Università di Brescia

DIPARTIMENTO DI INGEGNERIA MECCANICA E INDUSTRIALE

DOTTORATO DI RICERCA IN TRANSIZIONE ENERGETICA E SISTEMI PRODUTTIVI SOSTENIBILI

ING-IND/17

CICLO XXXVIII

ENERGYCARE: ANALYSIS AND DEVELOPMENT OF SUSTAINABLE ORGANISATIONAL METHODOLOGIES AND SOLUTIONS IN HEALTHCARE SYSTEMS

ANNA SAVIO

SUPERVISORE: Prof. Simone Zanoni

TUTOR: Ing. Matteo Fausti

Summary

List of Figures

List of Tables

Abstract

The healthcare system occupies a structurally paradoxical position within the contemporary sustainable transition: it is simultaneously exposed to the consequences of environmental degradation and significantly contributes to the processes it is institutionally called to contain. Climate change and the ecological crisis do not represent external threats to healthcare, but structural determinants of population health, reshaping the demand for care through heat-related mortality, the geographical redistribution of vector-borne pathogens, food insecurity, and the psychosocial consequences of climate-induced forced displacement. At the same time, the healthcare system generates a significant share of global greenhouse gas emissions through the energy consumption of facilities, pharmaceutical and medical device supply chains, anaesthetic gases, waste production, and the logistics of care delivery. This feedback loop, in which greater environmental damage produces a greater demand for care, which in turn generates further impacts, constitutes the structural motivation of this doctoral thesis.

Despite the growing international awareness of this paradox, most hospital management systems lack the necessary infrastructure to translate environmental concern into concrete operational action. The most significant barrier to healthcare decarbonisation is not the unavailability of low climate impact technologies; many viable alternatives already exist and are economically feasible. The real obstacle lies in the distributed invisibility of environmental impact within complex socio-technical organisations that neither measure it systematically nor translate the results into feedback loops capable of guiding clinical and managerial behaviour. This dissertation directly addresses that gap. Environmental sustainability in healthcare is not primarily a technological issue, nor exclusively a regulatory issue: it is a problem of distributed organisational knowledge, and its solution requires the construction of measurement, modelling, and decision support systems designed to operate within the socio-technical complexity of hospitals, not despite it.

The research programme is structured into four sequentially interconnected methodologies. Each phase produces outputs that serve as inputs for the next, following a cumulative logic. This logic progresses from a critical understanding of the existing literature to the proposal of conceptual and operational tools, and from their empirical validation to the construction of a decision-support model parameterised with real-world data. Eight scientific

contributions are presented along this methodological progression, all focused on two clinical domains that the international literature consistently identifies as the main environmental hotspots within hospitals: the operating theatres and the diagnostic imaging departments. The choice of these two areas is not arbitrary: both concentrate the highest densities of energy consumption, single-use material flows, gases with a high global warming potential, and resource-intensive processes, making them the most strategically relevant sites. All empirical studies were conducted in real Italian hospital settings, primarily in the Lombardy region, contributing primary evidence to a national context that remains systematically underrepresented in the international literature on healthcare sustainability.

The body of evidence produced by the research converges towards a reformulation of the problem: hospital sustainability is not a property of the institution, but the aggregated result of thousands of daily decisions distributed among departments, roles, shifts, and hierarchical levels, none of which are individually perceived as an environmental decision. This distributed nature of impact production has a direct and often overlooked consequence for governance: the interventions most capable of generating lasting reductions are not those aimed at the largest aggregate emission sources, but those that make the impact visible and actionable at the organisational level where the decisions that generate it are made. The evidence consistently shows that organisational and operational levers perform better than technological ones when evaluated at the level of the patient or the individual procedure, and that the reliability of the environmental data on which purchasing decisions are based cannot be taken for granted in the absence of independent validation. The resulting structural diagnosis is unequivocal: the most significant barrier to health sustainability is not the unavailability of solutions, as alternatives with a lower climate impact exist in most of the examined domains, but the absence of a measurement and feedback infrastructure that would make those solutions visible, comparable, and actionable within the governance structures of real health systems.

Sommario

Il sistema sanitario occupa una posizione strutturalmente paradossale all'interno della transizione sostenibile contemporanea: è simultaneamente esposto alle conseguenze del deterioramento ambientale e contribuisce in misura significativa ai processi che è istituzionalmente chiamato a contenere. Il cambiamento climatico e la crisi ecologica non rappresentano minacce esterne alla sanità, ma determinanti strutturali della salute delle popolazioni, che ridisegnano la domanda di cure attraverso la mortalità correlata al caldo, la redistribuzione geografica dei patogeni trasmessi da vettori, l'insicurezza alimentare e le conseguenze psicosociali degli spostamenti forzati dal clima. Al tempo stesso, il sistema sanitario genera una quota rilevante delle emissioni globali di gas serra attraverso il consumo energetico delle strutture, le catene di fornitura farmaceutica e dei dispositivi medici, i gas anestetici, la produzione di rifiuti e la logistica dell'erogazione delle cure. Questo circolo di retroazione, in cui un maggiore danno ambientale produce una maggiore domanda di assistenza, che a sua volta genera ulteriori impatti, costituisce la motivazione strutturale di questa tesi di dottorato.

Nonostante la crescente consapevolezza internazionale di tale paradosso, la maggior parte dei sistemi di gestione ospedaliera rimane priva dell'infrastruttura necessaria per tradurre la preoccupazione ambientale in azione operativa concreta. La barriera più rilevante alla decarbonizzazione sanitaria non risiede nell'indisponibilità di tecnologie a minore impatto climatico: molte alternative valide esistono già e sono economicamente praticabili. Il vero ostacolo è l'invisibilità distribuita dell'impatto ambientale all'interno di organizzazioni sociotecniche complesse, che non lo misurano sistematicamente e non traducono i risultati in circuiti di retroazione capaci di orientare il comportamento clinico e manageriale. Questa tesi affronta direttamente quel vuoto. La sostenibilità ambientale in sanità non è principalmente un problema tecnologico, né esclusivamente un problema regolatorio: è un problema di conoscenza organizzativa distribuita, e la sua soluzione richiede la costruzione di sistemi di misurazione, modellazione e supporto decisionale progettati per operare all'interno della complessità sociotecnica degli ospedali, non nonostante essa.

Il programma di ricerca è strutturato in quattro metodologie sequenzialmente interconnesse. Ciascuna fase produce output che fungono da input per la successiva, seguendo una logica

cumulativa. Tale logica procede dalla comprensione critica della letteratura esistente alla proposta di strumenti concettuali e operativi, e dalla loro validazione empirica alla costruzione di un modello di supporto decisionale parametrizzato con dati reali. Otto contributi scientifici vengono presentati lungo questa progressione metodologica, tutti focalizzati su due domini clinici che la letteratura internazionale identifica con consistenza come i principali hotspot ambientali all'interno degli ospedali: le sale operatorie e i reparti di diagnostica per immagini. La scelta di questi due ambiti non è arbitraria: entrambi concentrano le densità più elevate di consumo energetico, flussi di materiali monouso, gas ad elevato potenziale di riscaldamento globale e processi ad alta intensità di risorse, rendendoli i siti strategicamente più rilevanti. Tutti gli studi empirici sono stati condotti in contesti ospedalieri italiani, principalmente nella regione Lombardia, contribuendo con evidenza primaria a un contesto nazionale che rimane sistematicamente sottorappresentato nella letteratura internazionale sulla sostenibilità sanitaria.

Il corpo di evidenze prodotto dalla ricerca converge verso una riformulazione del problema: la sostenibilità ospedaliera non è una proprietà dell'istituzione nel suo insieme, ma il risultato aggregato di migliaia di decisioni quotidiane distribuite tra reparti, ruoli, turni e livelli gerarchici, nessuna delle quali viene individualmente percepita come una decisione ambientale. Questa natura distribuita della produzione di impatto ha una conseguenza diretta e spesso trascurata per la governance: gli interventi più capaci di generare riduzioni durature non sono quelli orientati alle fonti di emissione aggregate più grandi, ma quelli che rendono l'impatto visibile e governabile al livello organizzativo in cui vengono effettivamente prese le decisioni che lo generano. Le evidenze mostrano con coerenza che le leve organizzative e operative performano meglio di quelle tecnologiche quando valutate al livello del paziente o della singola procedura, e che l'affidabilità dei dati ambientali su cui si fondano le decisioni di acquisto non può essere data per scontata in assenza di una validazione indipendente. La diagnosi strutturale che ne deriva è univoca: la barriera più rilevante alla sostenibilità sanitaria non è l'indisponibilità di soluzioni, poiché alternative a minore impatto climatico esistono nella maggior parte dei domini esaminati, ma l'assenza dell'infrastruttura di misurazione e di retroazione che renderebbe quelle soluzioni visibili, comparabili e gestibili all'interno delle strutture di governance dei sistemi sanitari reali.

Contributions

Savio, A., Marchi, B., Roletto, A., Guizzi, P., Milano, G., Zavanella, L. E., and Zanoni, S. (2026). Carbon Footprint of Surgical Operations: 2023-2025 Systematic Review Update. PLOS ONE, 21(5), e0349415.

Savio, A., Marchi, B., Roletto, A., Milano, G., and Zanoni, S. (2024). Sustainable Operating Rooms: A Comprehensive Framework for Environmental Impact Analysis. Environmental and Climate Technologies, 28(1), 842–854.

Savio, A., Roletto, A., Marchi, B., Milano, G., and Zanoni, S. (2024). Greening Healthcare: An Approach to Assess the Environmental Impact of Medical Procedures. Proceedings of the Summer School Francesco Turco.

Roletto, A., Savio, A., Marchi, B., and Zanoni, S. (2024). Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging. Environmental and Climate Technologies, 28(1), 303–311.

Savio, A., Marchi, B., Roletto, A., Guizzi, P., Milano, G., Zavanella, L. E., and Zanoni, S. (2026). Assessing Energy and Waste Impacts in Orthopaedic Departments: A Case Study from an Italian Public Hospital. Energies, 19(3), 836.

Roletto, A., Verga, M., Savio, A., Viganò, G. L., and Zanoni, S. (2026). Energy performance of MRI systems: on-site validation and comparison with manufacturer declarations. European Radiology Experimental, 10(1), 3.

Roletto, A., Savio, A., Bertagna, E., Chiodini, N. S., Bonfitto, G. R., Chiti, A., and Zanoni, S. (2026). Environmental Life Cycle Assessment of [18F]FDG PET/CT Imaging in a Hospital-Based Nuclear Medicine Department. EANM Innovation, 100025.

Sferrazzo, F., Marchi, B., Savio A., Roletto, A., Zanoni S. (2026). Integrating Energy Efficiency into Healthcare Operations: A Discrete-Event Simulation Approach for Surgical Pathways. Healthcare, 14(9), 1134.

Other Contributions

Marchi, B., Savio, A., Zanoni, S., and Zavanella, L. E. (2024). Unlocking sustainability in the HORECA value chain: the power of business models. Proceedings of the Summer School Francesco Turco.

Savio, A., Marchi, B., Zavanella, L. E., and Zanoni, S. (2025). Implementing an Integrated Energy Management System: A Hotel Case Study. Proceedings of the Summer School Francesco Turco.

Roletto, A., Savio, A., Masperi, A., Bonfitto, G. R., Pala, F., Migliorisi, C., and Zanoni, S. (2025). Energy Usage Assessment and Energy Savings Estimation in a Radiology Department in Italy. Energies, 18(8).

Introduction

Environmental Burden of Healthcare Sector

Climate change and the environmental crisis are structural determinants of human health: they affect air and water quality, food security, the geographical distribution of infectious diseases, and the frequency of extreme weather events (Badanta et al., 2025). The healthcare sector thus finds itself in a paradoxical position: on the one hand, it is called upon to manage the increased demand for care caused also by environmental impacts; on the other, it contributes to these impacts itself through energy consumption, infrastructure, logistics, medicines and medical devices (Eckelman and Sherman, 2016; Lenzen et al., 2020). This self-reinforcing feedback loop, where greater environmental damage generates a greater need for care, which in turn generates further impacts, is the central motivation behind this doctoral thesis.

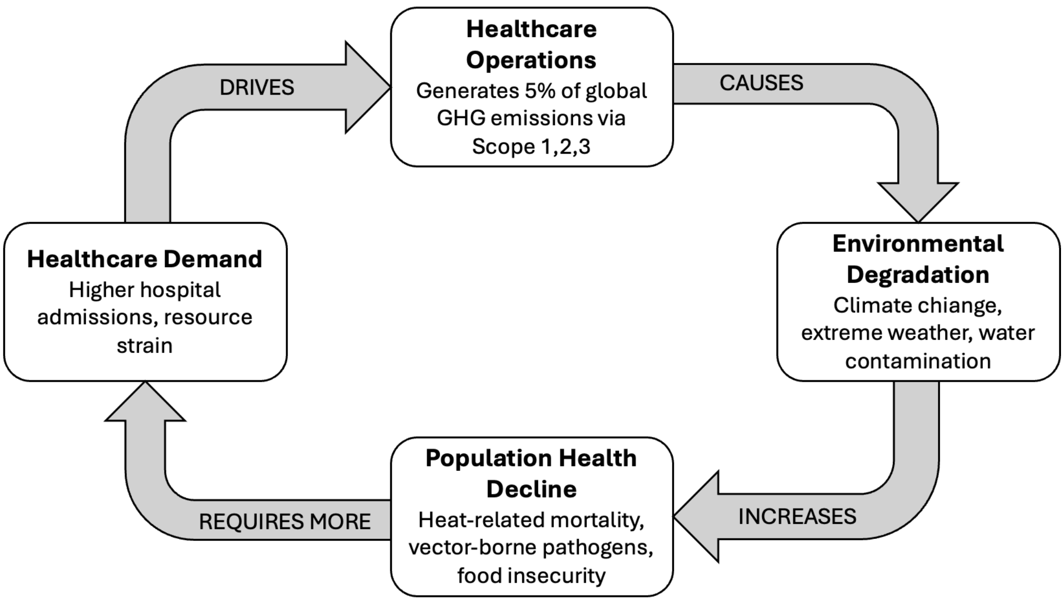


Figure 1: The healthcare sustainability paradox: a self-reinforcing feedback loop between clinical operations, environmental degradation, and population health outcomes.

It should be noted, however, that a purely reinforcing dynamic of this kind represents a theoretical tendency rather than an irreversible trajectory. Counteracting forces exist: fiscal constraints on healthcare expenditure, growing regulatory pressure for decarbonisation, and the progressive cost-competitiveness of low-carbon clinical alternatives, may slow or partially offset this dynamic. The analysis of the conditions under which these balancing mechanisms activate falls outside the scope of this dissertation. The research programme focuses instead on the specific institutional gap that currently limits their effectiveness: the distributed invisibility of environmental impact within hospital organisations that neither measure it systematically nor translate results into actionable feedback for clinical and managerial decision-making.

The scale and trajectory of this feedback loop are tracked with systematic rigour by the Lancet Countdown on Health and Climate Change, an international collaboration of more than 100 institutions whose annual reports compile fifty-plus indicators spanning exposure and vulnerability, adaptation capacity, mitigation actions and health system readiness (Romanello et al., 2023; Watts et al., 2021). The most recent Countdown evidence documents record heat-related mortality among populations over 65, a geographic expansion of dengue and malaria transmission zones, and reductions in agricultural yield that translate directly into food insecurity and undernutrition as health outcomes. The implications for health systems, however, extend beyond increased service demand: a growing body of evidence documents how climate hazards, such as flooding, wildfires, heat waves and extreme storms, compromise the operational continuity of health facilities through infrastructure damage, supply chain disruption and workforce displacement (Sorensen et al., 2020). The World Health Organisation has operationalised this challenge through the concept of climate-resilient health systems: systems capable of anticipating, absorbing and adapting to climate-related shocks whilst maintaining quality of care (World Health Organization, 2015). Research drawing on clinical, epidemiological and environmental evidence has demonstrated how heat stress, smoke inhalation and the redistribution of vector-borne pathogens are already reshaping emergency department utilisation and hospital admission patterns across North American and European settings (Alho et al., 2024; Gould et al., 2024; Sorensen et al., 2020; Sun et al., 2021; Thomson and Stanberry, 2022). The relevance of this evidence for the present dissertation is structural: a health system that cannot account for its own environmental footprint cannot credibly plan its adaptation to a climate emergency that it is, in part, generating. The construction of the measurement and decision-support infrastructure to close that accountability gap is precisely what this research programme sets out to address.

In a global, multi-regional analysis based on an environmentally extended input–output model (EE-MRIO), it was estimated that the healthcare sector is responsible for between 1% and 5% of the main global environmental stressors (Lenzen et al., 2020). On an international comparative basis, healthcare accounts for an average of around 5% of the carbon footprint in OECD countries (Pichler et al., 2019). A scoping review documenting the uneven geographical distribution of the empirical literature confirms that 4.4% of global net emissions are attributable to healthcare systems, and highlights that lower-income countries, including most Mediterranean nations, remain systematically under-represented in research on the subject (Cristiano et al., 2024).

National estimates confirm these proportions, with significant variations linked to the energy mix and expenditure intensity: 7% in Australia (Malik et al., 2018), between 8% and 10% in the United States (Eckelman and Sherman, 2016), 5% in Canada (Eckelman et al., 2018), 4.6% in Japan (Nansai et al., 2020) and 2.7% in China (Wu, 2019). These differences are not random: they reflect the structure of the national energy system, the composition of healthcare expenditure and the organisational characteristics of the supply systems.

There is broad consensus in the literature that the majority of the healthcare sector's environmental impact stems from indirect emissions along the supply chain (Scope 3), from the procurement of medicines, medical devices, sterile materials, food products and support services, rather than from direct operational consumption (Scope 1) or purchased energy (Scope 2). Estimates, however, vary significantly depending on the methodology used, the geographical context and the scope of the analysis.

At a systemic level, the analysis of the UK's NHS estimates that in 2019 approximately 62% of the total footprint was attributable to the supply chain, with only 24% attributable to the direct provision of care (Tennison et al., 2021). Similar estimates emerge at the European level: according to the World Economic Forum, the supply chain accounts for 71% of CO_2 emissions in the European Union's healthcare sector (World Economic Forum, 2022). In the United States, however, the supply chain is held responsible for approximately 80% of the sector's carbon footprint. This trend towards the dominance of Scope 3 emissions is not, however, without its critical nuances. The systematic review, based on 13 published studies, finds that Scope 3 emissions range between 50% and 75% of the total, whilst Scope 1 and 2 cover a share ranging from 15% to 50%, a range broad enough to preclude simplistic generalisations (Rodríguez-Jiménez et al., 2023). The same review highlights that geographical location significantly influences Scope 1 and 2 emissions: in a case study in Morocco, local climatic conditions meant that energy consumption accounted for just 0.2% of direct emissions. The age of buildings also plays a role: older facilities consistently show higher energy consumption.

The picture becomes even more complex when moving from the system level to that of individual clinical specialities. For specialities such as surgery, the contribution of physical infrastructure (systems, heating, ventilation) is particularly high compared to the average, partly reversing the hierarchy observed at the aggregate level.

