Optimization of radiotherapy infrastructure in cancer treatment facilities: A comprehensive review of strategies for treatment efficiency and patient safety

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► ***Review article***

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ABSTRACT

Background: Optimizing radiotherapy infrastructure is essential for delivering safe and effective cancer treatments while minimizing costs and improving sustainability. ***Materials and Methods:*** A narrative review was conducted using PubMed, Scopus, and Web of Science (2015–2024) with the terms “radiotherapy,” “infrastructure,” “energy efficiency,” and “patient safety.” Inclusion criteria focused on studies addressing energy systems, treatment planning technologies, and infrastructure optimization in cancer facilities. A case study of the Xinhua Cancer Center (Shandong, China) was also analyzed, including renewable energy integration, shielding layouts, and AI-driven maintenance strategies. ***Results:*** The literature review identified key strategies such as advanced electrical layouts, real-time dosimetry, AI-assisted planning, and integration of renewable energy. The Xinhua Cancer Center case demonstrated that solar (78,336 kWh/day), wind (1,071 kWh/day), and battery storage (200 kWh/day) provided 87.2% of energy needs, reducing treatment downtime to 12.6%. Ergonomic layouts decreased procedural errors by 17% and improved treatment readiness by 12%. Predictive maintenance lowered equipment downtime by 30% and improved treatment accuracy by 25%. Challenges included retrofitting costs (USD 80–250/m²) and regulatory constraints. ***Conclusion:*** Optimized radiotherapy infrastructure can substantially enhance treatment efficiency and patient safety. Future directions include AI-based treatment algorithms, hybrid energy storage, smart grid integration, and block chain-secured patient records.

INTRODUCTION

Modern radiotherapy is a cornerstone of cancer treatment, but its increasing technological complexity places unprecedented demands on hospital infrastructure. Cancer centers operate continuously, relying on energy-intensive equipment such as linear accelerators, computed tomography scanners, and real-time dosimetry systems, all of which require an uninterrupted and reliable power supply [1]. Together with lighting, HVAC (heating, ventilation, and air conditioning), and emergency backup mechanisms, oncology departments are among the most energy-consuming units in healthcare facilities [2].

Infrastructure optimization in radiotherapy encompasses efficient electrical distribution, radiation shielding, standby power systems, and integration with mechanical subsystems such as precision cooling for accelerators [3, 4]. Without systematic optimization, outdated designs, inefficient load balancing, or aging equipment increase both energy costs and operational risks. At the same time, global sustainability goals and financial constraints require solutions that minimize resource consumption while maintaining patient safety and treatment accuracy [5].

Recent research highlights strategies such as high-efficiency cooling systems, renewable energy integration, smart building automation, and predictive maintenance to improve both cost efficiency and reliability [6–9]. However, these studies typically address infrastructure elements in isolation - focusing either on energy performance, safety, or cost management - without providing a comprehensive framework tailored to radiotherapy facilities.

The present review fills this gap by synthesizing evidence across multiple domains - energy efficiency, redundancy planning, AI-driven optimization, and renewable integration - while illustrating practical applications through a case study of the Xinhua Cancer Center in Shandong, China. Unlike earlier reviews, this work emphasizes treatment efficiency and patient safety as dual outcomes of infrastructure optimization, an aspect often overlooked in previous studies. It also highlights novel directions such as AI-assisted planning, hybrid storage systems, and block chain-secured patient data.

To the best of our knowledge, this is the first review to explicitly integrate infrastructure optimization strategies with clinical performance outcomes in radiotherapy facilities. This novelty lies in demonstrating how technical interventions - traditionally viewed as engineering concerns - directly influence patient safety and treatment reliability in oncology. By combining a comprehensive literature review with an in-depth hospital case study, this manuscript provides new insights into sustainable design and clinical performance in modern cancer care. The following section outlines the methodology used for this review.

MATERIALS AND METHODS

Literature search strategy

This study followed a structured **narrative review approach**. A comprehensive search was conducted in PubMed, Scopus, and Web of Science to identify relevant studies published between January 2015 and March 2024. The search terms combined variations of "radiotherapy," "infrastructure," "cancer treatment facilities," "energy efficiency," "patient safety," "redundancy," "smart grid," "renewable energy," and "hospital optimization." Additional references were identified by screening the bibliographies of retrieved articles and relevant reviews.

