring cultural adoption.

**Constraints and Future Implications.**

The present research design utilized a multiple case study research design which provided an in-depth analysis but poor external validity. Data availability was somewhat different with Humber River Health and Albert Einstein Hospital indicating in depths about the quantitative indicators whereas Saudi hospitals had most of their findings as qualitative or compliance based, limiting the comparisons made [46]. Relying on published case studies is also prone to bias in reporting since the institutions might focus their attention on achievement at the expense of problems. The focus on hospitals where sustainability programs are developed provided a selection bias on advanced adopters. Even though the managerial views were included in the study by Dion et al., the lack of primary interviews in this study predetermined with diminished chances to investigate further the developing themes [1]. Future studies must be able to introduce primary qualitative interview and ethnographic study over a larger range of facilities involving under-resourced hospitals to reflect on ignored barriers. It should also be evaluated through longitudinal studies that can ascertain the development of the outcomes in the presence of changing conditions of policy and funds. The inclusion of life-cycle assessment and Scope 3 emissions data would give a better picture of the size of the healthcare carbon footprint and would make sure there are evidence-based avenues towards the systemic decarbonization.

**REFERENCES**

[1] B. Badanta *et al.*, "Advancing Environmental Sustainability in Healthcare: Review on Perspectives from Health Institutions," *Environments,* 2025-01-03 2025, doi: 10.3390/environments12010009.

[2] N. F. Arenas and M. Shafique, "Recent progress on BIM-based sustainable buildings: State of the art review," *Developments in the Built Environment,* 2023-05-01 2023, doi: 10.1016/j.dibe.2023.100176.

[3] R. Alotaiby and É. Krenyácz, "Energy efficiency in healthcare institutions," *Society and Economy,* 2023-07-04 2023, doi: 10.1556/204.2023.00013.

[4] A. Wilkinson *et al.*, "Environmental Sustainability in Respiratory Care: An Overview of the healthCARe-Based envirONmental Cost of Treatment (CARBON) Programme," *Advances in Therapy,* vol. 39, pp. 2270-2280, 2022-03-13 2022, doi: 10.1007/s12325-022-02076-7.

[5] S. Wagrell, M. Havenvid, Å. Linné, and V. Sundquist, "Building sustainable hospitals: A resource interaction perspective," *Industrial Marketing Management,* 2022-10-01 2022, doi: 10.1016/j.indmarman.2022.09.008.

[6] A.-M. Sumayya *et al.*, "Effect of Healthcare Facilities on Climate Change: A Systematic Review of the Carbon Footprint of the Nigerian Healthcare Sector," *International Journal of TROPICAL DISEASE & Health,* 2023-08-17 2023, doi: 10.9734/ijtdh/2023/v44i141455.

[7] P. Slathia, D. A. Vashishtha, D. P. K. Jena, and D. P. K. Sahu, "Examining the dynamic impact of carbon emissions, renewable energy and economic growth on healthcare expenditure in Asian countries," *Heliyon,* vol. 10, 2024-04-01 2024, doi: 10.1016/j.heliyon.2024.e30136.

[8] M. Sergeant *et al.*, "Identifying Opportunities for Greenhouse Gas Reductions and Cost Savings in Hospitals: A Knowledge Translation Tree," *Healthcare quarterly,* vol. 25 3, pp. 18-24, 2022-10-01 2022, doi: 10.12927/hcq.2022.26946.

[9] P. A. Prasad *et al.*, "Environmental footprint of regular and intensive inpatient care in a large US hospital," *The International Journal of Life Cycle Assessment,* vol. 27, pp. 38-49, 2021-12-04 2021, doi: 10.1007/s11367-021-01998-8.

[10] R. Mehra and M. Sharma, "Measures of Sustainability in Healthcare," *Sustainability Analytics and Modeling,* 2021-01-01 2021, doi: 10.1016/j.samod.2021.100001.

[11] C. Meena *et al.*, "Innovation in Green Building Sector for Sustainable Future," *Energies,* 2022-09-10 2022, doi: 10.3390/en15186631.

[12] S. AlHilali, H. B. Helayel, and S. Al-Swailem, "Advancing Sustainability in Ophthalmic Surgeries and Interventions: A Narrative Review of Environmental Impact and Best Practices," *Clinical Ophthalmology (Auckland, N.Z.)*, vol. 19, pp. 713-720, 2025-02-01 2025, doi: 10.2147/OPTH.S511472.

[13] S. Akinola and L. Obokoh, "Opportunities and challenges of empowering SMEs for sustainable Healthcare delivery," *Journal of Infrastructure, Policy and Development*, 2024-01-03 2024, doi: 10.24294/jipd.v8i2.2579.