From a methodological perspective, it should be noted that the variations in results between hospital studies and national estimates stem largely from differences in methodologies, the scope of analysis, and the availability of data. In particular, measuring Scope 3 emissions requires the entire supply chain to provide data on its emissions: a requirement that is still far from being met consistently.

The operational conclusion emerging from this complex picture is that of a two-pronged approach: sustainable procurement strategies based on life-cycle remain the most significant lever at the aggregate level, but effective decarbonisation also requires action on direct operational emissions, the relative importance of which varies considerably by clinical specialty, geographical context and local energy mix.

The Italian Context

The Italian National Health Service is responsible for greenhouse gas emissions estimated at around 5% of the national total, attributable mainly to the procurement of medicines, medical devices and anaesthetic gases, the energy consumption of healthcare facilities, and the generation of waste (Armocida et al., 2022; Vineis et al., 2022). Although these figures are comparable to those of the main European healthcare systems, Italy stands out for the absence of an integrated national plan for healthcare decarbonisation: the Integrated National Energy and Climate Plan in its 2023 revision, does not include specific action plans for the healthcare sector, unlike in other European countries (Ministero dell'Ambiente e della Sicurezza Energetica, 2023).

The most serious shortcoming in the Italian context, however, is not of a technical nature, but rather a lack of systematic environmental knowledge. In England, where the NHS's ecological footprint has been systematically measured since 1992, or in Australia and the United States, where national healthcare accounts have been produced with reasonable regularity, this knowledge infrastructure already exists. In Italy, by contrast, there are no estimates of the environmental footprint of healthcare services, neither at national level, nor at regional level, nor for individual facilities (Romizi, 2023). Healthcare decarbonisation in Italy is still at an early stage, with efforts that are predominantly local, focused on building energy efficiency, and disconnected from any national strategy. Beyond this governance gap, the evidence points to a deeper analytical blind spot: pharmaceutical and medical device supply chains constitute the dominant component of the Italian NHS's emissions profile yet remain systematically absent from both measurement frameworks and procurement policy (Armocida et al., 2022).

Of these, the impact of pharmaceuticals on the aquatic environment is perhaps the most underestimated aspect in the Italian debate. A recent study based on national drug utilisation data assessed the environmental risk of 90 drugs commonly used in Italy, finding that 13 posed a high risk, including cardiovascular agents, antibiotics, analgesics, antidepressants and antiparasitic drugs (Giunchi et al., 2025). The study maps, for the first time, the geographical distribution of pharmaceutical risk to surface waters across national macro-regions, concluding that mitigation requires both targeted environmental sampling and more informed clinical practice, alongside appropriate management of pharmaceutical waste. On a related front, a 2024 national study quantified the climate footprint of halogenated anaesthetic gas use in Italy, identifying desflurane as a particularly high-impact agent: with a global warming potential approximately two thousand times that of CO_2, it nonetheless remains widely used in Italian operating theatres despite the availability of clinically equivalent alternatives (Caviglia et al., 2025). This finding has immediate operational implications: anaesthetic gases fall under Scope 1, which is directly controllable by each facility, and represent one of the areas with the highest potential for reduction whilst maintaining the same clinical outcomes.

The production of hospital waste constitutes a further dimension of impact that the Italian literature has begun to explore. A study published in 2024 analysed the volume of healthcare waste and the associated CO_2 emissions in four Italian hospitals over the period 2016-2021, documenting the surge caused by the COVID-19 pandemic (Di Russo et al., 2025). High-temperature incineration of fossil-derived materials, a method that is necessary for hygiene but significantly emits greenhouse gases, is the predominant method of disposal, and the study quantifies the social cost of the associated emissions, highlighting how this waste stream represents a driver of environmental impact that is systematically underestimated in hospital carbon footprint analyses. This multi-dimensional picture is complemented by an exploratory study conducted in 2024-2025 across 18 acute care facilities in the Lombardy Region, which identified eight dimensions of hospital environmental sustainability: energy efficiency, resource and waste management, mobility, materials and construction, environmental compliance, emissions, site sustainability and design strategies. It reveals substantial gaps in key measures such as on-site installed renewable energy capacity, water reuse systems, environmental certifications and heat island mitigation (Brambilla et al., 2025) . The result empirically confirms what the theoretical literature had already suggested: the environmental sustainability of Italian hospitals is still predominantly attributed to the energy efficiency of buildings, neglecting the dimensions with the greatest potential impact along the value chain. In this context, energy consumption in hospitals remains a significant but not dominant factor. According to OECD estimates, the emissions profile of the National Health Service is in line with that of other member countries: hospitals account for around a third of the sector's total emissions, whilst the remainder is attributable mainly to the pharmaceutical and medical device supply chains (OECD, 2025). The first energy benchmarking study specifically for the Italian private hospital sector, conducted in collaboration with the ENEA and based on the mandatory energy audits required by Legislative Decree 102/2014 and its successive amendments, represents a tool of undoubted value, but one which, by its very nature, measures only internal and direct emissions, leaving out the entire supply chain dimension (Dadi et al., 2022).

It is precisely this mismatch between what is measured and what has the greatest impact that explains the gap between governance and implementation evident in all the available data. Existing initiatives are predominantly local and fragmented: according to the 7th 2024 Report by the Green Procurement Observatory, out of a sample of 41 local health authorities, the rate of Green Public Procurement (GPP) implementation in 2023 stood at 5%, compared to the 62% average for public administrations (Osservatorio Appalti Verdi, 2024). This figure is particularly significant because GPP represents the main lever for addressing Scope 3 emissions through environmental criteria in the specifications for medicines, medical devices and services. The NHS has sufficient market power to generate knock-on effects at national and European level, but mobilising this power requires reliable and comparable impact data at product and facility level. Building that measurement base requires, as a prior step, identifying where environmental impact concentrates within the clinical and organisational structure of a hospital: a question that the international literature has begun to answer with increasing precision.

Clinical Hotspots

Despite the methodological and geographical fragmentation that characterises the literature on the environmental impact of the healthcare system, with studies varying in terms of scope of analysis, choice of indicators and data availability, one element emerges consistently across different national contexts: the environmental impact of hospital facilities is not distributed evenly across departments, but is concentrated in certain resource-intensive organisational units. International literature consistently identifies operating theatres and diagnostic imaging as the main clinical hotspots, both in terms of direct energy consumption and the generation of waste, the use of climate-changing gases and the intensive use of single-use materials (J. D. Sherman et al., 2020).

Operating Theatres

Operating theatres represent the organisational unit with the highest environmental impact within hospitals, due to a combination of factors that are difficult to separate: stringent infection control requirements, the high energy consumption of air-conditioning systems, the intensive use of single-use materials, the use of anaesthetic gases with a high global warming potential, and highly variable multi-professional coordination. Operating theatres use 3 to 6 times more energy per square metre than any other area of the hospital, with the

HVAC system accounting for up to 65% of the hospital's total energy consumption in documented cases (Gordon, 2020).

A multicentre study across three healthcare systems (Canada, the US and the UK) has confirmed that HVAC systems account for between 90% and 99% of total energy consumption in operating theatres, due to air conditioning requirements that are much more stringent than in other inpatient wards (Macneill et al., 2017).

The energy aspect, however, is just one component of the environmental profile of operating theatres: two systematic reviews of the literature on the carbon footprint of surgical procedures agree that there are three main drivers: energy consumption, anaesthesia and single-use products, with smaller contributions from reusable items, water use and capital equipment (Rizan et al., 2020; Robinson et al., 2023).

The management of anaesthetic gases is one of the most significant sources of environmental impact, and at the same time one of the easiest to reduce. Inhalation anaesthetics have a global warming potential hundreds or thousands of times greater than an equivalent amount of CO_2. The differences between individual agents are substantial: desflurane has the highest GWP100, at 2,540, followed by isoflurane at 510, N_2O at 298 and sevoflurane at 130, meaning that 1 kg of desflurane traps the same amount of heat as 2,540 kg of CO_2 (J. Sherman et al., 2012). On a clinically normalised basis, the global warming potential of desflurane, scaled by clinical potency, is approximately 40-50 times higher than that of sevoflurane and isoflurane over a 100-year timeframe. Despite this profile, desflurane offers no documented clinical advantages over replacement agents, making its elimination one of the most accessible levers for immediate impact.

In terms of materials, operating theatres generate over 30% of total hospital waste and two-thirds of regulated waste requiring special disposal, including medicines, needles and biohazardous materials (Bae et al., 2024). Documented cases show that orthopaedic and cardiac surgery procedures can generate between 15 and 35 kg of waste per case (Amin et al., 2024; Kooner et al., 2020). Analysing the products used in the five most common surgical procedures within the NHS, it was found that the production of single-use items, the decontamination of reusable instruments and waste disposal are the main contributors to the carbon footprint of surgical products, with modelled potential reductions of between 23%

and 42% by switching from single-use to reusable items and optimising decontamination and disposal processes (Rizan et al., 2023). The tension between infection control and environmental sustainability represents a further structural friction. Current evidence does not support the superiority of high-energy-intensity HVAC systems over conventional alternatives in reducing surgical site infection rates, yet their adoption continues to expand, increasing the environmental footprint of operating theatres without a corresponding clinical justification (Bolten et al., 2022).

Diagnostic Imaging

Diagnostic imaging represents a second clinical hotspot, with an environmental impact profile that differs significantly from that of operating theatres: it is more varied in terms of imaging modalities, extends across the entire lifecycle of the equipment, and has significant implications for water resources due to the use of contrast agents. Radiology is estimated to account for around 1% of the healthcare sector's global greenhouse gas emissions, driven by energy-intensive imaging modalities, single-use materials and the depletion of finite resources such as helium (Roletto et al., 2024): a figure which, relative to the sector's overall size, is equivalent to the impact of a medium-sized manufacturing industry.

The environmental impact of diagnostic imaging varies across different modalities but follows a clear energy hierarchy that directly informs priorities for action. A recent scoping review, based on 115 studies, provides the most up-to-date and detailed estimate by modality: average annual emissions per machine range from 53.1 tonnes CO_2eq for MRI to 12.6 for CT, 9.6 for interventional radiology and just 0.3 for ultrasound; on a per-examination basis, LCA estimates range from 6.2 to 76.2 kg for MRI and from 1.1 to 13.4 kg for CT, compared with 0.1-1.2 kg for ultrasound (Woolen et al., 2026). This order of magnitude indicates that ultrasound is by far the modality with the lowest impact, a significant finding for policies on diagnostic appropriateness. The energy requirements of individual machines are considerable: the latest generation of MRI scanners consume between 80,000 and 170,000 kWh per year, equivalent to the consumption of 16-34 four-person households, with consumption rising further as the magnetic field strength and bore size increase, whilst CT scanners consume between 20,000 and 35,000 kWh per year (Vosshenrich et al., 2025). A study conducted in Basel on three CT scanners and four MRI scanners, with 40,276 patients per year, found a total consumption of over 1.1 GWh, equivalent to the energy requirements of a country with 852 inhabitants (Heye et al., 2020).

A distinctive and operationally significant feature of diagnostic imaging is the pattern of energy consumption in relation to activity: between 40% and 91% of the energy consumed by radiological equipment can be classified as non-productive, meaning that the devices are switched on but not in an active diagnostic phase (Roletto et al., 2024). MRI is the most problematic in this regard: even when not in use, MRI systems continuously consume between 7 and 9 kW due to the need to maintain helium-based cryogenic cooling, which makes the strategy of scheduled shutdown technically more complex compared to CT, for which the RSNA Sustainability Task Force has estimated emission reductions of up to 80% with the adoption of low-power modes (Heye et al., 2020; Rockall et al., 2025). This consumption pattern has direct operational implications: the amount of energy required for a single scan on a previously inactive system is far greater than that for any additional scan on a system already in operation, which makes the scheduling of scans, not just the technology, a key driver of sustainability.

However, the environmental footprint of radiology extends far beyond electricity consumption through an often-overlooked aspect: the contamination of surface water and aquatic ecosystems by contrast agents. Contrast agents used in MRI and CT scans are not adequately removed by conventional treatment plants, leading to the accumulation of gadolinium and iodinated by-products in water sources, with potential risks to human health and the environment (Oluwasola et al., 2022). The scale of the problem is considerable: around 300 million CT scans are performed worldwide each year, and assuming that 40% use an average of 100 ml of iodinated contrast agent, this amounts to approximately 12 million litres discharged into wastewater. Gadolinium has been detected in increasing concentrations in watercourses across all continents: measurements document annual discharges of 185 kg in Tokyo, 5.3 tonnes in Brazil and 12.2 tonnes in Europe (Woolen et al., 2026).

Hospital as a complex socio-technical system: implications for environmental sustainability

The description of clinical hotspots risks inducing an analytical simplification if read exclusively through the lens of emissions and consumption. Identifying a hotspot is not enough to act on it: between the knowledge of the impact and its reduction lies the organisational complexity of the hospital as an institution. Understanding this complexity is the preliminary condition for explaining why technically valid and clinically neutral interventions could systematically fail in implementation, and why environmental sustainability in healthcare requires analytical tools that go beyond measuring the carbon footprint.

Different hospital departments cannot be interpreted exclusively as technical environments nor as purely clinical systems regulated by protocols. They are complex socio-technical systems in which people, technologies, spaces, procedures, and regulatory constraints interact dynamically, producing outcomes that cannot be attributed to the sum of the components (Carayon, 2012). The Systems Engineering Initiative for Patient Safety (SEIPS) model describes clinical safety as an emergent property of the interaction between elements of the work system like person, tasks, technologies, organisation, physical environment, and care processes (Carayon et al., 2006). This framework proves equally relevant for environmental sustainability: the impact reduction levers do not act in isolation, but interfere with the logics of coordination, safety, and operational continuity that structure the work in the operating room. Evidence from focus group interviews with surgical teams demonstrates that keeping an operating theatre running is, in practice, an exercise in continuous complexity management: it requires planning under uncertainty, anticipating and adapting to the unexpected, and allocating resources dynamically as conditions evolve (Göras et al., 2020). The distinction between work-as-imagined, meaning what protocols prescribe, and work-as-done, meaning what actually unfolds in practice, is one of the reasons why sustainability interventions designed in a prescriptive manner can struggle to take hold in real clinical settings (Figure 2).

The hospital as a whole is an adaptable complex system in which elements co-evolve, interactions between subsystems generate non-linear emergent behaviours, and workers constantly adapt their work to local variables through workarounds and improvisations that are not documented in any protocol. Individuals in these systems rely on internalised rules and mental models that are not necessarily shared with others. Systems adapt to conditions and co-evolve with the systems around them. They produce tensions and conflicts that do not necessarily find resolution (Carayon et al., 2011). This socio-technical framing extends beyond the boundaries of the hospital building: the healthcare supply chain itself exhibits the characteristics of a complex adaptive system, in which fragmentation among stakeholders, regulatory rigidity and resource constraints constitute documented barriers to adaptation and systemic change, limiting the capacity of any single actor to govern supply chain impacts in an integrated and transformative manner (Piffari et al., 2026). The adaptable and distributed nature renders top-down change methods, particularly those for environmental sustainability, fundamentally vulnerable unless grounded in a comprehension of the actual operational context.

The empirical literature on the barriers to implementing sustainable practices in healthcare consistently confirms this. A recurring theme is that the burden of change should not fall on individual healthcare professionals, but on the institutions in which they operate, which should make sustainable practices the default choice; however, without addressing individual-level barriers, well-intentioned institutions will fail to produce lasting changes (Aboueid et al., 2023). The main identified organisational barriers include resistance to change, lack of top management support, absence of specific training, time constraints, bureaucratic complexity, and concerns related to the impact on patient care and infection control (Khosravi et al., 2025). This last point deserves attention: the tension between patient safety and reducing environmental impact is one of the most difficult structural frictions to manage in a hospital, and it cannot be resolved simply through technical or regulatory interventions.

A particularly relevant aspect is the multilayered stratification of barriers. Some of the main barriers to sustainable practices stem from clinical guidelines that neither consider nor prioritise sustainable products over alternatives, reflecting how the regulatory architecture of clinical work can itself be a structural obstacle to change. This means that a sustainability initiative that interferes with an established clinical protocol, for example, modifying standard surgical kits, reducing air exchanges in operating rooms during night-time hours, or replacing a usual anaesthetic, faces resistance at multiple levels. Beyond individual professional habits, it must also navigate the institutional resistance of accreditation systems, purchasing centres, scientific societies, and practice codes. Cultural resistance within the organisational culture of hospitals can hinder the adoption of sustainable practices; to these are added supply chain issues and technological limitations that do not always offer sustainable alternatives to the specific needs of healthcare facilities (Vallée, 2024).

The problem, however, is not limited to resistance to change. There is a deeper issue of cognitive distribution of the problem: the environmental impact of a hospital is produced by thousands of daily decisions distributed among departments, roles, shifts, and hierarchical levels, each of which appears locally rational but contributes to a systemic outcome that no single actor perceives or controls. The anaesthetist who chooses the most familiar volatile gas, the nurse who follows the protocol for opening surgical kits, the radiologist who leaves the scanner on during lunch break, the purchasing manager who prioritises price over clinical performance: none of these individuals are making an "environmental decision," but the aggregate of their choices defines the carbon footprint of the facility. This makes any approach to hospital sustainability that is not based on granular data and does not produce feedback at the operational level structurally insufficient.

The implications for the design of sustainability policies are significant. Siloed care models can be misaligned with the complexity of healthcare systems and the complex needs of patients; this is even more true for sustainability strategies, which by their nature cross departmental boundaries and require coordination among actors with different incentives, languages, and time horizons. Research on the barriers to implementing hospital interventions identifies contextual adaptation as one of the critical factors for their sustainability over time, in contrast to prescriptive application (Aboueid et al., 2023). Contextual adaptation, as opposed to universal standardisation, therefore represents a first-order methodological challenge for any environmental impact reduction programme that aims to produce lasting results.