Inclusion and exclusion criteria

Studies were included if they: (i) addressed infrastructure, energy systems, or optimization strategies in radiotherapy or oncology facilities; (ii) were peer-reviewed and published in English; and (iii) reported outcomes related to efficiency, reliability, safety, scalability, or sustainability. Studies were excluded if they consisted only of conference abstracts, if they were focused exclusively on non-medical buildings, or if they were published before 2015 unless considered of historical significance.

Data extraction and thematic synthesis

From each eligible study, data regarding study objectives, targeted infrastructure domains, optimization strategies, reported outcomes, and study limitations were extracted. Findings were analyzed thematically, which allowed categorization into five domains: energy consumption and optimization, reliability and redundancy, energy efficiency measures, safety and compliance, and scalability with emerging technologies. This approach provided a structured synthesis of existing evidence and facilitated comparison across studies.

Case study methodology

To complement the literature review, a case study of the Xinhua Cancer Center in Shandong, China, was performed. Data sources included institutional operational reports, energy audits, and infrastructure design documents. The evaluation focused on renewable energy integration through solar, wind, and battery storage systems, as well as electrical layout and shielding designs. The analysis further included the implementation of AI-based monitoring and predictive maintenance systems. Facility performance data, such as treatment downtime, procedural error rates, and operational efficiency before and after optimization, were assessed. These outcomes were compared with the themes identified in the literature to highlight convergences, practical implications, and areas where further evidence is needed.

RESULTS

Energy consumption and optimization needs

Cancer treatment facilities are among the most energy-intensive healthcare environments because they operate continuously and rely on high-demand technologies such as linear accelerators, CT scanners, and real-time dosimetry systems. Studies show that radiotherapy units consume substantially more energy per square meter compared with general hospitals, with cooling and ventilation systems alone accounting for nearly half of total energy use [10, 11]. In China, reported consumption ranges from 125 to 226 kWh/m^2 annually depending on climate, facility size, and operational practices [12].

Optimization measures, including adaptive cooling systems, demand-controlled ventilation, and energy recovery devices, have demonstrated savings of 15–40% while maintaining equipment stability and patient comfort [13]. These strategies directly reduce treatment downtime by preventing overheating and ensuring consistent equipment performance, which is critical for patient safety. A summary of energy-related systems and their clinical implications is presented in table 1.

Annual electricity consumption across different Chinese cities also demonstrates large regional variation, with Beijing hospitals reaching 226 kWh/m^2·a compared to 125 kWh/m^2·a in Yantai. This highlights the influence of climatic conditions and infrastructure design. These differences are visualized in figure 1.

Reliability and redundancy

Reliable power supply is essential in radiotherapy facilities, where treatment interruptions may compromise therapeutic accuracy and patient outcomes. Redundant systems such as uninterruptible power supplies (UPS) and backup generators are widely recommended [14]. Fail-safe

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distribution designs and dual power feeds reduce risks of outage-related treatment delays [15]. Recent work has emphasized the integration of predictive fault detection into redundancy systems, enabling early detection of equipment strain and reducing unexpected downtime (160. A synthesis of research findings on reliability and redundancy is summarized in table 2.

Table 1. Summary of energy-related systems in radiotherapy infrastructure.

System/Feature	Function	Energy Impact	Health/Treatment Benefit	Standard/References
Cooling Systems (Centralized)	Cooling for linear accelerators and treatment rooms	~50% of facility energy use	Maintains equipment functionality, ensures patient safety	Maddalena *et al.* [12]
Adaptive Cooling Systems	Variable cooling responsive to equipment load	15–30% energy savings	Prevents overheating, ensures treatment precision	Maddalena *et al.* [12]
Demand-Controlled Ventilation	Adjusts ventilation by occupancy/CO_2 sensors	Reduced overuse	Improves air quality, lowers infec-tion risk	Maddalena *et al.* [12]
Energy Recovery Ventilators	Reuse exhaust heat	15–40% reduction in cooling/heating load	Maintains recovery environments	Delgado *et al.* [11]
Humidity Control Systems	Maintain indoor RH 30–60%	Reduces HVAC load	Prevents mold, supports respiratory health	Maddalena *et al.* [12]
Double-Pipe Heat Exchanger	Pre-treats ventilation air	Cuts cooling/heating loads in humid zones	Improves air quality, supports sterile rooms	Ghani *et al.* [9]
Circadian Lighting	Tuned lighting by time of day	LED-based savings	Enhances recovery, staff alertness	Delgado *et al.* [11]