[14] S. Akdağ and H. Yıldırım, "Toward a sustainable mitigation approach of energy efficiency to greenhouse gas emissions in the European countries," *Heliyon*, vol. 6, 2020-03-01 2020, doi: 10.1016/j.heliyon.2020.e03396.

[15] E. Alsawaf and A. Albadry, "Principles for the Sustainable Design of Hospital Buildings," *International Journal of Sustainable Development and Planning*, 2022-10-21 2022, doi: 10.18280/ijsdp.170614.

[16] Y. Labaran, V. Mathur, S. U. Muhammad, and A. A. Musa, "Carbon footprint management: A review of construction industry," *Cleaner Engineering and Technology*, 2022-07-01 2022, doi: 10.1016/j.clet.2022.100531.

[17] M. Jaušovec and B. Gabrovec, "Architectural Evaluation of Healthcare Facilities: A Comprehensive Review and Implications for Building Design," *Buildings*, 2023-11-23 2023, doi: 10.3390/buildings13122926.

[18] A. Hussain, M. Umair, S. Khan, W. Alonazi, S. S. Almutairi, and A. Malik, "Exploring sustainable healthcare: Innovations in health economics, social policy, and management," *Heliyon*, vol. 10, 2024-06-01 2024, doi: 10.1016/j.heliyon.2024.e33186.

[19] P. Hohne, K. Kusakana, and B. Numbi, "Improving Energy Efficiency of Thermal Processes in Healthcare Institutions: A Review on the Latest Sustainable Energy Management Strategies," *Energies*, 2020-01-24 2020, doi: 10.3390/en13030569.

[20] P. Gonzalez-Pizarro *et al.*, "European Society of Anaesthesiology and Intensive Care consensus document on sustainability: 4 scopes to achieve a more sustainable practice," *European journal of anaesthesiology*, 2024-01-19 2024, doi: 10.1097/EJA.0000000000001942.

[21] A. Franco, M. Shaker, D. Kalubi, and S. Hostettler, "A review of sustainable energy access and technologies for healthcare facilities in the Global South," *Sustainable Energy Technologies and Assessments*, vol. 22, pp. 92-105, 2017-08-01 2017, doi: 10.1016/J.SETA.2017.02.022.

[22] C. Corvalan *et al.*, "Towards Climate Resilient and Environmentally Sustainable Health Care Facilities," *International Journal of Environmental Research and Public Health*, vol. 17, 2020-11-28 2020, doi: 10.3390/ijerph17238849.

[23] L. Chen *et al.*, "Green construction for low-carbon cities: a review," *Environmental Chemistry Letters*, vol. 21, pp. 1627-1657, 2023-01-18 2023, doi: 10.1007/s10311-022-01544-4.

[24] A. Balabel and M. Alwetaishi, "Toward Sustainable Healthcare Facilities: An Initiative for Development of "Mostadam-HCF" Rating System in Saudi Arabia," *Sustainability*, 2021-06-15 2021, doi: 10.3390/SU13126742.

[25] H. A. Amosh and S. Khatib, "Environmental Innovation and Carbon Emissions reduction in European Healthcare: The Moderating Role of Environmental Monitoring Practices," *Cleaner and Responsible Consumption*, 2025-01-01 2025, doi: 10.1016/j.clrc.2025.100255.

[26] F. Althoey, W. Ansari, M. Sufian, and A. Deifalla, "Advancements in low-carbon concrete as a construction material for the sustainable built environment," *Developments in the Built Environment*, 2023-11-01 2023, doi: 10.1016/j.dibe.2023.100284.

[27] S. K. Ak and S. Yılmaz, "CORPORATE SUSTAINABILITY IN THE HEALTH SECTOR: A THEORETICAL FRAMEWORK," *Journal of Empirical Economics and Social Sciences*, 2023-10-10 2023, doi: 10.46959/jeess.1333490.

[28] T. H. Koo, X. B. Leong, Y. L. Lee, M. H. Zakaria, and A. Zakaria, "Implementation of Green Surgery Approach in Healthcare System and its Effect on Carbon Footprint Reduction in Operating Theatres," *The Malaysian Journal of Medical Sciences : MJMS*, vol. 32, pp. 56-68, 2025-02-01 2025, doi: 10.21315/mjms-11-2024-884.

[29] S. Johnson *et al.*, "Sustainability in surgical practice: a collaborative call toward environmental sustainability in operating rooms," *Surgical Endoscopy*, vol. 38, pp. 4127-4137, 2024-07-01 2024, doi: 10.1007/s00464-024-10962-0.