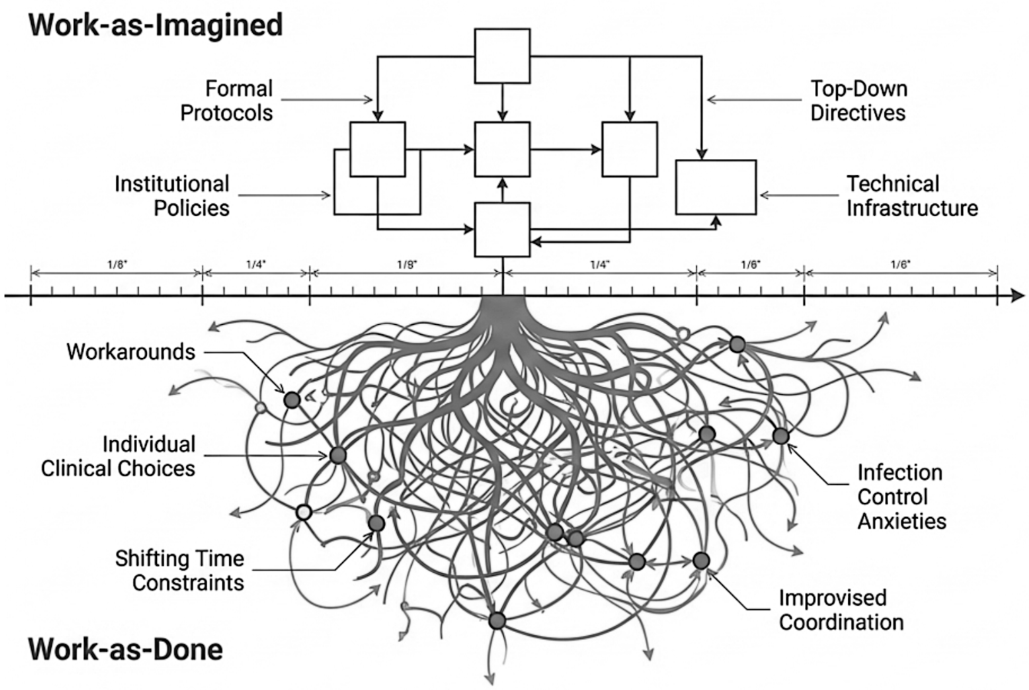


Figure 2: Sociotechnical complexity in healthcare organisations: the structured rationality of formal governance (above) contrasts with the dynamic, non-linear character of clinical practice as it unfolds in real operating conditions (below)

The essential starting point, from this perspective, is measurement: not as an exercise in reporting, but as a cognitive infrastructure that makes visible to local decision-makers what organisational complexity would otherwise render invisible. A department that does not know how much energy it consumes, how much waste it produces, or what portion of the footprint is associated with its purchases has neither the motivation nor the tools to act. This is the fundamental premise of this dissertation: environmental sustainability in healthcare is not primarily a technological issue, nor exclusively a regulatory one. It is a problem of distributed organisational knowledge, and the solution lies in the construction of measurement, reporting, and feedback systems that are designed to function within the socio-technical complexity of hospitals, not despite it.

Environmental Impact Assessment in Healthcare: Methods and Gaps[1]

Identifying environmental hotspots and quantifying the impact of clinical activities requires tools capable of transforming operational data, such as energy consumption, material flows, clinical activities, expenditure, transport, into environmental indicators that can inform decision-making. In the healthcare sector, four main methodological families are identified, often used in combination. Understanding the logic, scope and limitations of each approach is a prerequisite for interpreting the evidence discussed in the previous chapters and, more directly, for justifying the methodological choices of this research programme.

The Life Cycle Assessment (LCA), governed by ISO 14040 and ISO 14044, is a structured analytical framework that quantifies the environmental impacts associated with all stages of a product or service's life cycle, from the extraction of raw materials through to production, use and disposal. ISO 14040 provides the principles and framework, whilst ISO 14044 specifies the requirements and operational guidelines for the four stages: definition of the objective and scope, life cycle inventory analysis, impact assessment and interpretation. When applied to the healthcare sector, process LCA serves as the methodological benchmark for comparing clinical alternatives at the level of individual procedures, devices or care pathways, thanks to its ability to simultaneously cover different impact categories: climate change, resource and energy consumption, water use, land use, and toxicity to humans and ecosystems. Its application to healthcare settings has seen substantial growth over the last decade, with studies on reusable versus single-use devices, comparisons of anaesthetic techniques and procedure-level carbon accounts now constituting a well-established body of knowledge. Its main limitation remains its data-intensive nature and the difficulty of scaling the analysis from the procedure level to that of the system or organisation. The challenge of integrating this LCA evidence with the operational and organisational complexity of healthcare delivery has been approached from the perspective of engineering management

[1] All ISO standards cited in this chapter have been adopted within the European normative framework under the corresponding EN ISO designation, technically identical to the international standard. ISO 50002 constitutes a partial exception: within Europe, energy audit requirements are addressed by the parallel standard EN 16247, which covers equivalent scope but was developed independently rather than as a direct adoption of the international standard.

and operations research, with contributions emphasising that the implementation of sustainability improvements in hospital settings must be calibrated to the process structures, professional hierarchies and decision logics that govern clinical work, not merely to its material flows (Drew et al., 2021; Seifert et al., 2021).

Carbon footprinting is a simplified subset of LCA, focusing solely on the climate change impact category and expressed in CO_2 equivalents. Governed by ISO 14067 for product-level quantification and by ISO 14064-1 for organisational-level GHG inventories, it offers a concise and more communicable metric, particularly useful for benchmarking, public reporting and setting reduction targets. At the systemic level, as discussed in previous chapters, national and sub-national carbon footprint studies have produced the most widely cited estimates of the healthcare sector's contribution to global emissions. At the facility or procedure level, carbon footprint studies have proliferated rapidly, although their comparability remains structurally limited by the heterogeneity of methodological choices in defining system boundaries and selecting emission factors.

Environmentally extended input-output (EE-IO) models, whether single-region or multi-regional, operate at the opposite end of the granularity spectrum. Rather than tracing specific material and energy flows from the bottom up, they attribute supply chain emissions to final demand sectors using national or global input-output tables enriched with environmental satellite accounts. Their main advantage is coverage: they capture indirect emissions along the entire supply chain, including internationally traded goods and services, which process-based LCA often excludes for practical reasons. They have therefore been the primary tool for documenting the dominance of Scope 3 emissions in healthcare, as discussed in the opening section of this thesis. Their corresponding limitation is the loss of granularity: the sectoral aggregation inherent in input-output tables makes it difficult to distinguish between specific products, clinical pathways or organisational choices within a sector, reducing their operational applicability. Hybrid models, which combine the top-down coverage of input-output approaches with bottom-up process data for the most significant emission categories, represent the methodological compromise adopted by the most rigorous national studies to balance coverage and accuracy in the disaggregation by scope and emission source.

Energy audits, regulated internationally by the ISO 50002 within the European context, by EN 16247 standard, and the related environmental key performance indicators (EKPIs) constitute the fourth category, focused not on a comprehensive life cycle or supply chain assessment, but on operational management and internal governance. In the healthcare context, energy audits produce disaggregated consumption profiles by building area, system, or department, allowing for the identification of operational inefficiencies and the prioritisation of retrofit interventions. EKPIs extend this logic beyond energy, incorporating waste, water, transportation, and other operational dimensions into a monitoring framework that can be integrated into hospital governance structures.

The regulatory framework supporting these families is largely harmonised internationally through the ISO 14040/14044, ISO 14067, ISO 14064-1, and ISO 50002 standards, integrated by the GHG Protocol for Scope 1, 2, and 3 accounting (*The Greenhouse Gas Protocol : The GHG Protocol for Project Accounting*, 2005). These standards are substantially consistent with each other, but their interaction in multi-method studies, where, for example, a hybrid model combines LCA modules compliant with ISO 14040 with Scope 3 accounting according to the GHG Protocol, requires explicit choices on the alignment of boundaries and allocation procedures that are rarely reported transparently in the literature.

Table 1: Comparative overview of environmental impact assessment methodologies applied in healthcare research: scale of analysis, data granularity, primary use case, and structural limitations.

Methodology	Scale	Granularity	Use Case	Blindspot
Life Cycle Assessment	- Procedure - Device	Extremely high	Comparing clinical alternatives	Data-intensive and difficult to scale system-wide
Carbon Footprinting	- Organisation - Product	Moderate	Benchmarking and public reporting	Inconsistent system boundaries between studies
EE-MRIO	- National - Global	Low	Tracking emission of entire sectors	Sectoral aggregation hides specific operational choices
Energy Audits	-Facility - Department	High (but only for energy)	Internal governance and retrofits	Ignores non-energy emission factors

On a scientific level, the literature demonstrates the ability of these methods to produce actionable evidence, but at the same time highlights three structural tensions that recur across the methodological landscape and directly motivate the research design of this dissertation.

The first concerns the definition of the functional unit and the boundaries of the system. In healthcare, the same clinical activity can be described as a procedure, pathway, episode of care, or health outcome, and the scope can include or exclude pre- and post-operative phases, transportation, building infrastructure, and supply chain emissions. The variability in these choices is the main reason why carbon footprint estimates for seemingly similar procedures differ by orders of magnitude between studies, making benchmarking structurally impossible without prior harmonisation of the measurement framework.

The second tension concerns the quality and origin of the emission factors and inventory data. Generic databases may not represent the specific materials and processes of healthcare; the EPDs issued by manufacturers are built on standardised test conditions that may significantly deviate from actual operational usage patterns. Top-down input-output estimates are subject to sectoral aggregation errors that can misrepresent the relative contribution of specific groups of products or clinical activities. The practical consequence is that the carbon account of a procedure or department depends not only on what is measured, but also on how it is measured and from which source, a source of systematic uncertainty that is rarely quantified or explicitly stated.

The third tension, and the most fundamental, concerns the integration of environmental indicators with clinical and organisational ones. No decision in healthcare is made solely based on CO_2 per functional unit: it must be weighed against clinical outcomes, patient safety, infection control requirements, regulatory compliance, and economic constraints. The absence of standard procedures to integrate environmental metrics and clinical outcome measures prevents the translation of environmental assessment results into actionable evidence for clinicians, hospital managers, and procurement officers. This gap is not just a technical problem of indicator selection: it reflects the broader socio-technical challenge of the sector, namely that sustainability interventions must adapt to the real decision-making structures of complex healthcare organisations. Addressing these three structural tensions (boundary heterogeneity, data quality, and clinical-environmental integration) requires not only methodological refinement but a new generation of practical instruments capable of operating within the governance constraints of real health systems.

Research Approaches

Research Objectives

This dissertation explores the intersection between environmental sustainability and healthcare system management, with a particular focus on the energy and environmental impact of clinical and organisational processes within hospitals. In a context where healthcare facilities face growing pressure to reduce their ecological footprint whilst maintaining high standards of care, this research develops methodological frameworks and analytical tools to assess, quantify and improve the environmental performance of medical activities. The main aim of this research project was to develop models and approaches to achieve the objectives outlined in Table 2.

Table 2: Research Objectives

Research Objectives	RO1: To critically review the current state of the art on the environmental impact of medical procedures, identifying recurring environmental hotspots and methodological gaps that limit the comparability and aggregation of evidence.
	RO2: To develop standardised and scalable methodological frameworks for environmental impact assessment in healthcare, applicable across different institutional contexts and levels of data availability.
	RO3: To generate primary empirical evidence on the environmental impact of representative clinical and diagnostic processes in real hospital settings, and to validate and refine the proposed frameworks against field data.
	RO4: To develop and validate a simulation tool that integrates energy metrics into hospital surgical pathways, enabling comparative assessment of organisational and technological intervention scenarios in terms of energy intensity per patient.

Research Design

The research programme is structured around four sequentially interconnected methodologies: the outputs of each serve as inputs for the next. This progression reflects the programme's logic: from a critical understanding of the existing literature to the proposal of conceptual and operational tools, to their empirical validation, and finally to the development of a decision-making model parameterised using real-world data.

Table 3: Methodology

Methodology	RM1: Systematic literature review following the PRISMA 2020 protocol, mapping the state of the art on the environmental impact of medical procedures through a structured methodological synthesis.
	RM2: Development of methodological frameworks producing innovative constructs, models and methods grounded in normative standards and evaluated through application to real case.
	RM3: Empirical case studies with primary field data collection in real hospital settings, generating consumption profiles and environmental impact assessment.
	RM4**:** Deploying simulation as an analytical tool to comparatively assess the energy intensity of hospital care pathways under different organisational and technological intervention scenarios

RM1 produces the critical literature map that guides the selection of clinical domains and the structure of the RM2 frameworks. RM2 produces the standardised frameworks that define system boundaries and levels of analysis: these guide the measurement protocols of RM3. RM3 produces the validated empirical data that constitute the parameterisation inputs for the simulation tool in RM4. The RM4 translates the empirical data from RM3 into predictive capabilities for scenarios not yet observed, producing outputs that can be used directly for planning decisions.

Given the research objectives outlined in the previous section, the following research questions have been formulated to explore the aim of the research programme.

Table 4: Research Questions

Research Questions	RQ1: What is the current state of the art on the environmental impact of medical procedures, and what methodological gaps limit the comparability and aggregation of evidence? RQ2: How can standardised and scalable methodological frameworks for environmental impact assessment in healthcare be developed to support decision-making across different institutional contexts and data availability levels? RQ3: How does the environmental impact of representative clinical and diagnostic processes manifest in real Italian hospital settings, and how do the empirical findings validate and refine the proposed frameworks? RQ4: How can simulation tools be used to integrate sustainability metrics into hospital surgical pathways and identify the most effective organisational and technological interventions for reducing energy intensity per patient?

Summary of Results

The previous chapters have laid the theoretical and methodological foundations of this dissertation: the systemic paradox of healthcare as a sector simultaneously exposed to the effects of climate change and a contributor to its causes; the nature of clinical hotspots in operating theatres and imaging diagnostics; the socio-technical complexity that conditions the implementation sustainability intervention; and the methodological families available to measure environmental impact at different scales of analysis. This chapter presents the results of the eight scientific contributions that make up the research programme, illustrating their main content and their highlights.

The contributions are organised according to the methodological progression described in Chapter 2: from the systematic review of the literature (Paper 1), to the development of methodological frameworks (Paper 2, 3, and 4), to case studies in real hospital contexts (Paper 5, 6, and 7), up to the construction of the simulation model (Paper 8). This sequence reflects the cumulative logic of the programme, where the outputs of each phase serve as inputs for the next phase (Figure 3). The systematic review guides the structure of the frameworks; the frameworks define the measurement protocols of empirical studies; the empirical data parameterise the simulation model.

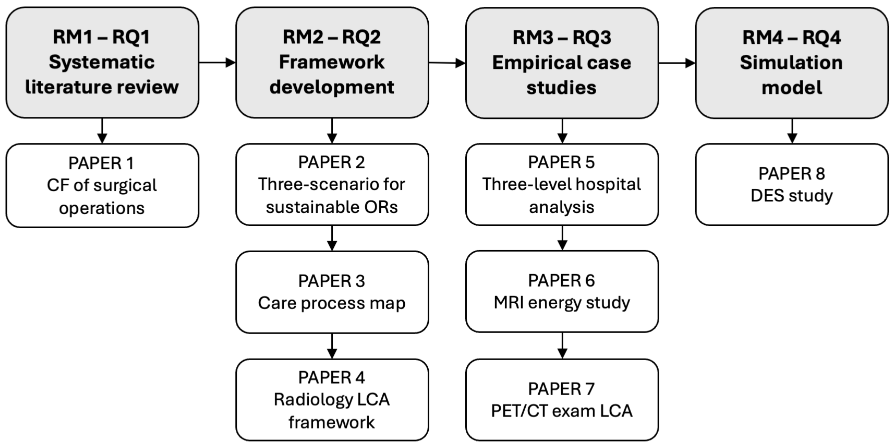


Figure 3: The four-phase research programme: from systematic evidence mapping (RM1-RQ1) through framework development (RM2-RQ2) and empirical validation (RM3-RQ3) to simulation-based scenario analysis (RM4-RQ4).

PAPER 1 - THE CARBON FOOTPRINT OF SURGICAL OPERATIONS: 2023-2025 SYSTEMATIC REVIEW UPDATE

This systematic review analyses the literature published between January 2023 and September 2025 on the carbon footprint of surgical procedures, updating two previous studies. The research conducted following PRISMA 2020 guidelines and registered on PROSPERO, includes 26 studies on over 3,200 initial records from different scientific databases. The studies cover a wide range of surgical specialities, with the predominance of orthopaedic surgery and are concentrated in western countries, such as the United Kingdom (10 studies), United States (8 studies), and France (4 studies). Emissions associated with procedures vary considerably: from less than 1 $kgCO_2e$ for less invasive techniques to 1005 $kgCO_2e$ for multistage patient pathways, with most routine interventions falling between 50 and 150 $kgCO_2e$. The review identifies five recurring emission hotspots: the supply chain of medical devices, the energy consumption for HVAC and electricity, patients and staff travel, anaesthetic gases, and sterilisation and waste disposal. A structured assessment of the quality of studies across four domains is included: completeness, coherence, transparency, and accuracy. More recent studies demonstrate higher quality, however main methodological issues persist, including heterogeneity of system boundaries and the large use of secondary data. The discussion evidences that reductions in the environmental footprint of surgical operations are achievable through a combination of behavioural, organisational, and infrastructural interventions.

Highlights:

- ***Wide range of emissions and surgical specialities.*** *The review includes 26 studies (2023-2025) covering different surgical procedures, with footprints ranging from less than 1 $kgCO_2e$ for minor interventions to 1,005 $kgCO_2e$ for multistage reconstructive surgery pathways.; orthopaedic surgery appears to be the most studied speciality, while large areas remain devoid of LCA evidence.*
- ***Recurring emission hotspots.*** *Five sources systematically dominate the emissions: the supply chain of single-use materials, energy for HVAC and lighting, high GWP anaesthetic gases, the transportation of patients and staff, sterilisation and waste disposal.*

- ***High methodological variability.*** *Only about half refer to recognised standards, almost none report uncertainty analyses, and the inconsistency in system boundaries makes absolute values not directly comparable between studies.*
- ***Reductions of 30-80% are already achievable.*** *Behavioural and organisational interventions allow for substantial reductions in the footprint without impacting clinical outcomes, without requiring complex infrastructural transformations.*
- ***Need for standardisation and cultural engagement.*** *The review emphasises the urgency of shared LCA frameworks and open repositories of emission factors specific to the healthcare sector, accompanied by clinical staff training programmes, identified as a critical lever to translate institutional goals into daily practical change.*

PAPER 2 - SUSTAINABLE OPERATING ROOMS: A COMPREHENSIVE FRAMEWORK FOR ENVIRONMENTAL IMPACT ANALYSIS

The paper proposes a structured methodological framework for assessing the environmental impact of surgical procedures in the operating room. The framework is articulated in three temporal phases and three scenarios of increasing complexity. The three phases (pre-operative, intra-operative, and post-operative) delineate the boundaries of the analysed system and three different scenarios based on data availability: from an evaluation of what is consumed during the surgery, to a complete LCA of the process with an extensive data collection and multidisciplinary expertise.