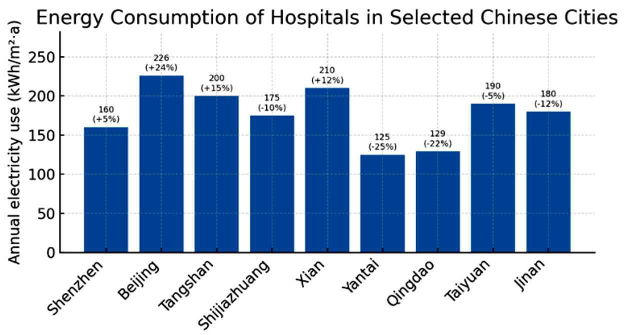

Figure 1. Annual electricity consumption of hospitals in selected Chinese cities (kWh/m²·a). Values in parentheses indicate relative mean difference compared to dataset average. Data adapted from Shi *et al.* [14].

Table 2. Strategies to optimize reliability and redundancy in radiotherapy infrastructure.

Strategy	Description	Impact on Reliability	Implementation Considerations
UPS (Uninterruptible Power Supply)	Battery-based backup for treatment equipment	Prevents interruptions during outages	Requires regular battery maintenance
Backup Generators	Onsite fuel-based power for critical units	Supports extended power loss	Must comply with environmental and safety standards
Dual Power Feeds	Two independ-ent feeds from grid	Reduces outage risk	Higher upfront infrastructure costs
Predictive Fault Detection	AI/IoT sensors monitor system health	Early detection, minimizes downtime	Requires trained staff and real-time monitoring

Energy efficiency strategies

Several studies have documented the impact of energy-efficient technologies in oncology centers. LED lighting, advanced insulation, high-efficiency chillers, and building automation systems can collectively reduce facility energy consumption by 20 -40% [17]. On-site renewable energy generation, particularly through solar photovoltaics, has been shown to offset up to 30% of electricity demand [18]. Integrating predictive maintenance using artificial intelligence (AI) further improves equipment uptime and energy performance [19]. Table 3 outlines representative efficiency strategies and their impacts.

Safety and compliance

Infrastructure safety standards are critical to protect both patients and staff. Compliance with the National Electrical Code (NEC), international radiation shielding guidelines, and robust grounding systems reduces hazards such as power surges, electrical faults, and exposure risks [20]. Case studies report that adherence to rigorous safety protocols lowers the incidence of equipment malfunction and enhances confidence in treatment reliability [21]. Research gaps and compliance-related issues are summarized in table 4.

Table 3. Energy efficiency strategies in radiotherapy infrastructure.

Category	Optimization Strategy	Energy Efficiency Impact	Clinical/Operational Benefit
Cooling Systems	High-efficiency chillers (≥ IEER 15)	20–30% less cooling energy	Stable operation of accelerators
Ventilation	Demand-controlled ventilation	10–25% savings	Air quality and infection control
Energy Recovery	Heat exchangers, ERVs	15–40% recovery	Optimal patient/staff comfort
Lighting	LED replacement	40–60% less lighting energy	Better visibility, low heat load
Lighting Controls	Dimming, daylight sensors	20–40% savings	Eye comfort, reduced strain
Building Envelope	Insulation, glazing upgrades	10–20% HVAC savings	Consistent sterile environment
Renewables	Rooftop solar PV	Up to 30% offset	Reduced carbon footprint

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Table 4. Safety, scalability, and smart technologies in radiotherapy infrastructure.

Aspect	Strategy	Outcome	Future Research Needs
Safety & Compliance	NEC grounding, radiation shielding	Prevents hazards, ensures regulatory compliance	Long-term impacts of compliance on equipment life
Scalability	Modular infrastructure, flexible layouts	Supports new radiotherapy technologies	Cost-benefit of scalable vs. fixed designs
Smart Tech	IoT-based monitoring, predictive maintenance	Real-time reliability, reduced downtime	Integration with AI-driven fault detection
Redundancy	Hybrid battery–generator systems	Enhanced resilience during outages	Evaluation of hybrid systems in cancer centers
Renewable Integration	Solar + wind + storage	Lower costs, reliable backup	Financial feasibility in diverse climates

Scalability and flexibility

The growing patient burden and rapid advances in radiotherapy technologies demand scalable infrastructures. Flexible designs accommodate new modalities such as image-guided radiotherapy, proton therapy, or AI-assisted planning systems without costly overhauls [22]. Studies highlight that scalable infrastructure reduces long-term expenditures while enabling facilities to keep pace with innovations in cancer care [23].