[30] M. Golbazi and C. Aktas, "LEED CERTIFICATION AND PATIENT WELLBEING IN GREEN HEALTHCARE FACILITIES," *Journal of Green Building*, 2020-09-01 2020, doi: 10.3992/jgb.15.4.3.

[31] K. B. De Oliveira and O. De Oliveira, "Making Hospitals Sustainable: Towards Greener, Fairer and More Prosperous Services," *Sustainability*, 2022-08-08 2022, doi: 10.3390/su14159730.

[32] S. Annura, J. Arabikum, R. Aminingrum, Z. Ulu, D. Wahyudi, and L. Zuhriyah, "EFFICIENT AND SUSTAINABLE ENERGY MANAGEMENT FOR HOSPITAL BUILDING," *Journal of Community Health and Preventive Medicine*, 2022-09-05 2022, doi: 10.21776/ub.jochapm.2022.002.02.1.

[33] Y. Komenan, "Impact of Green Energy Transition on Healthcare Infrastructure: A Case Study of MRI Systems," *Journal of Scientific Research and Reports*, 2025-03-20 2025, doi: 10.9734/jsrr/2025/v31i32891.

[34] F. Moldovan, L. Moldovan, and T. Bataga, "Assessment of Labor Practices in Healthcare Using an Innovatory Framework for Sustainability," *Medicina*, vol. 59, 2023-04-01 2023, doi: 10.3390/medicina59040796.

[35] L. Xu *et al.*, "The Role of Healthcare Employees' Pro-Environmental Behavior for De-Carbonization: An Energy Conservation Approach from CSR Perspective," *Energies*, 2022-05-07 2022, doi: 10.3390/en15093429.

[36] K. Wyssusek, K. Lo Chan, G. Eames, and Y. Whately, "Greenhouse gas reduction in anaesthesia practice: a departmental environmental strategy," *BMJ Open Quality*, vol. 11, 2022-08-01 2022, doi: 10.1136/bmjoq-2022-001867.

[37] A. Waqar, I. Othman, N. Saad, M. Azab, and A. M. Khan, "BIM in green building: Enhancing sustainability in the small construction project," *Cleaner Environmental Systems*, 2023-10-01 2023, doi: 10.1016/j.cesys.2023.100149.

[38] Z. Ullah, A. R. Nasir, F. Alqahtani, F. Ullah, M. J. Thaheem, and A. Maqsoom, "Life Cycle Sustainability Assessment of Healthcare Buildings: A Policy Framework," *Buildings*, 2023-08-23 2023, doi: 10.3390/buildings13092143.

[39] A. Soares *et al.*, "A Review of the Applicability of Current Green Practices in Healthcare Facilities," *International Journal of Health Policy and Management,* vol. 12, 2023-05-07 2023, doi: 10.34172/ijhpm.2023.6947.

[40] M. Yang *et al.*, "Advancing environmental sustainability in construction through innovative low-carbon, high-performance cement-based composites: A review," *Materials Today Sustainability,* 2024-02-01 2024, doi: 10.1016/j.mtsust.2024.100712.

[41] C. Xi and S.-J. Cao, "Challenges and Future Development Paths of Low Carbon Building Design: A Review," *Buildings,* 2022-02-02 2022, doi: 10.3390/buildings12020163.

[42] J. Read and C. Meath, "A Conceptual Framework for Sustainable Evidence-Based Design for Aligning Therapeutic and Sustainability Outcomes in Healthcare Facilities: A Systematic Literature Review," *Herd,* vol. 18, pp. 86-107, 2024-12-10 2024, doi: 10.1177/19375867241302793.

[43] K. Pickles *et al.*, "Clinician and health service interventions to reduce the greenhouse gas emissions generated by healthcare: a systematic review," *BMJ Evidence-Based Medicine,* vol. 29, 2024-05-01 2024, doi: 10.1136/bmjebm-2023-112707.

[44] S. Mousa, J. Fernandez-Crehuet, and Yousef Ayman Y. Thaher, "Advancing Sustainable Performance in Healthcare: Mediating Roles of Green HRM and Green Innovation Under Green Transformational Leadership," *Business Strategy and the Environment,* 2025-03-17 2025, doi: 10.1002/bse.4238.

[45] D. Licina, P. Wargocki, C. Pyke, and S. Altomonte, "The future of IEQ in green building certifications," *Buildings and Cities,* 2021-01-01 2021, doi: 10.5334/bc.148.

[46] M. Costa, M. De Fátima Castro, and R. Mateus, "Methodology to Identify and Prioritise the Sustainability Aspects to Be Considered in the Design of Brazilian Healthcare Buildings," *Applied Sciences,* 2023-03-16 2023, doi: 10.3390/app13063807.