Highlights:

- ***Three scalable scenario framework on data availability.*** *The central contribution is a framework structured in three phases (pre-, intra-, and post-operative) and three scenarios of increasing complexity: from Scenario 1 (intra-operative audit without emission factors, for quick comparisons between techniques) to Scenario 2 (extended to the post-operative phase with standardised emission factors) to Scenario 3 (complete cradle-to-grave LCA according to ISO 14040/14044 with specialised software).*
- ***Accessibility as a design principle.*** *The framework is designed to be adoptable even in contexts with limited resources: Scenario 1 requires only a basic operational data collection, while Scenario 2 introduces emission quantification in a pragmatic way, significantly lowering the entry threshold for hospitals and researchers lacking advanced LCA skills.*

- ***Need for databases of emission factors specific to surgery.*** *The accuracy and comparability of evaluations depend on the availability of emission factors contextualised to the healthcare sector; the paper advocates for the construction of centralised and open-access databases dedicated to surgical procedures, which are currently absent from the literature.*

PAPER 3 - GREENING HEALTHCARE: AN APPROACH TO ASSESS THE ENVIRONMENTAL IMPACT OF MEDICAL PROCEDURES

The aim of this paper is to integrate the environmental assessment with the well-being of the patient. The starting point is the paradox recognised in scientific literature: existing studies on the environmental impact of medical procedures treat the patient as a passive subject, without considering how clinical decisions can influence the quality of life. This reductionism produces partial and potentially misleading evaluations. The central contribution is a Care Process Map (CPM) as a logical and sequential map that articulates the patient's journey in three temporal phases: clinical evaluation, medical treatment, and recovery. The CPM allows for the positioning of each activity within an interconnected system in the whole care process, associating with each phase both the resource flows and GHG as well as the clinical outcome indicators relevant to the patient. This dual perspective is developed through example: endoscopic surgery. The endoscopic technique has a higher intra-operative footprint than traditional surgery, due to more sophisticated instrumentation and longer surgical times, but it produces significant benefits for the patient: less tissue trauma, reduced post-operative pain, shorter recovery times, and reduced hospital stay. A limited evaluation to the operating room would classify the endoscopic technique as less sustainable; an evaluation of the entire care pathway could reverse this conclusion.

Highlights:

- ***The patient as an active variable in the assessment of sustainability***. *The paper introduces a paradigm shift compared to the existing literature: the patient is not a passive subject in the care process, but an active agent whose well-being must be integrated into the sustainability assessment alongside environmental indicators.*
- ***The Care Process Map as a tool for holistic integration.*** *The central methodological contribution is a sequential map of the surgical care pathway divided into three phases (clinical assessment, surgery, recovery), which allows associating both resource flows and GHG emissions as*

well as outcomes relevant to patient well-being with each clinical activity, overcoming the fragmentation of studies that analyse only the operating room.

- ***The paradox of endoscopic surgery as an emblematic case.*** *Techniques with a higher intra-operative footprint can be overall more sustainable when considering the entire pathway: endoscopic surgery, while consuming more resources during the procedure, reduces hospital stays, analgesic medications, and recovery times, overturning the conclusions reached by evaluations with narrow boundaries.*
- ***Environmental and social sustainability as inseparable dimensions.*** *In the healthcare sector any sustainability assessment that ignores the clinical and social impact of organisational choices is structurally incomplete; integrating the dimension of patient well-being is not an optional addition, but a necessary condition for reliable evaluations and responsible clinical decisions.*

PAPER 4 - TOWARDS A GREENER RADIOLOGY: A COMPREHENSIVE LIFE CYCLE ASSESSMENT FRAMEWORK FOR DIAGNOSTIC IMAGING

The paper proposes a comprehensive LCA framework specifically designed to assess the environmental impact of diagnostic imaging procedures, filling a scientific literature gap. A review conducted on 17 original articles highlights that only 5 adopted an LCA approach with marked heterogeneous and not-comparable methodologies. Functional units vary between "single scan" and "complete patient examination," system boundaries range from gate-to-gate to cradle-to-grave approaches, and inventory databases and impact models are not shared across studies. The proposed framework divides the diagnostic activity's life cycle into three phases: pre-clinical, clinical and post-clinical. The framework also includes guidelines on selecting the LCA method based on the study's geographic location and recommends sensitivity analysis to quantify the uncertainty of the results.

Highlights

- ***Methodological fragmentation in the radiological LCA literature.*** *Of the 17 original articles identified on sustainability in radiology, only 5 adopt an LCA approach; among these, none share the same functional unit, system boundaries, inventory database, or impact model, making any direct comparison between studies impossible.*
- ***Three-phase cradle-to-grave framework.*** *The central contribution is an LCA framework structured into a preclinical phase (production and transport of equipment and consumables), a*

clinical phase (energy consumption, single-use materials, travel), and a post-clinical phase (waste management, maintenance, data storage), designed to systematically cover all impact items overlooked by existing studies.

- ***Geographic variability of emission factors as a critical variable.*** *The environmental impact of electricity consumption depends critically on the national energy mix; the framework integrates this variable as a structural element of the methodology, making the results contextualizable and comparable across healthcare systems in different countries.*

PAPER 5 - ASSESSING ENERGY AND WASTE IMPACTS IN ORTHOPAEDIC DEPARTMENTS: A CASE STUDY FROM AN ITALIAN PUBLIC HOSPITAL

This case study is articulated in three-tiered carbon accounting framework applied to the Orthopaedics and Traumatology Department of a large public hospital in Lombardy, Italy. The objective is to provide a replicable tool for estimating CO_2e emissions related to energy consumption and infectious waste management, without requiring advanced LCA expertise or comprehensive sub-metering data.

The methodological strength is its replicability: the two flows analysed, energy consumption and infectious waste, are systematically recorded in any hospital facility, as they are subject to regulatory and contractual obligations independent of any environmental reporting choices. The proposed framework does not require the collection of new primary data, but only their reinterpretation through the lens of carbon accounting. This structurally lowers the barrier to entry for environmental reporting, making it feasible for managers and clinicians without specialized training in LCA.

At the macro level, the hospital's energy consumption is distributed as follows: 41% for district heating, 31% for district cooling, and 28% for electricity; hazardous waste accounts for 65% of the total waste produced. At the meso level, the Department of Orthopaedics and Traumatology contributes 1.91% of total emissions, with infectious waste accounting for 6% of the department's footprint, indicating an intensity per unit of floor area higher than the hospital average. At the micro level, referring to individual surgical procedures, the share of infectious waste reaches 37% of the total operational footprint, with the remaining 63% attributable to energy consumption.

Highlights

- ***Universal replicability as a central methodological contribution.*** *The framework is built exclusively on data already mandatorily recorded in every hospital making environmental reporting feasible without LCA software, sub-metering, or specialized expertise.*
- ***The macro-meso-micro gradient as the main finding****. The share of emissions from infectious waste in total operational emissions rises from 2% at the hospital level, to 6% at the departmental level, up to 37% per individual surgical procedure: only breaking down emissions by level allows for the correct identification of hotspots.*
- ***HVAC as a priority lever.*** *Over 70% of hospital energy consumption is for heating and cooling; in operating rooms, HVAC accounts for more than half of measured electricity consumption. Setback mode during non-surgical hours can reduce ventilation consumption by between 50% and 70%.*
- ***Hazardous waste is overestimated due to excessive caution.*** *The expected share is about 10% of the total, but in practice it is consistently higher due to over-classification. Proper segregation can reduce emissions from waste by up to 85%.*
- ***Limited scope, but guaranteed comparability.*** *The explicit exclusion of Scope 3 emissions is not a flaw: it makes the results internally consistent and immediately usable for internal benchmarking, serving as a basis for future extensions towards a complete carbon footprint.*

Methodological note on data standardisation, assumptions, and transferability. Energy consumption data were drawn from annual utility contracts and facility metering records (kWh/year), disaggregated to the departmental level using floor area ratios and to the procedural level using operative caseload. Infectious waste volumes were extracted from mandatory disposal contracts (kg/year) subject to regulatory tracking under DPR 254/2003. Carbon conversion was performed using the 2022 Italian national electricity emission factor (0.233 kgCO_2eq/kWh, ISPRA) and IPCC default incineration factors. The framework is transferable to any hospital department that produces statutory energy and waste records; adaptation to non-Italian settings requires substitution of the national electricity emission factor and the applicable waste disposal emission factors.

PAPER 6 - ENERGY PERFORMANCE OF MRI SYSTEMS: ON-SITE VALIDATION AND COMPARISON WITH MANUFACTURER DECLARATIONS

This paper presents a field evaluation of the energy consumption of two generations of MRI scanners, with the dual objective of quantifying the energy benefits of technological replacement and comparing actual measurements with scanners' Environmental Product Declarations (EPDs).

The methodology is based on direct measurement of electricity consumption using a power quality analyser connected to the electrical panel of each scanner, for two-week periods before and after the replacement.

The results show an overall reduction in electricity consumption of 10% between the two models, with an asymmetric distribution across the states: the active phase shows only a 2% reduction, the idle phase a 39% reduction, and the standby phase a 10% reduction. Standby accounts for 32% of total consumption in both models, due to the continuous operation of the helium cooling system.

Since EPDs do not indicate which Primary Energy Factor was used for the calculation, a direct comparison is not possible, and the results should be interpreted as sensitivity analyses rather than absolute comparisons.

Highlights

- ***The energy savings from the technological replacement are concentrated in non-productive phases.*** *The reduction in electricity consumption between the old and new models is 10% overall, but almost entirely attributable to idle (-39%) and standby (-10%) phases. The generational improvement therefore concerns the management of standby states, not scanning performance.*
- ***Standby mode consumes 32% of total energy in both models.*** *Cryogenic helium cooling, which must remain active continuously, represents a structural hotspot independent of the technological generation. Emerging helium-free MRI systems are identified as the most promising lever for addressing this issue systematically.*

- ***The national energy mix triples the environmental impact for the same scanner.*** *Primary energy savings over 10 years range from 235.6 to 687.1 MWh depending on the PEF applied. This range is wider than the difference between the old and new models, demonstrating that the scanner's geographic location is as critical a variable as the equipment's technology generation.*
- ***The EPDs declared by manufacturers can deviate from reality.*** *With the standard European PEF, EPDs overestimate actual primary energy consumption by approximately 35%; with the maximum national PEF, they underestimate it by up to 23%. Since EPDs do not indicate which PEF they used, direct comparison is structurally impossible: on-site validation is the only tool for obtaining reliable data for sustainable procurement decisions.*
- ***Energy efficiency is a necessary but insufficient criterion for equipment replacement.*** *Treating sustainability as a standalone criterion for replacement risks misaligning management decisions with the primary objectives of patient care.*

Methodological note on data standardisation, assumptions, and transferability. Electricity consumption was measured using a calibrated power quality analyser (Fluke 435-II) connected at the electrical panel of each scanner, recording at one-second intervals over two-week periods before and after equipment replacement. Operational states (active scan, idle, standby) were classified against manufacturer documentation and operational logbook records. Primary Energy Factors were drawn from EN 15316-4-5 and Italian national values (ISPRA 2022). Since EPD documents do not disclose which PEF was applied in their calculations, comparisons with declared values are treated as sensitivity analyses rather than absolute validations. The measurement protocol is equipment-agnostic and applicable to any imaging modality; replication in other national contexts requires updating the PEF and grid emission factor to local regulatory values.

PAPER 7 - ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF [^{18}F]FDG PET/CT IMAGING IN A HOSPITAL-BASED NUCLEAR MEDICINE DEPARTMENT

The paper presents the first detailed cradle-to-grave LCA of a [^{18}F]FDG PET/CT scan conducted at the Department of Nuclear Medicine of the IRCCS San Raffaele Hospital in Milan, in accordance with ISO 14040 standards. The functional unit is a single PET/CT scan performed on an adult patient.

Data collection combines direct measurements of the scanner's electricity consumption, HVAC estimates based on official data from facility records, and a detailed inventory audit of single-use and reusable materials. The analysis was performed using SimaPro software and the Ecoinvent database.

The impact of a single examination is estimated at approximately 7.6 kgCO_2eq, with HVAC systems accounting for 47%.

Highlights

- ***The scanner is the smallest contributor: 5.4% of the total GWP.*** *The direct electricity consumption of the PET/CT equipment accounts for a marginal portion of the overall footprint. The real hotspots are HVAC (47%) and radiopharmaceutical production (36%): focusing sustainability strategies solely on scanner efficiency would mean addressing the wrong part of the system.*
- ***HVAC is the primary contributor, yet it is almost always excluded from LCA studies in radiology.*** *The air conditioning of the four functional spaces generates nearly half of the examination's climate impact. This finding is systematically overlooked in the literature: previous studies that exclude HVAC from the system boundaries structurally underestimate the impact of diagnostic imaging.*
- ***Radiopharmaceutical production accounts for as much as the entire acquisition phase.*** *The on-site cyclotron and the conditioning of the radiopharmacy contribute 36% of the GWP, a share comparable to the sum of the scan room and control room. This hotspot is specific to nuclear medicine and absent in LCAs of other imaging modalities, making PET/CT environmentally incomparable with MRI or CT without a dedicated analysis.*
- ***Decarbonizing the electricity mix is the most powerful lever available.*** *Sensitivity analysis shows that a 50% reduction in the national grid's emission factor would cut the GWP per exam by over 1.8 kgCO_2eq, more than the combined total contribution of the scanner and single-use materials. National energy policies have a greater impact on the environmental footprint of nuclear diagnostics than any internal procedural optimisation.*
- ***Single-use materials dominate the toxicity categories, not the GWP***. *With 28% of the GWP, single-use devices are the third-largest contributor to climate change; however, in terms of ecotoxicity, fossil resource scarcity, and solid waste generation, they are the dominant factor. This*

differentiated impact profile suggests that mitigation strategies must be designed separately for the two dimensions.

Methodological note on data standardisation, assumptions, and transferability. Scanner electricity was measured directly with a power quality analyser; HVAC consumption was estimated from facility engineering records using nominal air exchange rates and measured operating hours. The LCA was performed in SimaPro 9.5 using the Ecoinvent 3.9 database and the ReCiPe 2016 (H) impact assessment method. The functional unit is one adult [^{18}F]FDG PET/CT examination; system boundaries follow a cradle-to-grave approach for equipment and gate-to-grave for consumables. The framework is transferable to other nuclear medicine departments, but radiopharmaceutical data must be collected on-site, as production parameters vary significantly between facilities. HVAC contributions will also vary with building age, climatic zone, and air-conditioning technology.

PAPER 8 - INTEGRATING ENERGY EFFICIENCY INTO HEALTHCARE OPERATIONS: A DISCRETE-EVENT SIMULATION APPROACH FOR SURGICAL PATHWAYS

The paper proposes a discrete-event simulation (DES) model that combines operational efficiency and energy consumption metrics into the orthopaedic surgical pathway.

The aim of the model is to simulate a typical operating day combining primary and secondary data as input parameters. The pathway is divided into two functional units: the diagnostic imaging unit and the orthopaedic surgical unit. Daily consumption is calculated by aggregating the power of each device over the duration of each operating state across all simulated patients, with 50 replicates to ensure statistical robustness. The results show 21.1 kWh energy consumption per patient in the surgical unit and 10.1 kWh in the diagnostic unit.

Three different scenarios are simulated and compared: organisational optimisation of the operating room, replacement of surgical lighting with LEDs, and a combination of the two measures.

Highlights

- ***Hospital sustainability is a management issue before it is a technological one.*** *The key finding is that organisational decisions have a greater impact on energy consumption per patient* *than technological interventions. Increasing surgical throughput from 6 to 8 procedures per day reduces the footprint per patient by 21%, compared to the 6% reduction achieved through LED retrofits: the organisational lever is three times as effective as the technological one.*

- ***HVAC turns idle time into environmental costs.*** *With operating rooms used for less than 40% of available time, the fixed HVAC load is distributed across a small number of patients, amplifying the energy intensity per procedure. Every minute of unused operating room time has a real energy cost: the model makes this measurable and therefore actionable.*
- ***DES as an energy decision support tool, not just an operational one.*** *The paper's methodological contribution is to integrate dynamic consumption profiles by operational state (idle, base load, peak) directly into the simulation logic, generating KPIs such as kWh/patient and* $kgCO_2$*/procedure alongside traditional metrics like wait times and resource utilization. This makes the trade-off between clinical performance and environmental impact visible within the same decision-making interface.*

The papers included in this dissertation were developed to address the research objectives and to respond to the research questions outlined in Table 3. Their relationships are concisely delineated as follows.

Concluding Remarks

Discussion and Contribution

The structural contradiction from which this dissertation originates, that the healthcare system both generates and is harmed by the environmental deterioration it is charged with managing, is not a new conceptual observation, but its operational implications have taken time to penetrate the institutional structures of hospital governance and clinical practice. The most recent decade of systematic evidence documents with increasing precision the closing of this feedback loop: the carbon embedded in healthcare operations returns as heat-related mortality, the geographic redistribution of vector-borne pathogens, and the nutritional and psychosocial consequences of climate-driven displacement that translate directly into hospital admissions and long-term care demands (Romanello et al., 2023; Watts et al., 2021). The eight papers constituting this dissertation are constructed as a response to the specific institutional infrastructure gap that this contradiction exposes: the absence, within most hospital management systems, of the measurement, modelling and decision-support frameworks necessary to make the environmental consequences of clinical operations visible at the level of the individuals and organisational units that generate them. The most consequential barrier to healthcare decarbonisation is not the unavailability of lower-carbon technologies or processes, many of the most impactful substitutions are already technically mature and economically viable (MedTech Europe, 2025), but the distributed invisibility of environmental impact within complex socio-technical organisations that neither measure it systematically nor translate results into the feedback loops through which clinical and managerial behaviour might change. The structural logic connecting problems, contributions, and outcomes is summarised in Figure 4.

Contribution 1: Multi-level Environmental Measurement Frameworks

The first substantial contribution of this research corpus is the empirical demonstration that the environmental impact in hospital contexts is structured in a nested hierarchy of concentration, from the facility to the department, to the individual procedure, and that this gradient has direct and non-negligible consequences for the design of governance and monitoring systems. The macro-meso-micro structure documented in Paper 5, where infectious waste represents 2% of total hospital emissions at an aggregated level but reaches 37% of the operational footprint at the level of a single orthopaedic procedure, is not a methodological artefact, but rather a structural characteristic of how resource-intensive activities concentrate within clinical microsystems operating within larger structures. This result has a categorical implication for sustainability policy that cannot be derived from aggregate data alone: interventions calibrated on footprints at the structural level will systematically allocate resources incorrectly compared to those informed by departmental and procedural accounting, as the structure of environmental costs in clinical activity does not reflect the organisational structure through which it is administratively managed. The practical corollary is that the development of scalable and multi-level measurement frameworks, of the type proposed in Papers 2, 4, and 5, does not represent a mere methodological contribution, but an operational prerequisite for directing sustainability investments towards the organisational places where the environmental impact is generated. This evidence is in direct dialogue with international environmental data collection platforms that in recent years have attempted to bridge the gap between academic research and hospital management practices. The Hippocrates Data Center of the Global Green and Healthy Hospitals network, for example, collects indicators of energy consumption, waste generation, and greenhouse gas emissions from over two thousand healthcare facilities in more than seventy countries, producing comparative dashboards that enable cross-institutional benchmarking (Health Care Without Harm and Global Green and Healthy Hospitals, n.d.). Similarly, commercial platforms like Dcycle aggregate data from energy audits, procurement databases, and direct emissions to calculate organisational carbon footprints disaggregated by scope (Scope 1, 2, and 3) and by operational category (Dcycle, n.d.). These platforms operationalise, at scale, a multi-level measurement logic similar to what this research programme has demonstrated to be necessary. Their structural limitation, however, is that the granularity of the data remains constrained by the scale of the facility: in the absence of sub-metering for individual departments or equipment systems, even the most sophisticated aggregation platforms produce results that are no more detailed than the totals at the institutional level. The multi-level frameworks developed in this dissertation, which demonstrate how it is possible to construct environmental reports at the departmental and procedural levels through proportional allocation procedures calibrated on empirical consumption profiles, offer a direct methodological response to this limitation and indicate the direction in which the data collection modules of existing platforms should evolve.