Smart grid and IoT applications

The integration of smart grid technologies improves efficiency, resilience, and sustainability in hospital power systems. Internet of Things (IoT)-based monitoring devices allow real-time tracking of energy flows across departments, enabling dynamic redistribution to prioritize radiotherapy suites during peak use [24]. AI-driven demand response algorithms predict high-load periods based on patient schedules and environmental conditions, balancing supply with clinical demand [25]. Predictive maintenance frameworks using IoT data have demonstrated significant reductions in unplanned equipment downtime, enhancing treatment reliability [26].

Renewable and sustainable energy integration

The deployment of renewable energy solutions has become a cornerstone of sustainable oncology infrastructure. Solar panels, wind energy, and hybrid battery storage systems reduce dependence on the public grid and enhance resilience during outages. Microgrid models enable localized energy management, ensuring critical radiotherapy equipment remains functional even in unstable external power conditions [27]. Studies confirm that renewable integration not only decreases operational costs and carbon emissions but also improves continuity of care, reducing the risk of treatment interruptions during grid failures [28].

Case study: Xinhua cancer center

Facility backgrounds

The Xinhua Cancer Center in Shandong, China, is a large tertiary oncology hospital with 1,500 inpatient beds and a built area of 256,000 m^2. The center operates continuously and relies on high-energy modalities including linear accelerators, computed tomography (CT), magnetic resonance imaging (MRI), and real-time dosimetry systems. Prior to optimization, the facility faced high electricity costs, frequent equipment downtime, and increasing regulatory pressures for energy efficiency. These challenges created an opportunity to evaluate infrastructure interventions aimed at improving both treatment reliability and sustainability.

Optimization interventions

Beginning in 2019, the hospital introduced multiple infrastructure upgrades. The electrical layout was redesigned to incorporate renewable energy systems, including a 12 MW rooftop solar photovoltaic array generating an average of 78,336 kWh per day and a wind power system producing 1,071 kWh per day. A hybrid lithium-ion battery storage unit with a capacity of 200 kWh was installed to provide short-term backup during peak loads and grid disturbances. Ergonomic zoning of shielding and control areas was also implemented to minimize radiation exposure and streamline clinical workflow.

Smart grid integration enabled real-time redistribution of power across oncology departments, while predictive maintenance algorithms were applied to monitor linear accelerators and imaging devices. These measures were further supported by building automation systems (BAS) for centralized management of lighting, HVAC, and energy distribution [29, 30].

Operational outcomes

Following optimization, renewable energy sources supplied 87.2% of the facility's daily electricity demand, substantially reducing reliance on the public grid. Treatment downtime decreased to 12.6% compared with baseline rates above 20%, reflecting improvements in both power reliability and predictive maintenance. Ergonomic redesign of treatment zones lowered procedural error rates by 17% and increased treatment readiness by 12%. AI-based predictive maintenance and automated dosimetry calibration reduced unplanned equipment downtime by 30% and improved radiation delivery accuracy by 25%.

Despite these improvements, challenges remained. Retrofitting costs were estimated at USD 80–250 per square meter, posing financial burdens, while regulatory delays hindered rapid adoption of

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renewable energy solutions [31-33].

Implications for treatment efficiency and patient safety

The case study demonstrates that infrastructure optimization can directly influence clinical outcomes. Enhanced energy reliability and redundancy reduced the frequency of treatment interruptions, ensuring consistent fraction delivery and minimizing deviations from prescribed treatment plans. Ergonomic shielding layouts and control zones supported staff safety while reducing treatment errors. AI-driven predictive maintenance improved treatment accuracy, lowering the likelihood of suboptimal dose delivery.

By aligning sustainability goals with clinical performance, the Xinhua Cancer Center illustrates how infrastructure planning can serve as a foundation for operational efficiency and patient safety in modern oncology.

DISCUSSION

This review demonstrates that optimization of radiotherapy infrastructure can significantly improve the efficiency, safety, and sustainability of cancer treatment facilities. Evidence from the literature confirms that oncology departments are among the most energy-demanding environments in healthcare, with cooling, ventilation, and radiotherapy equipment driving disproportionately high consumption [10–13]. The Xinhua Cancer Center case study provides practical validation of these findings, showing that targeted interventions in energy distribution, redundancy, and smart control systems translate directly into clinical and operational gains.

A consistent theme emerging from both the literature and the case study is the critical importance of reliability and redundancy. Studies have highlighted that power disruptions, even of short duration, may compromise treatment accuracy and safety [14, 15]. At Xinhua, integration of battery storage and predictive maintenance reduced unplanned downtime by 30%, ensuring continuous delivery of prescribed treatment fractions. This finding reinforces earlier reports that predictive fault detection and dual power supply systems are essential for safeguarding patient outcomes [16, 34].

The evidence also underscores the role of energy efficiency and smart management systems in reducing operational costs without compromising care. Hospital energy consumption can be reduced by 20-40% through upgrades such as LED lighting, efficient chillers, and building automation systems [17, 18, 35]. At Xinhua, automation and AI-driven load balancing ensured that radiotherapy equipment received uninterrupted power during treatment sessions, while non-clinical areas were deprioritized during peak loads. These measures enhanced both sustainability and treatment readiness, linking infrastructure efficiency directly with clinical reliability. Safety and compliance emerged as another vital domain. Literature indicates that strict adherence to standards such as NEC and radiation shielding protocols reduces risks of equipment malfunction and improves patient protection [20, 21, 36]. The ergonomic redesign at Xinhua, which reduced procedural errors by 17%, highlights how infrastructure planning extends beyond energy considerations to directly influence clinical safety.

Nevertheless, several barriers to implementation remain. Retrofitting costs for energy-efficient designs have been reported to range from USD 80-250 per square meter, creating financial challenges for many hospitals, particularly in resource-limited settings [31, 37]. Regulatory processes for renewable energy integration also introduce delays, especially in countries where hospital micro grid policies are underdeveloped [32, 38]. These obstacles align with findings from other large healthcare projects, where capital costs and administrative hurdles frequently limit adoption of sustainable infrastructure.

Although the findings highlight significant improvements in treatment efficiency and patient safety, they should be interpreted with caution. The Xinhua Cancer Center case study represents a single-institution experience, and the high retrofitting costs and regulatory delays identified may limit generalizability to other contexts. Further multi-center studies and international comparisons are needed to validate the scalability of these strategies.

Looking forward, opportunities exist for more advanced integration of digital and renewable technologies. Artificial intelligence can play a pivotal role in predictive maintenance, adaptive load balancing, and personalized treatment scheduling [25, 39]. Hybrid energy storage systems combining lithium -ion with super capacitors may further enhance resilience by smoothing power fluctuations [33, 40]. Block chain-secured patient data systems and wireless energy monitoring platforms represent additional avenues for improving security and transparency in hospital operations.

In summary, both the literature review and the Xinhua Cancer Center case study converge on the conclusion that infrastructure optimization is not merely a technical improvement but a clinical imperative. By ensuring reliable power delivery, enhancing energy efficiency, and prioritizing safety, optimized infrastructure directly contributes to treatment continuity, accuracy, and patient well-being.

CONCLUSION

Optimization of radiotherapy infrastructure is essential for ensuring treatment efficiency, patient safety, and sustainability in cancer care facilities. The

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literature and the Xinhua Cancer Center case study both demonstrate that improvements in energy distribution, redundancy, and smart management systems can reduce downtime, enhance accuracy, and lower operational costs. Future work should focus on integrating advanced digital technologies, such as AI-driven predictive maintenance and adaptive load balancing, alongside hybrid renewable energy systems to further strengthen reliability and resilience. Broader multi-center studies will be needed to validate these strategies across diverse healthcare settings and to establish international benchmarks for infrastructure optimization in oncology.

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Ethical considerations**:** This study did not involve human participants or animal experiments. All data used from the Xinhua Cancer Center were aggregated facility-level operational data and did not include patient identifiers.

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