Contribution 2: Organisational Vs. Technological Levers in Hospital Energy Management

The second contribution reconfigures the relationship between technological and organisational levers as a primary strategic issue in hospital sustainability management. The discrete event simulation of Paper 8 provides quantitative evidence supporting a conclusion that the broader literature on operations management and healthcare sustainability has only addressed qualitatively: the dominant determinant of energy intensity per patient in surgical settings is not the technology employed, but the intensity of its use. Increasing the surgical volume from six to eight procedures per day results in a 21% reduction in energy per patient; replacing conventional lighting with LED technology produces a 6% reduction: a ratio of about 3.5 to 1 in favour of organisational leverage. This reflects a structural characteristic of hospital energy consumption that research on ventilation and equipment has consistently documented: the fixed loads determined by HVAC, cryogenic cooling, and standby consumption are distributed over a denominator of patients established by programming and process management decisions, rather than by any technical property of the equipment itself (Heye et al., 2020). Healthcare sustainability strategies primarily focused on high capital intensity technological replacement, such as renewable energy installations, equipment upgrades, building retrofits, will systematically produce a lower environmental return per unit of investment compared to strategies that also target the operational logic through which high-energy intensity infrastructure is used. The management of hospital operations is not just a secondary aspect of sustainability, but a core component of it. This supports what healthcare management literature has long argued: that the way organisations are designed strongly influences both the quality of care and the efficient use of resources (Carayon et al., 2006). This evidence finds an important connection with the advanced modelling technologies that are emerging in the management of hospital facilities. Digital twin systems, which are computational replicas of physical systems continuously updated with IoT sensor and Building Management System data, are progressively being employed for continuous energy monitoring, predictive maintenance of HVAC systems and clinical equipment, and dynamic optimisation of operational programmes (Cumo et al., 2025; Jiang et al., 2025). The simulation framework developed in Paper 8 and digital twin technologies are not alternative tools, but complementary ones: Simulation provides the prospective evaluation of intervention scenarios before implementation, while digital twins provide the real-time operational feedback necessary to continuously support and optimise the organisational choices that the analysis identifies. Together, these two levels of modelling constitute the minimum technical architecture necessary to translate the knowledge of the structure of hospital energy costs into stable and verifiable operational improvements.

Contribution 3: Environmental Data Reliability and Green Public Procurement

The third contribution focuses on the reliability of environmental data as a basis for procurement-driven decarbonisation, a topic that has received limited attention in both academic research and sustainability governance debates. Paper 6 establishes that the Environmental Product Declarations (EPD) issued by manufacturers of imaging diagnostic equipment systematically and undisclosedly deviate from the energy measurements taken in situ: the discrepancy ranges from an overestimation of 35% to an underestimation of 23%, depending on the primary energy conversion factor applied, a methodological choice that the EPDs do not make explicit, rendering it structurally impossible to compare products based solely on the declared data. This reveals a fundamental information asymmetry at the core of Green Public Procurement (GPP): if the environmental data underlying the sustainability criteria in equipment tenders cannot be validated against actual operational performance, those criteria cannot fulfil their policy function, regardless of how seriously institution apply them. This finding connects to the governance gap in Italy described earlier. The limited use of GPP in healthcare is not just a matter of weak political commitment or capacity, but also of possible unreliable data. Improving measurement is an essential first step, even if it is not enough on its own. This gap is not yet adequately addressed by the currently available environmental reporting tools. The same ESG tracking platforms, while providing Scope 3 estimates for multi-site systems, do not achieve the necessary granularity to guide procurement decisions on individual product categories: anaesthetic agents, single-use devices, imaging diagnostic equipment. The reason is structural: EPDs and product-level LCA studies that would provide this granularity remain the exception in the medical device and pharmaceutical sector, and their integration into hospital procurement systems represents an unresolved governance challenge in all the examined jurisdictions. The evidence produced in Paper 6 identifies the precise mechanism through which this gap is perpetuated, the non-disclosure of methodological choices that render the declared data non-comparable, and thereby also indicates the direction of the solution: the introduction of methodological transparency requirements in EPDs as a prerequisite for their usability as a selection criterion.

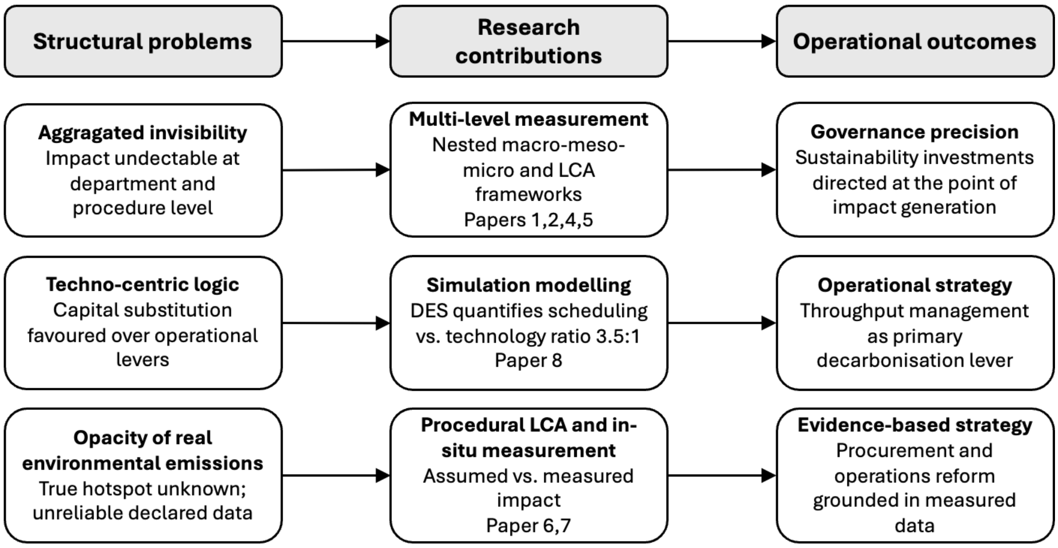


Figure 4: Theory of change: the three structural problems addressed by this dissertation, the corresponding research contributions, and their operational outcomes for hospital sustainability governance.

Policy and Managerial Implications

For hospital managers, the central implication is that environmental performance is primarily an organisational and governance challenge before it is a technological one. The simulation evidence from Paper 8 and the hierarchical measurement framework of Paper 5 converge on the same operational conclusion: reducing the energy and waste intensity of clinical activities does not require capital-intensive infrastructure replacement as a first step, but rather the construction of departmental and procedural measurement systems capable of making environmental impact visible at the level where the decisions that generate it are actually made. Scheduling optimisation, anaesthetic protocol standardisation, and surgical kit rationalisation are all organisationally feasible levers whose implementation requires data visibility and feedback mechanisms rather than new capital investment.

For national healthcare authorities and regulators, the implications concern both measurement standards and procurement governance. The evidence from Paper 6 identifies a fundamental flaw in the current EPD-based approach to Green Public Procurement for medical equipment: the non-disclosure of primary energy conversion factors renders manufacturer declarations structurally non-comparable and unsuitable as selection criteria without independent on-site validation. Correcting this flaw requires regulatory intervention, specifically the introduction of mandatory methodological transparency requirements as a condition for EPD acceptance in procurement procedures. More broadly, the absence of a national healthcare carbon accounting framework in Italy represents the systemic precondition for most of the measurement gaps this dissertation addresses, and one that only coordinated regulatory action can resolve.

For international policy frameworks, the scalable and transferable nature of the methodological approaches developed in this dissertation suggests that their adaptation to healthcare systems outside Italy is technically feasible, provided that national electricity emission factors and clinical activity profiles are updated accordingly. The integration of these approaches into the WHO operational framework for climate-resilient health systems or into European Green Deal implementation programmes for healthcare would provide the normative scaffolding needed to move from isolated academic case studies to systematic institutional adoption.

Research Contributions and the Healthcare Sustainability Landscape

The three contributions described above do not operate in isolation from the broader landscape of practical tools that have emerged in recent years to support healthcare sustainability governance. The need to translate environmental evidence into operationally usable tools has generated a structured ecosystem of practical resources: strategic management toolkits such as the Sustainability Accelerator Tool from the International Hospital Federation, which guides hospital managers in setting emission reduction targets aligned with international commitments; clinical carbon calculators like the Care Pathways Carbon Calculator from the Sustainable Healthcare Coalition, which allows clinicians and pathway managers to estimate the emissions associated with entire care pathways; integrated quality frameworks such as the SusQI Toolkit, which incorporates environmental metrics within clinical quality improvement cycles; training programmes such as the Carbon Literacy Healthcare Toolkit, which develops environmental competence among healthcare professionals lacking specialised training in LCA (Carbon Literacy Project, n.d.; Centre for Sustainable Healthcare, n.d.; International Hospital Federation, n.d.; Sustainable Healthcare Coalition, n.d.). The design of these tools, especially the choice to base environmental impact calculations on a limited number of key clinical variables, is supported by the systematic review in Paper 1. This review shows that the main sources of environmental impact in clinical practice are linked to specific and well-defined procedures, which are stable enough to be represented accurately using standardised parameters. This evidence not only retroactively legitimises the approach of existing clinical calculators but also defines their limits: where high-impact decisions fall outside these well-defined contexts, such as in the case of procurement choices spanning multiple departments or scheduling changes involving the entire structure, it is necessary to resort to higher-order analytical tools, of the type developed in the subsequent Papers of this dissertation. These tools are, overall, better designed to function within the sociotechnical complexity of real hospital organisations compared to purely academic frameworks: they speak the language of clinical governance, produce outputs comparable to existing management metrics, and, in many cases, can be employed without specialised lifecycle assessment skills.

Their limitations, however, exactly reflect the structural tensions that this dissertation has investigated. The heterogeneity of system boundaries persists because emission factor databases lack the standardisation that normalised LCA frameworks could provide: clinical calculators carry the methodological assumptions and associated uncertainties of the studies from which their preconfigured factors are derived. The constraints of data quality persist because the measurement infrastructure at the structural level is underdeveloped in most healthcare systems. The clinical-environmental integration is more fully achieved in training and quality improvement tools than in quantitative decision support tools: complex decisions, such as the comparison between anaesthesiologic techniques with different clinical and environmental impact profiles, or the evaluation of the trade-off between surgical throughput and the energy intensity of the equipment, require a quantitative integration of metrics that tools which were developed during these years, in their current configuration, do not achieve. The contributions of this dissertation do not replace this ecosystem, but rather form its methodological foundation: the systematic review of Paper 1 maps the landscape of high-impact decisions and delineates their parameterizability; the standardised LCA frameworks of Papers 2, 3, and 4 provide the scaffolding for a more consistent generation of emission factors; the empirical evidence from Papers 5, 6, and 7 demonstrates that departmental and procedural reporting is achievable without sub-metering; the simulation model in Paper 8 provides the quantitative integration between environmental and clinical metrics that existing tools do not achieve, making environmental evidence systematically actionable in the operational decisions that determine the real footprint of healthcare facilities.

The implementation of more sustainable practices in the healthcare sector has become a systemic necessity. The sector faces a structural gap in measurement that prevents this awareness from translating into operational action. Yet a structural gap in measurement prevents this awareness from translating into operational action: without reliable and comparable environmental data, health systems lack the evidence base to prioritise investments and direct change. This dissertation is based on the belief that environmental sustainability in healthcare is not simply a technological issue, nor exclusively a regulatory one: it is a far more complex problem, and its solution lies in the development of measurement, modelling, and feedback systems designed to operate within the complexity of hospitals, systems that this research programme substantially contributes to establishing.

Limitations of the Research

The most significant limiting condition of this dissertation is its deliberate restriction of scope to two clinical domains, operating theatres and diagnostic imaging, whose selection was justified by the consistent identification of these settings as the primary inpatient hotspots in both the energy and the materials dimensions of the hospital environmental footprint. This scope restriction renders the research tractable and generates contributions with internal coherence and methodological precision, but it means that the full environmental profile of a hospital or integrated health system lies outside the analytical frame. The frameworks and quantitative findings presented here should accordingly be understood as components of a broader measurement architecture rather than as self-contained accounts of institutional environmental impact, and their extension to domains not covered by the empirical studies requires independent validation rather than direct extrapolation.

Within the scope of the studies conducted, a second limiting condition concerns the heterogeneity of system boundaries across the eight papers: a heterogeneity that reflects the tension between methodological rigour and operational feasibility that is endemic to LCA research in clinical settings. Paper 5, by design, restricts its scope to Scope 1 and 2 operational emissions, excluding the upstream supply chain; Papers 6 and 7 focus on the use phase of specific imaging equipment, leaving aside end-of-life emissions and the capital goods component of manufacturing impact. This variation in boundary conditions is a deliberate adaptation to the data environments and research questions of each study, and each paper makes its choices explicit; nevertheless, the consequence is that findings cannot be aggregated across papers into a coherent cumulative footprint estimate without prior harmonisation of scope. The comparability of results across the research programme is therefore primarily analytical and methodological: the studies share conceptual frameworks, measurement approaches and decision logics, rather than quantitatively additive.

A third constraint concerns the geographic and institutional representativeness of the empirical evidence base. The case study facilities are concentrated in the Lombardy region of northern Italy, an area that, whilst nationally significant in terms of clinical volume and resource intensity, differs substantially in building stock, energy infrastructure, clinical organisation and procurement practices from hospitals in southern Italian regions, in Mediterranean healthcare systems with different climatic profiles, or in Central and Eastern European health systems with lower per-capita healthcare expenditure and different energy mixes. The quantitative benchmarks generated by the empirical studies are contextually valid reference values for the northern European and northern Italian setting and provide meaningful points of comparison for similar institutional contexts, but they cannot be applied without adjustment to settings with substantially different energy infrastructure or clinical organisation. Sensitivity analyses in Papers 6 and 7 partially address this limitation by modelling the environmental consequences of different national electricity emission factors, a variable whose impact on the findings consistently exceeds that of the equipment-level efficiency differences under comparison, but the organisational and procurement dimensions of cross-contextual variability remain outside the sensitivity analyses and require independent empirical attention.

A fourth and structurally fundamental limitation concerns the analytical separation between environmental performance and clinical outcome that characterises the entire research programme. Each empirical study adopts a functional unit defined in terms of clinical procedures or diagnostic examinations, and none models the downstream health consequences of the environmental interventions it analyses: whether changes in anaesthetic gas selection, scheduling reorganisation or equipment replacement produce measurable differences in patient recovery trajectories, complication rates or readmission frequencies is not addressed. This analytical separation reflects the current state of an evidence base that is not yet sufficiently developed to permit reliable integrated environmental-clinical modelling, but it creates a consequential distance between the environmental optimisation that this research enables and the value-based clinical decision-making that healthcare governance ultimately requires.

Future Research

The studies presented in this dissertation open several interconnected lines of inquiry whose pursuit would substantially advance both the scientific foundations and the practical applicability of environmental management in healthcare settings.

An overarching priority concerns the translation of the measurement frameworks developed at the procedural and departmental levels into tools that hospital management can routinely adopt, without the intensive data collection typical of academic LCA studies. Future work should focus on simplified indicators and modular assessment methods that draw on data already available in hospital information systems, enabling environmental feedback loops at the department and pathway levels and, critically, empowering clinical professionals to conduct meaningful analyses without relying on external consultants. Closely related is the need to extend the discrete-event simulation framework introduced in Paper 8 beyond the orthopaedic surgical pathway treated there as an isolated system. In clinical reality, scheduling decisions in the operating theatre propagate effects upstream towards diagnostic imaging and downstream towards post-operative care; explicitly modelling these interdependencies would yield more realistic estimates of the environmental impact of organisational decisions and open the way for pathway optimisation that jointly pursues clinical and environmental performance objectives.

The procurement dimension of healthcare sustainability warrants dedicated methodological development. The findings of Paper 6 have direct implications for the design of Green Public Procurement criteria: future research could develop standardised on-site validation protocols integrable into procurement procedures and investigate whether mandatory measurement requirements as a condition for equipment certification would measurably reduce the gap between declared and actual environmental performance. Alongside procurement, HVAC systems represent a persistent methodological blind spot: despite constituting the main environmental hotspot in both operating theatres and diagnostic imaging facilities, they remain systematically excluded from most clinical LCA studies. Standardised guidelines for incorporating HVAC-related energy consumption within clinical system boundaries are needed, as is investigation of the trade-offs between infection control requirements that drive ventilation specifications and the environmental costs they generate, particularly given that current evidence does not consistently support the clinical superiority of high-performance configurations over more energy-efficient alternatives. The decarbonisation of hospital HVAC systems thus emerges as a structurally underexplored research frontier, one that sits at the intersection of infection control, building engineering, and environmental management, and whose investigation would both resolve a methodological gap in clinical LCA and provide the empirical basis for ventilation standards that are simultaneously clinically safe and environmentally defensible.

The socio-technical complexity of hospitals suggests that measurement and modelling tools are necessary but not sufficient for generating lasting impact. Future research should therefore integrate the analytical frameworks developed here with implementation science methods, to identify the organisational conditions under which environmental interventions achieve durable adoption at the level of clinical practice. This integration must extend upward into governance: the frameworks for sustainable operating rooms, integrated care pathway assessment and diagnostic imaging LCA developed in this dissertation were designed with scalability in mind, but the pathway from validated academic framework to adopted governance tool involves regulatory, political and institutional dimensions that empirical research alone cannot traverse. Collaborative work with hospital management, national procurement agencies and health ministry policy units would be required to embed environmental performance standards in hospital accreditation criteria, equipment tenders and the mandatory sustainability reporting obligations increasingly imposed on large healthcare organisations under European legislation.

A final and conceptually integrative direction concerns the co-benefits that arise when sustainability investments are designed to address simultaneously the mitigation and adaptation dimensions of the climate-health nexus (Figure 5). These two imperatives have been treated largely independently in the literature, yet the operational evidence increasingly suggests they are structurally entangled: a hospital that has reduced its energy dependence through process efficiency is, by the same token, more resilient to grid disruptions during extreme heat events; procurement diversification that reduces upstream Scope 3 emissions also reduces the concentration risk inherent in single-supplier-dependent supply chains. Future research should develop analytical frameworks capable of modelling these co-benefits explicitly, drawing on the intersection of environmental management systems research, health system resilience planning and infrastructure vulnerability analysis. The institutional scaffolding for such work already exists in the WHO operational framework for climate-resilient health systems, the Lancet Countdown monitoring architecture and the European Green Deal health implementation programmes and provides a ready context within which joint mitigation-adaptation modelling for healthcare could be meaningfully situated and practically applied.

The healthcare sector occupies a singular and structurally paradoxical position in the sustainability transition. It is the only major sector in which the imperative to continue operating regardless of environmental cost is grounded not in economic logic but in the unconditional moral obligation of care; and yet its sustained operational capacity depends, in the medium and long term, on the ecological stability that its own emissions contribute to undermining. This tension is irreducible in the abstract but not unmanageable in practice. Managing it requires a knowledge infrastructure within which clinical teams, hospital managers and procurement officers can make decisions that are simultaneously medically defensible, economically viable and environmentally responsible, not as exceptional acts of institutional virtue, but as the default outcome of a well-governed, data-informed health system.

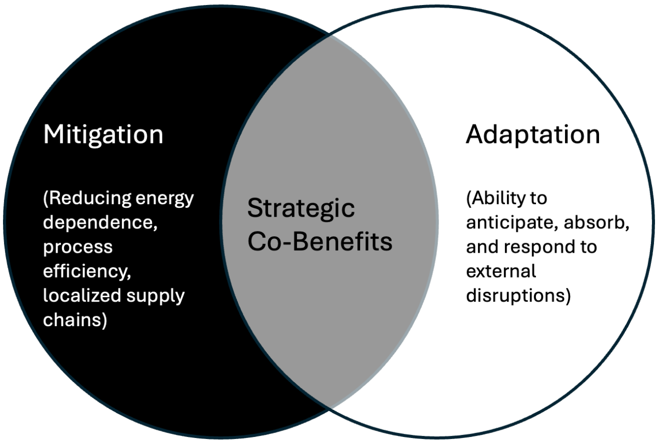


Figure 5: Mitigation and adaptation as entangled objectives in healthcare decarbonisation: the intersection identifies strategic co-benefits, interventions that simultaneously reduce the sector's environmental footprint and enhance its resilience to climate-driven disruptions.

The evidence developed in this dissertation contributes to that infrastructure, arguing on empirical rather than normative grounds that the most consequential barrier to sustainable healthcare is the distributed invisibility of environmental impact within organisations that are structurally complex, operationally pressured and institutionally underprepared to account for what they consume and emit. Making that impact visible, at the scale, resolution and institutional level at which the decisions that generate it are made, is both technically achievable and, given the trajectory of the climate data, urgently necessary. The work that remains is substantial. If this dissertation contributes anything beyond its individual findings, it is the evidence that the problem, however complex, is not beyond the reach of systematic research.

References

Aboueid, S., Beyene, M., and Nur, T. (2023). Barriers and enablers to implementing environmentally sustainable practices in healthcare: A scoping review and proposed roadmap. *Healthcare Management Forum*, *36*(6), 405–413. https://doi.org/10.1177/08404704231183601

Alho, A. M., Oliveira, A. P., Viegas, S., and Nogueira, P. (2024). Effect of heatwaves on daily hospital admissions in Portugal, 2000–18: an observational study. *The Lancet Planetary Health*, *8*(5), e318–e326. https://doi.org/10.1016/S2542-5196(24)00046-9

Amin, H., Yousif, N., and Lüscher, T. F. (2024). An Audit of Recyclable and Contaminated Waste From Invasive Cardiac Procedures. *Journal of the Society for Cardiovascular Angiography & Interventions*, *3*(11), 102390. https://doi.org/10.1016/j.jscai.2024.102390

Armocida, B., Formenti, B., Ussai, S., Missoni, E., De Marchi, C., Panella, M., Onder, G., Mancini, L., Pistis, M., Martuzzi, M., and Barone-Adesi, F. (2022). Decarbonization of the Italian healthcare system and European funds. A lost opportunity? *Frontiers in Public Health*, *10*. https://doi.org/10.3389/fpubh.2022.1037122

Badanta, B., Porcar Sierra, A., Fernández, S. T., Rodríguez Muñoz, F. J., Pérez-Jiménez, J. M., Gonzalez-Cano-Caballero, M., Ruiz-Adame, M., and de-Diego-Cordero, R. (2025). Advancing Environmental Sustainability in Healthcare: Review on Perspectives from Health Institutions. In *Environments - MDPI* (Vol. 12, Number 1). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/environments12010009

Bae, J. H., Ravinal, L., Barth, E., Yanda, M., Bae, D. S., Arato, G., and Lewandowski, K. (2024). The "6th R" of sustainability: Repurposing operating room waste for community benefit. *The American Journal of Surgery*, *238*, 115930. https://doi.org/10.1016/j.amjsurg.2024.115930

Bolten, A., Kringos, D. S., Spijkerman, I. J. B., and Sperna Weiland, N. H. (2022). The carbon footprint of the operating room related to infection prevention measures: a scoping review. *Journal of Hospital Infection*, *128*, 64–73. https://doi.org/10.1016/j.jhin.2022.07.011

Brambilla, A., Poli, R., Dolcini, M., Pattaro, B., and Capolongo, S. (2025). Assessing Environmental Sustainability in Acute Care Hospitals: A Survey-Based Snapshot from an Italian Regional Health System. *International Journal of Environmental Research and Public Health*, *23*(1), 20. https://doi.org/10.3390/ijerph23010020

Carayon, P. (2012). Sociotechnical systems approach to healthcare quality and patient safety. *Work (Reading, Mass.)*, *41 Suppl 1*(0 1), 3850–3854. https://doi.org/10.3233/WOR-2012-0091-3850

Carayon, P., Bass, E. J., Bellandi, T., Gurses, A. P., Hallbeck, M. S., and Mollo, V. (2011). Sociotechnical systems analysis in health care: a research agenda. *IIE Transactions on Healthcare Systems Engineering*, *1*(3), 145–160. https://doi.org/10.1080/19488300.2011.619158

Carayon, P., Schoofs Hundt, A., Karsh, B.-T., Gurses, A. P., Alvarado, C. J., Smith, M., and Flatley Brennan, P. (2006). Work system design for patient safety: the SEIPS model. *Quality in Health Care*, *15*(suppl 1), i50–i58. https://doi.org/10.1136/qshc.2005.015842

Carbon Literacy Project. (n.d.). *Carbon Literacy Healthcare Toolkit*. Retrieved https://carbonliteracy.com/healthcare/

Caviglia, M., Ucciero, A., Conti, A., Di Filippo, A., Trotta, F., Ragazzoni, L., Della Corte, F., and Barone-Adesi, F. (2025). Trends in greenhouse gas emissions from volatile anaesthetics in 41 countries: 2013–2023. *Anaesthesia*, *80*(12), 1476–1483. https://doi.org/10.1111/anae.16709

Centre for Sustainable Healthcare. (n.d.). *SusQI*. Retrieved https://www.nhsfindyourplace.co.uk/toolkits/

Cristiano, W., De Marchi, C., di Domenico, K., Punzo, O., Mancini, A., and Mancini, L. (2024). The elephant in the room in greenhouse gases emissions: rethinking healthcare systems to face climate change. A rapid scoping review. *Environmental Sciences Europe*, *36*(1), 24. https://doi.org/10.1186/s12302-024-00839-3

Cumo, F., Giovenale, A. M., Pennacchia, E., and Tiburcio, V. A. (2025). Towards a Healthier Hospital Environment: The Role of Digital Twins in Achieving Optimal

Environmental Comfort. *Digital Twins and Applications*, *2*(1). https://doi.org/10.1049/dgt2.70002

Dadi, D., Introna, V., Santolamazza, A., Salvio, M., Martini, C., Pastura, T., and Martini, F. (2022). Private Hospital Energy Performance Benchmarking Using Energy Audit Data: An Italian Case Study. *Energies*, *15*(3), 806. https://doi.org/10.3390/en15030806

Dcycle. (n.d.). *ESG and carbon footprint management platform*. Retrieved https://www.dcycle.io/it/

Di Russo, M., Heidar Alizadeh, A., Nurchis, M. C., Capizzi, S., Cavuto, C., Di Bella, O., Di Piazza, G., Figini, A., La Milia, D. I., Nasi, G., Sapienza, M., Rosano, A., Ricciardi, W., and Cadeddu, C. (2025). Hospital waste management before and during COVID-19 pandemic: An analysis of the environmental impact of CO_2 emissions in four Italian facilities. *International Journal of Healthcare Management*, *18*(4), 663–673. https://doi.org/10.1080/20479700.2024.2358704

Drew, J., Christie, S. D., Tyedmers, P., Smith-Forrester, J., and Rainham, D. (2021). Operating in a climate crisis: A state-of-the-science review of life cycle assessment within surgical and anesthetic care. In *Environmental Health Perspectives* (Vol. 129, Number 7). Public Health Services, US Dept of Health and Human Services. https://doi.org/10.1289/EHP8666

Eckelman, M. J., and Sherman, J. (2016). Environmental impacts of the U.S. health care system and effects on public health. *PLoS ONE*, *11*(6). https://doi.org/10.1371/journal.pone.0157014

Eckelman, M. J., Sherman, J. D., and MacNeill, A. J. (2018). Life cycle environmental emissions and health damages from the Canadian healthcare system: An economic-environmental-epidemiological analysis. *PLOS Medicine*, *15*(7), e1002623. https://doi.org/10.1371/journal.pmed.1002623

Giunchi, V., Fusaroli, M., Cangini, A., Fortinguerra, F., Zito, S., Pierantozzi, A., Lunghi, C., Poluzzi, E., and Trotta, F. (2025). Assessing the environmental impact of medicines in Italy using data from the Italian Medicines Agency. *British Journal of Clinical Pharmacology*, *91*(5), 1297–1305. https://doi.org/10.1002/bcp.70046

Göras, C., Nilsson, U., Ekstedt, M., Unbeck, M., and Ehrenberg, A. (2020). Managing complexity in the operating room: a group interview study. *BMC Health Services Research*, *20*(1), 440. https://doi.org/10.1186/s12913-020-05192-8

Gordon, D. (2020). Sustainability in the Operating Room: Reducing Our Impact on the Planet. *Anesthesiology Clinics*, *38*(3), 679–692. https://doi.org/10.1016/j.anclin.2020.06.006

Gould, C. F., Heft-Neal, S., Johnson, M., Aguilera, J., Burke, M., and Nadeau, K. (2024). Health Effects of Wildfire Smoke Exposure. *Annual Review of Medicine*, *75*(1), 277–292. https://doi.org/10.1146/annurev-med-052422-020909

Health Care Without Harm, and Global Green and Healthy Hospitals. (n.d.). *Hippocrates Data Center*. Retrieved https://greenhospitals.org/hippocrates-data-center

Heye, T., Knoerl, R., Wehrle, T., Mangold, D., Cerminara, A., Loser, M., Plumeyer, M., Degen, M., Lüthy, R., Brodbeck, D., and Merkle, E. (2020). The Energy Consumption of Radiology: Energy- and Cost-saving Opportunities for CT and MRI Operation. *Radiology*, *295*(3), 593–605. https://doi.org/10.1148/radiol.2020192084

International Hospital Federation. (n.d.). *Sustainability Accelerator Tool*. Retrieved https://ihf-fih.org/what-we-do/geneva-sustainability-centre/sustainability-accelerator-tool/

Jiang, F., Xie, H., Gandla, S. R., and Fei, S. (2025). Transforming Hospital HVAC Design with BIM and Digital Twins: Addressing Real-Time Use Changes. *Sustainability*, *17*(8), 3312. https://doi.org/10.3390/su17083312

Khosravi, M., Mojtabaeian, S. M., Marzaleh, M. A., and Izadi, R. (2025). A Systematic Review of Factors Influencing the Adoption of Green Practices Within Healthcare Centers to Mitigate Climate Change. *Environmental Health Insights*, *19*, 11786302251332058. https://doi.org/10.1177/11786302251332058

Kooner, S., Hewison, C., Sridharan, S., Lui, J., Matthewson, G., Johal, H., and Clark, M. (2020). Waste and recycling among orthopedic subspecialties. *Canadian Journal of Surgery*, *63*(3), E278–E283. https://doi.org/10.1503/cjs.018018

Lenzen, M., Malik, A., Li, M., Fry, J., M Chaves, L. S., Weisz, H., Pichler, P., Malik, A., Lenzen, M., Li, M., Fry, J., Weisz, H., Pichler, P.-P., Suveges Moreira Chaves, L., Capon, A., and Pencheon, D. (2020). The environmental footprint of health care: a global assessment. In *Articles Lancet Planet Health* (Vol. 4). www.thelancet.com/

Macneill, A. J., Lillywhite, R., and Brown, C. J. (2017). Articles The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. In *planetary-health* (Vol. 1). www.thelancet.com/

Malik, A., Lenzen, M., McAlister, S., and McGain, F. (2018). The carbon footprint of Australian health care. *The Lancet Planetary Health*, *2*(1), e27–e35. https://doi.org/10.1016/S2542-5196(17)30180-8

MedTech Europe. (2025). *Decarbonising Healthcare: How a Competitive MedTech Industry Can Contribute*. https://www.medtecheurope.org/2025/06/05/decarbonising-healthcare-how-a-competitive-medtech-industry-can-contribute/

Ministero dell'Ambiente e della Sicurezza Energetica. (2023). *PIANO NAZIONALE INTEGRATO PER L'ENERGIA E IL CLIMA*. https://www.mase.gov.it/portale/documents/d/guest/pniec_2023-pdf

Nansai, K., Fry, J., Malik, A., Takayanagi, W., and Kondo, N. (2020). Carbon footprint of Japanese health care services from 2011 to 2015. *Resources, Conservation and Recycling*, *152*, 104525. https://doi.org/10.1016/j.resconrec.2019.104525

OECD. (2025). *Decarbonising Health Systems Across OECD Countries*. OECD Publishing. https://doi.org/10.1787/5ac2b24b-en

Oluwasola, I. E., Ahmad, A. L., Shoparwe, N. F., and Ismail, S. (2022). Gadolinium based contrast agents (GBCAs): Uniqueness, aquatic toxicity concerns, and prospective remediation. *Journal of Contaminant Hydrology*, *250*, 104057. https://doi.org/10.1016/j.jconhyd.2022.104057

Osservatorio Appalti Verdi. (2024). *VII Rapporto 2024 - I numeri del green public procurement in Italia*.

Pichler, P. P., Jaccard, I. S., Weisz, U., and Weisz, H. (2019). International comparison of health care carbon footprints. *Environmental Research Letters*, *14*(6). https://doi.org/10.1088/1748-9326/ab19e1

Piffari, C., Lagorio, A., Boffelli, A., and Pinto, R. (2026). Strengthening healthcare supply chains: a social–ecological perspective on resilience. *International Journal of Physical Distribution & Logistics Management*, *56*(11), 70–101. https://doi.org/10.1108/IJPDLM-03-2025-0118

Rizan, C., Lillywhite, R., Reed, M., and Bhutta, M. F. (2023). The carbon footprint of products used in five common surgical operations: identifying contributing products and processes. *Journal of the Royal Society of Medicine*, *116*(6), 199–213. https://doi.org/10.1177/01410768231166135

Rizan, C., Steinbach, I., Nicholson, R., Lillywhite, R., Reed, M., and Bhutta, M. F. (2020). The Carbon Footprint of Surgical Operations: A Systematic Review. In *Annals of Surgery* (Vol. 272, Number 6, pp. 986–995). Wolters Kluwer Health. https://doi.org/10.1097/SLA.0000000000003951

Robinson, P. N., Surendran, K. S. B., Lim, S. J., and Robinson, M. (2023). The carbon footprint of surgical operations: a systematic review update. In *Annals of the Royal College of Surgeons of England* (Vol. 105, Number 8, pp. 692–708). Royal College of Surgeons of England. https://doi.org/10.1308/rcsann.2023.0057

Rockall, A. G., Allen, B., Brown, M. J., El-Diasty, T., Fletcher, J., Gerson, R. F., Goergen, S., Marrero González, A. P., Grist, T. M., Hanneman, K., Hess, C. P., Ho, E. L. M., Salama, D. H., Schoen, J., and Sheard, S. (2025). Sustainability in Radiology: Position Paper and Call to Action from ACR, AOSR, ASR, CAR, CIR, ESR, ESRNM, ISR, IS3R, RANZCR, and RSNA. *Radiology*, *314*(3). https://doi.org/10.1148/radiol.250325

Rodríguez‐Jiménez, L., Romero‐Martín, M., Spruell, T., Steley, Z., and Gómez‐Salgado, J. (2023). The carbon footprint of healthcare settings: A systematic review. *Journal of Advanced Nursing*, *79*(8), 2830–2844. https://doi.org/10.1111/jan.15671

Roletto, A., Zanardo, M., Bonfitto, G. R., Catania, D., Sardanelli, F., and Zanoni, S. (2024). The environmental impact of energy consumption and carbon emissions in radiology departments: a systematic review. *European Radiology Experimental*, *8*(1), 35. https://doi.org/10.1186/s41747-024-00424-6

Romanello, M., Napoli, C. di, Green, C., Kennard, H., Lampard, P., Scamman, D., Walawender, M., Ali, Z., Ameli, N., Ayeb-Karlsson, S., Beggs, P. J., Belesova, K., Berrang Ford, L., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., Cross, T. J., … Costello, A. (2023). The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *The Lancet*, *402*(10419), 2346–2394. https://doi.org/10.1016/S0140-6736(23)01859-7

Romizi, R. (2023, August). *Impronta ecologica dei servizi sanitari. Panorama Sanità.*

Seifert, C., Koep, L., Wolf, P., and Guenther, E. (2021). Life cycle assessment as decision support tool for environmental management in hospitals: A literature review. *Health Care Management Review*, *46*(1), 12–24. https://doi.org/10.1097/HMR.0000000000000248

Sherman, J. D., Thiel, C., MacNeill, A., Eckelman, M. J., Dubrow, R., Hopf, H., Lagasse, R., Bialowitz, J., Costello, A., Forbes, M., Stancliffe, R., Anastas, P., Anderko, L., Baratz, M., Barna, S., Bhatnagar, U., Burnham, J., Cai, Y., Cassels-Brown, A., … Bilec, M. M. (2020). The Green Print: Advancement of Environmental Sustainability in Healthcare. In *Resources, Conservation and Recycling* (Vol. 161). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2020.104882

Sherman, J., Le, C., Lamers, V., and Eckelman, M. (2012). Life cycle greenhouse gas emissions of anesthetic drugs. *Anesthesia and Analgesia*, *114*(5), 1086–1090. https://doi.org/10.1213/ANE.0b013e31824f6940

Sorensen, C. J., Salas, R. N., Rublee, C., Hill, K., Bartlett, E. S., Charlton, P., Dyamond, C., Fockele, C., Harper, R., Barot, S., Calvello-Hynes, E., Hess, J., and Lemery, J. (2020). Clinical Implications of Climate Change on US Emergency Medicine: Challenges and Opportunities. *Annals of Emergency Medicine*, *76*(2), 168–178. https://doi.org/10.1016/j.annemergmed.2020.03.010

Sun, S., Weinberger, K. R., Nori-Sarma, A., Spangler, K. R., Sun, Y., Dominici, F., and Wellenius, G. A. (2021). Ambient heat and risks of emergency department visits among adults in the United States: time stratified case crossover study. *BMJ*, *375*, e065653. https://doi.org/10.1136/bmj-2021-065653

Sustainable Healthcare Coalition. (n.d.). *Patient Care Pathway Carbon Calculator*. Retrieved https://carepathwaycarbon.org/

Tennison, I., Roschnik, S., Ashby, B., Boyd, R., Hamilton, I., Oreszczyn, T., Owen, A., Romanello, M., Ruyssevelt, P., Sherman, J. D., Smith, A. Z. P., Steele, K., Watts, N., and Eckelman, M. J. (2021). Health care's response to climate change: a carbon footprint assessment of the NHS in England. *The Lancet Planetary Health*, *5*(2), e84–e92. https://doi.org/10.1016/S2542-5196(20)30271-0

The greenhouse gas protocol : the GHG protocol for project accounting. (2005). World Business Council for Sustainable Development ; World Resources Institute.

Thomson, M. C., and Stanberry, L. R. (2022). Climate Change and Vectorborne Diseases. *New England Journal of Medicine*, *387*(21), 1969–1978. https://doi.org/10.1056/NEJMra2200092

Vallée, A. (2024). Green hospitals face to climate change: Between sobriety and resilience. *Heliyon*, *10*(2), e24769. https://doi.org/10.1016/j.heliyon.2024.e24769

Vineis, P., Romanello, M., Michelozzi, P., and Martuzzi, M. (2022). Health co-benefits of climate change action in Italy. *The Lancet Planetary Health*, *6*(4), e293–e294. https://doi.org/10.1016/S2542-5196(22)00061-4

Vosshenrich, J., Merkle, E. M., and Heye, T. (2025). The carbon footprint of modern imaging. *Current Opinion in Urology*, *35*(6), 674–678. https://doi.org/10.1097/MOU.0000000000001337

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Coleman, S., Dalin, C., Daly, M., Dasandi, N., Dasgupta, S., Davies, M., Di Napoli, C., … Costello, A. (2021). The 2020 report of The Lancet Countdown on health and climate change:

responding to converging crises. *The Lancet*, *397*(10269), 129–170. https://doi.org/10.1016/S0140-6736(20)32290-X

Woolen, S. A., Martin, M., Foster, C. A., MacEachern, M. P., and Maturen, K. E. (2026). Green Imaging: Scoping Review of Radiology's Environmental Impact. *Journal of the American College of Radiology*, *23*(1), 123–135. https://doi.org/10.1016/j.jacr.2025.09.013

World Health Organization. (2015). *Operational framework for building climate resilient health systems*. World Health Organization. https://www.who.int/publications/i/item/operational-framework-for-building-climate-resilient-health-systems

Wu, R. (2019). The carbon footprint of the Chinese health-care system: an environmentally extended input–output and structural path analysis study. *The Lancet Planetary Health*, *3*(10), e413–e419. https://doi.org/10.1016/S2542-5196(19)30192-5

APPENDIX

PAPER 1

PLOS One

RESEARCH ARTICLE

The carbon footprint of surgical operations: 2023–2025 systematic review update

Anna Savio[1]*, Beatrice Marchi[1], Andrea Roletto[1], Pierangelo Guizzi[2], Giuseppe Milano[3], Lucio Enrico Zavanella[1], Simone Zanoni[4]

1 Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Brescia, Italy, **2** Department of Orthopaedic Surgery, Ospedale di Gardone Val Trompia, Brescia, Italy, **3** Department of Medical and Surgical Specialties, Radiological Sciences, and Public Health, Università degli Studi di Brescia, Brescia, Italy, **4** Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Brescia, Italy

* anna.savio@unibs.it

OPEN ACCESS

Citation: Savio A, Marchi B, Roletto A, Guizzi P, Milano G, Zavanella LE, et al. (2026) The carbon footprint of surgical operations: 2023–2025 systematic review update. PLoS One 21(5): e0349415. https://doi.org/10.1371/journal.pone.0349415

Editor: Manuel Herrador, University of Jaen: Universidad de Jaen, SPAIN

Received: January 29, 2026

Accepted: April 29, 2026

Published: May 18, 2026

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pone.0349415

Copyright: © 2026 Savio et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution,

Abstract

Surgical care significantly contributes to greenhouse gas emissions, with operating rooms consuming three to six times more energy than other departments relying heavily on single-use materials and anaesthetic gases. We conducted a systematic review of literature from 2023 to 2025 following PRISMA guidelines. The PubMed, Scopus and Healthcare LCA databases were searched, and eligibility criteria were applied. A total of 26 studies met inclusion criteria. Data were extracted on each study's scope and system boundaries, reported emission values, identified carbon hotspots, and any mitigation strategies evaluated. A structured quality assessment was conducted to evaluate the reliability of the included studies and to identify potential sources of bias. The included studies demonstrated wide variability in reported carbon footprints of surgery, ranging from under 5 kgCO_2e for minor procedures to over over 400 kgCO_2e for complex single-stage operations and approximately 1,000 kgCO_2e for whole multistage patient pathways. This systematic review underscores that surgical operations could have a significant carbon footprint, with emissions hotspots concentrated in consumable materials and energy consumption. It also reveals substantial variability and methodological heterogeneity in how surgical carbon footprints are calculated, pointing to the urgent need for standardized life-cycle based frameworks in surgical settings. Establishing common standards will enable more reliable benchmarking of surgical emissions and better comparisons across studies.

Introduction

Climate change poses an urgent threat to global health, and the healthcare sector is a significant contributor to greenhouse gas (GHG) emissions. Worldwide, healthcare is responsible for roughly 4–5% of total GHG emissions. In

and reproduction in any medium, provided the original author and source are credited.

Data availability statement: All relevant data are within the manuscript and its Supporting Information files.

Funding: The author(s) received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Abbreviations: CH_4, Methane; CO_2e, Carbon dioxide equivalent; CT, Computed tomography; GHG, Greenhouse gas; GWP, Global warming potential; HVAC, Heating, Ventilation and Air Conditioning; ISO, International Organization for Standardization; kWh, Kilowatt-hours; LCA, Life-cycle assessment; MRI, Magnetic resonance imaging; N_2O, Nitrous oxide; OR, Operating room.

high-income countries, this share can be even greater (e.g., 8% in the US and 5.4% in the UK) [1–3]. Within healthcare, hospitals, and specifically surgical services, are known to be particularly energy and resource intensive. Operating theatres have been reported to be three to six times more energy-intense than the hospital, making them major hotspots for emissions [4]. They also generate disproportionately large amounts of waste, 20–70% of a hospital's waste comes from operating rooms. As a result, surgery's environmental footprint has come under increasing scrutiny from both healthcare professionals and policymakers aiming to achieve carbon reduction targets, such as the UK National Health Service (NHS) commitment to achieve its interim target of an 80% reduction in direct emission by 2032 [5].

Despite this importance, systematic assessments of the carbon footprint of surgical operations only began to appear in the literature over the past decade. A landmark systematic review in 2020 was the first to compile studies of surgical carbon footprints [6]. Searching over 50 years of records, the study identified just 8 scientific articles, all published after 2011, that quantified the carbon footprint of any surgical procedure. Those studies reported a wide variation in per-procedure emissions, from about 6 $kgCO_2e$ up to 814 $kgCO_2e$ for a single operation. The largest values were associated with complex surgeries (e.g., some robotic or cardiac procedures). Across the board, medical devices and consumable supplies were identified as the biggest contributors to surgical emissions. The authors noted marked methodological heterogeneity and called for standardized reporting to enable reliable comparison.

An updated systematic review in 2023 sought to incorporate new studies that had emerged since 2020 [7]. This review included 7 studies in total. It found a slightly narrower range of carbon footprints, from 28.5 $kgCO_2e$ to 505.1 $kgCO_2e$ per operation, across those studies. Single-use devices and consumables again emerged as the dominant emission source, and the authors reiterated the need for international standards in surgical carbon footprinting.

Since early 2023, however, interest in the environmental sustainability of surgery has grown rapidly, and many new studies have been published across various surgical specialties. This systematic review aims to build upon and update the prior reviews with the latest evidence. We incorporate 26 new studies that quantify the carbon footprint of surgical operations, providing the most up-to-date and comprehensive synthesis of data in this emerging field. In doing so, we expand the scope to cover a wider range of procedures, including orthopaedic surgeries, obstetric and gynaecologic procedures, otolaryngology surgeries, urologic oncology, plastic surgery, cardiothoracic surgery, and more, and new geographical settings.

The objectives of this review are to:

a) Quantitatively summarize the carbon footprints reported for different surgical procedures and specialties in recent literature, including typical ranges and outliers. We compare footprints across procedure types, and, where possible, across different countries/health systems.

b) Identify common emissions hotspots in surgical pathways, such as the contribution of single-use consumables, energy use, anaesthetic gases, patient/staff travel, sterilization processes, and waste disposal, as reported by these studies.

c) Highlight proposed mitigation strategies and interventions that have been evaluated or suggested to reduce surgical carbon footprints. This includes measures like switching anaesthetic techniques, using reusable instrumentation, waste reduction and recycling initiatives, optimizing OR utilization and energy efficiency, among others.

d) Assess methodological variability among studies, including differences in life-cycle assessment (LCA) boundaries, functional units, GHG scopes, and data sources for emission factors. We discuss how these differences impact results and interpretability.

By addressing these aims, this review provides a timely and comprehensive overview for surgeons and health system leaders interested in understanding and reducing the environmental impact of surgical care. It also serves to update prior reviews by incorporating the surge of recent evidence, identifying knowledge gaps and research needs for the field of sustainable surgery. Ultimately, improving the sustainability of surgery aligns with the broader healthcare mission to "do no harm", recognizing that protecting planetary health is integral to protecting human health.

Methods

Protocol and reporting

This review was designed and reported in accordance with the PRISMA 2020 guidelines for systematic reviews and meta-analyses [8] and registered with the International Prospective Register of Systematic Reviews (PROSPERO, ID CRD420251175778). The PRISMA flow diagram illustrating the study identification, screening, eligibility, and inclusion process is shown in Fig 1. The PRISMA checklist is provided in the Supporting Information (S1 File).

Eligibility criteria

We sought to include studies that quantitatively evaluated the carbon footprint of surgical operations. Specifically, eligible publications had to report a carbon footprint calculation or life-cycle assessment (LCA) for one or more surgical procedures or surgical care pathways. We included original research articles, both prospective and retrospective analyses were eligible, as well as modelling studies, case studies, and comparative studies (e.g., comparing techniques or scenarios) as long as a carbon footprint or CO_2e emission was quantified.
We excluded:

- Non-original contributions (editorials, letters);
- Systematic reviews/meta-analyses (used only as secondary sources);
- Articles that only measured waste or energy consumption without translating them into CO_2e;
- Studies focused exclusively on a single element (e.g., anaesthetic gasses) without the overall context.

Some partial studies (e.g., only on waste) were included if they reported CO_2e estimates, in order to ensure comparative breadth. No restrictions were applied regarding surgical specialty, type of intervention, or country.

No language restrictions were applied, ensuring that studies were identified and screened regardless of the language of publication and minimizing the risk of language-related selection bias. When full texts were not available online, the corresponding authors were contacted; studies were excluded if no response was received. The publication date range was January 1, 2023, through September 1, 2025.

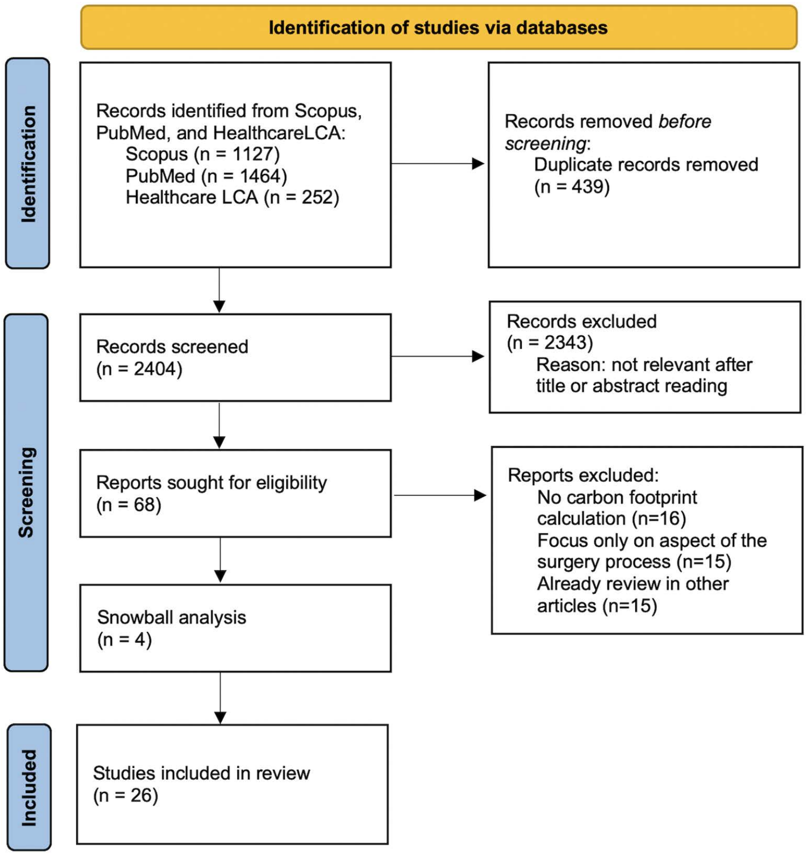


Fig 1. PRISMA flow chart of study selection process.

https://doi.org/10.1371/journal.pone.0349415.g001

Information sources and search strategy

We performed systematic searches in multiple databases: PubMed, Scopus, and a specialized database for healthcare life-cycle assessments, the Healthcare LCA database [9]. Our search strategy combined terms related to environmental impact and sustainability, healthcare settings, and surgical, clinical, and diagnostic activities. The complete search strings for all databases are reported in the Supporting Information (S2 File). The final database searches were conducted in September 2025. We also examined the reference lists of relevant articles (including the prior reviews and any new studies found) for snowball sampling of potentially missed studies. Using Google Scholar, we identified a few additional records that did not appear in the database search but met inclusion criteria. These were screened and added if eligible. As shown in Fig 1, 4 studies were included via this snowball method, supplementing the database search results. All references were imported into a reference manager, and duplicates were removed (both automatic deduplication and manual checking).

Selection process

Two reviewers independently assessed titles and abstracts (n = 3,293). With an inclusive approach, every uncertain citation has been advanced to the full text. 68 full articles were examined and 46 were excluded for:

- No carbon footprint calculation (16 studies): The article discussed environmental issues in surgery but did not actually quantify CO_2e emissions;
- Focused only on a sub-component (15 studies): The analysis was restricted to a single aspect such as anaesthetic gas usage or sterilization energy and did not consider overall surgical footprint;
- Already covered by other included studies or reviews (15 studies): this included, for instance, earlier reports that were superseded by updated analyses from the same group, or cases where the data were part of a larger study that we included. Systematic reviews were also excluded in this category.

Any disagreements in inclusion were resolved through discussion, and if needed, consultation with a third reviewer. Ultimately, we reached consensus to include 26 studies in the qualitative synthesis.

The PRISMA flow (Fig 1) summarizes this selection: out of >4,200 records identified (including 252 from the specialized LCA source), 3,293 unique records were screened, 3,228 were excluded at title/abstract stage, 68 full texts were assessed, 4 were identified with a snowball analysis and 26 met criteria and were included.

Data extraction and synthesis

A data extraction form was developed and pilot-tested on a few initial papers to ensure consistency with the approach used in prior reviews. For each included study, we extracted key characteristics and results, including:

a) Study reference (author, year) and geographical setting;

b) Clinical context and surgical procedure(s) assessed, including any comparative techniques or scenarios within the study;

c) Methodology approach: type of carbon accounting or LCA, standards or guidelines referenced (e.g., ISO 14040, GHG Protocol, etc.), system boundaries, study design (prospective/retrospective), and the sample size;

d) Functional unit and analytical scope, including time boundaries and emission sources included or excluded;

e) Greenhouse gases accounted for and sources of emission factors (e.g., Ecoinvent, national datasets);

f) Main carbon footprint outcomes ($kgCO_2e$ per functional unit), including all reported comparators and summary statistics;

g) Key findings related to mitigation opportunities or emissions drivers;

h) Notes on study design, assumptions, and limitations relevant to interpretation.

The compiled extraction table was used as the basis for the results synthesis and for constructing Table 1 and Table 2 below. The results of the quality assessment are reported in S1 Table, while S2 Table summarizes the type of data collected, study scope, and emission factors considered. Stated boundary exclusions, assumptions made during data collection, and other study limitations are detailed in S3 Table.

Results

Overview of included studies

We included 26 studies published from 2023 to September 2025, reflecting the surge in research on surgical environmental impact in this period.

Table 1 presents a summary of each included study, organized by year and first author, with information on country, surgical context, methodology, and key findings.

Table 1. Study Characteristics and Scope of Product Inventory.

Study	Study setting; Country	Focus of study; surgical specialty	Carbon Footprinting Approach; Guideline	Sample size	Sampling duration or year	Functional Unit: start point-end point	Included GHGs; guideline/ database
[27]	2 hospitals; Wrexham Maelor Hospital & Ysbyty Gwynedd; UK	Orthopaedics; carpal tunnel release (1) standard surgery vs (2) lean and green surgery	Process-based CF calculation; Centre of Sustainable Healthcare Guidelines	110 carpal tunnel release surgery (7 standard surgery and 103 lean and green surgery)	18 months (2022–2023)	1 carpal tunnel release;	CO_2; Centre of Sustainable Healthcare Database
[17]	Stamford Hospital; USA	Obstetrics and gynaecology; Hysterectomy procedure (1) robotic assisted vs (2) laparoscopic vs (3) vaginal vs (4) abdominal	waste-focused carbon footprint analysis; nil	100 patients (56 robotic assissted, 34 laparoscopic, 7 abdominal, 3 vaginal)	9 months (Nov 2021-Jul 2022)	1 hysterectomy; post-operative collection of non-reusable waste	CO_2; EPA emission factors
[14]	Orthopaedic surgery department, Institut Mutualiste Montsouris & Hôpital Pitié-Salpêtrière; Francee	Orthopaedics; arthroscopic rotator cuff repair under (1) locoregional anaesthesia (LRA) and (2) general anaesthesia (GA)	Process-based; GHG Proctocol	52 patients (26 under LRA and 26 under GA)	1 year Nov 2018-Apr 2019 & Nov 2020-Apr 2021	1 arthroscopic rotator cuff repair for a single tendon rupture; patient and staff travel to theatre, patient and staff travel home	CO_2; ADEME & literature emission factors
[21]	Large multi-center urban health system (Mass General Brigham); USA	Orthopaedics; open carpal tunnel release (oCTR) vs endoscopic carpal tunnel release (eCTR)	Process-based LCA; nil	28 patients (14 oCTR, 14 eCTR)	2020	1 carpal tunnel release procedure from OR entry to exit	CO_2; EPA emission factors; UK Govt landfill factors
[25]	Single reconstructive centre (Royal Free NHS Foundation Trust & UCL); London; UK	Plastic/Reconstructive surgery; Deep inferior epigastric perforator (DIEP) flap for autologous breast reconstruction	Process-based eco-audit (bottom-up); nil	42 unilateral DIEP flaps (retrospective)	17 months (Apr 2022 – Sep 2023)	1 DIEP flap patient; first plastic surgery encounter – end of immediate postoperative recovery	CO_2e; GOV.UK 2023 Conversion Factors, published LCA literature
[75]	Welsh Centre for Burns and Plastic Surgery, Morriston Hospital; UK	Dermatology/ Plastic Surgery; Non-melanoma skin cancer excision surgery (NMSC): (1) direct closure (DC) vs (2) split-thickness skin graft (STSG) vs (3) full-thickness skin graft (FTSG)	Hybrid life-cycle assessment (process-based + EEIO); GHG Accounting Sector Guidance, PAS2050	32 NMSC cases (13 DC, 12 FTSG, 7 STSG)	3 weeks (Mar 2023)	1 NMSC; Patient arrival for day-case surgery – completion of waste collection post-surgery	CO_2; BEIS UK GHG Conversion factors, Greener NHS emission factors, ICE Database (v.3)
[12]	Large university teaching hospital; UK	Otolaryngology; adult tonsillectomy;	Process-based CF; GHG Protocol	48 patients	1 year (2021)	1 adult tonsillectomy; patient and staff enter theatre-leave	CO_2; UK Govt conversion factors; published healthcare CF studies

(Continued)

Table 1. (Continued)

Study	Study setting; Country	Focus of study; surgical specialty	Carbon Footprinting Approach; Guideline	Sample size	Sampling duration or year	Functional Unit: start point-end point	Included GHGs; guideline/ database
[15]	Orthopaedic University Hospital, Würzburg; Germany	Orthopaedics; 8 different procedures: total hip arthroplasty (THA), total knee arthroplasty (TKA), knee arthroscopy (KA), anterior cruciate ligament reconstruction (ACLR), shoulder arthroscopy (SA), elective foot surgery (FO), revision hip arthroplasty (RHA), revision knee arthroplasty (RKA)	Process-based bottom-up LCA; Greenhouse Gas Protocol (Scopes 1–3)	5 procedures per operation type	Apr-Aug 2023	1 operation: patient enters surgical area – leaves (including acclimatized adjacent rooms)	CO_2, CH_4, N_2O converted to CO_2e (GWP100); local electricity/gas factors; German EF (BAFA); Anaesthetic Impact Calculator; Ecoinvent/ lit for supply chain
[13]	Yale-New Haven Hospital, tertiary centre; USA	Otolaryngology; standard direct laryngoscopy surgery	Process-based LCA; ISO 14040	Not applicable (modelling study)	2022	1 direct laryngoscopy surgery:	CO_2,CH4, N2O; Open LCA, ReCiPe 2016, Ecoinvent v3.7.1
[76]	Ambulatory surgery center, University of Utah Health; USA	Orthopaedics; Carpal tunnel release surgery performed in (1) procedure room (PR) vs (2) operating room (OR)	Process-based LCA; US EPA, Practice Greenhealth	14 patients (14 bilateral open carpal tunnel release with one procedure performed in each setting)	10 years (retrospective) 2013–2023	1 carpal tunnel release surgery; patient enter theatre-leave	CO_2; US EPA, Practice Greenhealth
[77]	Clinique du Sport, Paris; France	Orthopaedics; Anterior cruciate ligament reconstruction (ACLR) with different techniques: (1) ST4 vs (2) BPTB (3) ITBG vs (4) HG vs (5) QTG	Process-based LCA; ISO 14040	10 ACLR per day per surgical crew (Modelling study)	ND	1 anterior cruciate ligament reconstruction (ACLR); from medical prescription and decision to operate to patient discharge	CO_2; ReCiPe 2016, IPCC GWP100
[78]	Wrexham Maelor Hospital; UK	Orthopaedics; Total hip arthroplasty (THA) (1) cemented vs (2) hybrid procedure	Process-based LCA; ISO 14040, Centre for sustainable healthcare	20 patients (10 uncemented THA and 10 hybrid THA)	3 months (2023)	1 total hip arthroplasty surgery; patient enter the anaesthetic room-patient leave the recovery room	CO_2; Ecoinvent v3.9.1, Centre for sustainable Healthcare carbon factors
[79]	Yale New Haven Hospital; USA	Otolaryngology; Endoscopic sinus surgery (ESS) considering (1) landfill scenario vs (2) incineration scenario	Process-based LCA cradle-to-grave; SimaPro 9.5	1 ESS procedure (modelling study)	Single ESS analysed, projections for 2024 and 2030	1 endoscopic sinus surgery: raw material extraction, use, disposal of every material used during surgery	CO_2; IPCC 2021, EcoInvent, USCLI
[16]	Hospital for Special Surgery, New York; USA	Orthopaedics; adult spinal deformity (ASD) surgery	Process-based LCA; ISO 14040, Umberto ver. 11.9.2	30 patients	5 years (retrospective data) 2017–2021	1 adult spinal deformity surgery; patient enter theatre-leave	CO_2; Ecoinvent 3.9.1

(Continued)

Table 1. (Continued)

Study	Study setting; Country	Focus of study; surgical specialty	Carbon Footprinting Approach; Guideline	Sample size	Sampling duration or year	Functional Unit: start point-end point	Included GHGs; guideline/ database
[80]	Ambulatory surgery centre, academic hospital; USA	Orthopaedics; minor foot and ankle surgery with (1) traditional protocol vs (2) PRiSM protocol	Process-based CF calculation; nil	40 patients (20 traditional protocol and 20 PRiSM protocol)	5 months (2023)	One foot/ankle procedure (foreign body removal, hammertoe correction, toe amputation, hardware removal, mass excision, gastrocnemius recession); waste audit at the end of the procedure	CO_2; US EPA & literature emission factors
[32]	4 UK hospitals (2 district general, 2 tertiary); UK	Orthopaedics; arthroscopic ACL reconstruction (ACLR) & rotator cuff repair (RCR)	Waste audit with CO_2e calculation; nil	10 patients (5 RCR and 5 ACLR for each hospital)	ND	1 arthroscopic surgey; waste audit at the end of the procedure	CO_2; Waste management contractor emission factors
[19]	Tertiary maternity units & home births; UK and Netherlands	Obstetrics and gynaecology; (1) planned caesarean birth vs (2) uncomplicated vaginal birth in hospital vs (3) uncomplicated vaginal birth at home (comparison between UK and Netherlands)	Process-based LCA; Open LCA	ND	2022-2023	1 birth of a live baby; woman enter-leave the hospital and midwives enter-leave home	CO_2e; Idemat 2023, Ecoinvent, DEFRA, Healthcare LCA DB
[30]	Single plastic surgery department, Royal Free NHS Foundation Trust; London; UK	Plastic/Reconstructive surgery; Autologous microtia reconstruction (quaternary, multistage)	Hybrid eco-audit (bottom-up for operative + top-down for inpatient stay);NHS England Sustainable Care Pathways	23 patients undergoing autologous microtia reconstruction (5 with both stages completed, 12 only stage 1, 6 only stage 2) (retrospective)	2 years (Apr 2022 – Apr 2024)	1 patient pathway for multistage autologous microtia reconstruction; first plastic surgery encounter – final dressing clinic following second stage (includes 2 inpatient stays)	CO_2e; GOV.UK 2023 Conversion Factors, NHS England inpatient bed-day framework, published LCA literature
[26]	Single reconstructive centre (Royal Free NHS Foundation Trust); London; UK	Plastic/Reconstructive surgery; Immediate breast implant reconstruction	Process-based eco-audit with life-cycle analysis (bottom-up); nil	34 immediate breast implant reconstructions (retrospective)	13 months (Sep 2022 – Oct 2023)	1 breast implant reconstruction patient; first appointment regarding implant surgery – end of immediate postoperative recovery	CO_2e; GOV.UK 2023 Conversion Factors, published LCA literature
[20]	Two French university hospitals – paediatric ENT departments; France	Otolaryngology; Subtotal tonsillectomy: (1) cold instruments-bipolar electrocoagulation vs (2) single-use or reusable radiofrequency electrodes vs (3) coblation	Retrospective CF calculation based on device weight, energy consumption, and production location; emission factors applied	Not stated (all subtotal tonsillectomies in 2022 using 4 techniques)	2022	One subtotal tonsillectomy procedure	CO_2; emission factors by weight, energy, origin of manufacture
[36]	Tertiary hospital (Amsterdam UMC, location AMC); Netherlands	Obstetrics and gynecology; Total laparoscopic hysterectomy (TLH) vs uterine artery embolization (UAE);	Process-based LCA; ISO 14040/14044; ReCiPe 2016, Hierarchist midpoint and endpoint	40 waste inventories (10 per procedure, 8 per hospital stay, 2 per outpatient visit)	Nov 2023-Aug 2024	1 patient treated for uterine fibroids via TLH or UAE; outpatient to follow-up	CO_2; Ecoinvent v3.10; adjusted NL-specific datasets

(Continued)

Table 1. (Continued)

Study	Study setting; Country	Focus of study; surgical specialty	Carbon Footprinting Approach; Guideline	Sample size	Sampling duration or year	Functional Unit: start point-end point	Included GHGs; guideline/ database
[33]	Regional hospital (Lismore Base Hospital); Australia	Orthopaedics; total knee arthroplasty (TKA), total hip arthroplasty (THA), ankle fracture and hand injury surgery	Waste audit + CO_2 emissions estimation via emission factors (0.879 tCO_2e/tonne waste); Australian National Greenhouse Accounts Factors	60 procedures (15 per subtype)	Jul-Sep 2024	1 surgical procedure from waste generation to disposal	CO_2; Australian National Greenhouse Accounts Factors (2023)
[10]	Royal Devon University Healthcare NHS Trust; UK	Urology; Perioperative transurethral resection of bladder tumour (TURBT) pathway	Process-based cradle-to-grave LCA; ISO 14040	30 patients	8 months (Dec 2022-Jul 2023)	perioperative TURBT pathway for one patient; first outpatient visit-hospital discharge	CO_2; Ecoinvent v3.10, Defra/BEIS
[18]	University Hospital of Lille (CHU Lille); France	Oral and maxillofacial surgery; Orthognathic surgery: (1) Bilateral sagittal split osteotomy (BSSO) vs (2) Le Fort I osteotomy vs (3) Bimaxillary osteotomy (Bimax)	Process-based LCA; Greenhouse Gas Protocol Scopes 1–3	122 patients	Jan-Jul 2024	Patient pathway from preoperative consultation to 3 postoperative consultations; cradle-to-grave	CO_2; Carebone tool (AP-HP, Paris)
[81]	Outpatient surgical center (Bethel Park Surgical Center, UPMC); USA	Orthopaedics; Anterior cruciate ligament reconstruction (ACLR)	Process-based LCA + Material Flow Analysis (MFA) + Material Circularity Indicator (MCI); ISO 14040/14044	1 ACLR case (data from 3 observation sessions)	2022-2023	1 ACL reconstruction, cradle-to-grave (material production to disposal/recycling)	CO_2; TRACI 2.1, Cumulative Energy Demand; SimaPro v9.4; Ecoinvent database
[11]	Radboud University Medical Centre; Netherlands	Cardiology; Coronary artery bypass grafting (CABG)	Process-based LCA cradle-to-grve; ISO 14040/14044	12 patients	May-June 2022	CABG patient trajectory from OR admission to ICU discharge	CO_2; Ecoinvent v3.9; ReCiPe2016 method,national datasets for energy/transport

ADEME, Agence de la Transition Écologique (France); AP-HP, Assistance Publique-Hôpitaux de Paris; BAFA, Bundesamt für Wirtschaft und Ausfuhrkontrolle (Germany); BEIS, Department for Business, Energy and Industrial Strategy (UK); CF, carbon footprint; CH_4, methane; CO_2, carbon dioxide; DEFRA, Department for Environment, Food & Rural Affairs (UK); EEIO, environmentally extended input–output; EF, emission factor(s); EPA, Environmental Protection Agency; GHG, greenhouse gas; GWP100, global warming potential over 100 years; ICE, Inventory of Carbon and Energy database; IPCC, Intergovernmental Panel on Climate Change; ISO, International Standards Organization; LCA, life cycle assessment; NHS, National Health Service (UK); PAS 2050, publicly available specification for assessing life cycle greenhouse gas emissions; TRACI, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts; UMC, University Medical Center; UPMC, University of Pittsburgh Medical Center.

https://doi.org/10.1371/journal.pone.0349415.t001

Geographically, the studies were conducted in the United Kingdom (10 studies), United States (8 studies), France (4 studies), Netherlands (2 studies), Germany (1 study), and Australia (1 study), with some collaboration across countries in a few cases. This spread reflects a concentration of interest in countries with active healthcare sustainability initiatives (e.g., NHS England's net-zero plan, academic centers in the US like Yale and University of California focusing on medical LCAs, etc.) and in Europe (often motivated by hospital or national carbon reduction goals).

There is an uneven distribution of published studies across surgical specialties, with orthopaedic surgery being the most frequently investigated (12 studies), whereas most other specialties are represented by only one or a few studies.

The carbon footprint range results reported in each study are summarized in Fig 2. Overall, the reported CO_2e emissions associated with surgical procedures span a wide range across the literature, from values close to 1 $kgCO_2e$ (for

Table 2. Comparison of Inventory Boundaries.

Process		[27]	[17]	[14]	[21]	[25]	[75]	[12]	[15]	[13]	[76]	[77]	[78]	[79]	[16]	[80]	[32]	[19]	[30]	[26]	[20]	[36]	[33]	[10]	[18]	[81]	[11]
Travel	Staff			x		x		x											x	x		x		x			x
	Patient			x		x		x											x	x		x		x	x		x
Energy & Natural Resources	Electronic equipment			x	x	x	x	x	x			x	x	x	x			x	x	x	x	x		x	x	x	x
	HVAC			x	x	x	x	x	x		x	x	x		x			x	x	x	x	x		x	x	x	x
	Lighting			x	x	x	x	x	x		x	x	x		x			x	x	x	x	x		x	x	x	x
	Water					x						x	x	x					x	x		x		x			x
Consum-ables	Manufacturing and Procurement	x		x		x	x	x	x	x	x	x	x	x		x		x	x	x	x	x		x	x	x	x
	Transport					x				x		x		x	x				x	x		x		x		x	x
Medical Devices	Manufacturing and Procurement	x		x		x			x	x				x				x	x	x	x	x		x	x	x	x
	Transport					x				x		x		x	x				x	x		x		x		x	x
Reusables	Manufacturing and Procurement	x		x		x	x	x	x	x		x	x	x				x	x	x	x	x		x	x	x	x
	Transport					x				x		x		x	x				x	x		x		x		x	x
Repro-cessing	Sterilization	x		x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x
	Laundry	x		x		x	x		x	?		x	x	?		x		x	x	x		x		x		x	x
Pharma-ceuticals	Manufacturing and Procurement			x			x	x						x				x			x	x			x		x
	Transport													x								x					
	Anaesthesia			x		x		x	x			x			x			x	x	x	x	x		x	x		x
Waste manage-nent	Transport			x			x	x				x		x				x				x	x	x		x	x
	Disposal		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x

An ‘x’ indicates that the process was explicitly included within the study boundary, while blank cells denote omission; question marks (‘?’) indicate uncertainty or unclear reporting

https://doi.org/10.1371/journal.pone.0349415.t002

certain low-resource tonsillectomy techniques and other minimal scenarios) up to 414 $kgCO_2e$ per case for a CABG procedure in a Dutch hospital. When entire multistage care pathways are considered, the upper bound rises substantially: the eco-audit of autologous microtia reconstruction, a quaternary plastic-surgery proceure spanning two operative stages, multiple pre-operative and follow-up visits, and two inpatient admissions, reported approximately 1,005 kgCO2e per patient. Most routine elective surgeries (with general anaesthesia in a hospital setting) tended to fall in the range between a few kilograms to a few hundred kilograms of $kgCO_2e$.

The typical carbon footprint of a common elective surgery (e.g., knee arthroplasty, laparoscopic hysterectomy, etc.) appears to be on the order of 50–150 $kgCO_2e$, whereas more minor procedures or those done under streamlined protocols can be less than 30 $kgCO_2e$, and very complex or resource-intense procedures can be more than 400 $kgCO_2e$.

The system boundary for each included study was mapped to identify which processes were accounted for in the carbon footprint assessment. Table 2 summarizes the inclusion or omission of key process categories, such as travel, energy use, consumables, medical devices, reprocessing, pharmaceuticals, and waste management, across studies. When specific processes were excluded, the resulting footprint likely underestimates the total environmental impact of the surgical pathway. This comparison highlights substantial heterogeneity among studies in terms of which stages were considered, suggesting that results are not directly comparable when inventory boundaries differ.

Emission hotspots in surgical operations

Despite the diversity of procedures and methods, the studies overwhelmingly point to a few common GHG emission hotspots in the surgical process.

Medical devices, surgical supplies, and implants. The production and use of single-use disposable items and other consumables emerge as the top contributor to surgical carbon footprints in 17 of 26 studies. For example, consumables accounted for 22% of the TURBT pathway emissions in the UK [10] and 39% of total emissions in CABG procedures [11]. Similarly, in the tonsillectomy LCA, consumables contributed 17%, the largest single category after utilities [12]. This group encompasses surgical gloves, gowns, drapes, single-use instruments or device components, procedure packs, synthetic implants (mesh, screws), and certain pharmaceuticals, with emissions arising from the entire upstream supply chain (raw material extraction, manufacturing, sterilization, packaging) and the downstream disposal (often incineration). Comparative analyses further highlight their impact: in direct laryngoscopy, reusable instrument kits contributed less than 1 $kgCO_2e$, while sterile single-use supplies added approximately 7 kg CO_2e per procedure, corresponding to nearly 90% of the total footprint [13]; in shoulder arthroscopy, single-use anchors and suture devices were identified as principal drivers of emissions, and their partial replacement achieved roughly a 12% reduction in total carbon output [14]. A German assessment of eight orthopaedic procedures similarly identified consumables as the largest source, accounting for 34.6% of emissions [15]. In spine fusion, metallic implants and bone graft materials were among the most carbon-intensive components due to manufacturing and material processing [16]. Even when comparing abdominal hysterectomy with uterine artery embolization, the higher footprint of the surgical route was partially attributable to more resource-intensive surgical supplies (staplers, sutures, and mesh) compared with interventional materials (coils, catheters) [17].

Energy use (HVAC and lighting). Hospitals run energy-intensive HVAC systems to maintain strict air exchanges and climate control in operating rooms. Many studies pointed to electricity and natural gas use for OR ventilation, heating, and lighting as a major hotspot. One analysis of tonsillectomy procedures found utilities (mainly HVAC) to be the largest source of GHGs (over 50%) [12]. In another CABG LCA, energy use contributed 48 kgCO2e (12%), and they note most of that was from OR HVAC systems [11]. In maxillofacial surgery, energy use was a smaller contributor (0,5%−0,8%) compared with patient travel, which dominated the total footprint [18]. The contribution of energy can vary substantially depending on the type of energy carrier used (e.g., electricity, natural gas, district heating) and, in the case of electricity, on the carbon emission factor of the national grid. For example, heating with natural gas has broadly similar carbon intensity across countries, whereas electricity-related emissions differ widely: a kWh in France, largely produced from

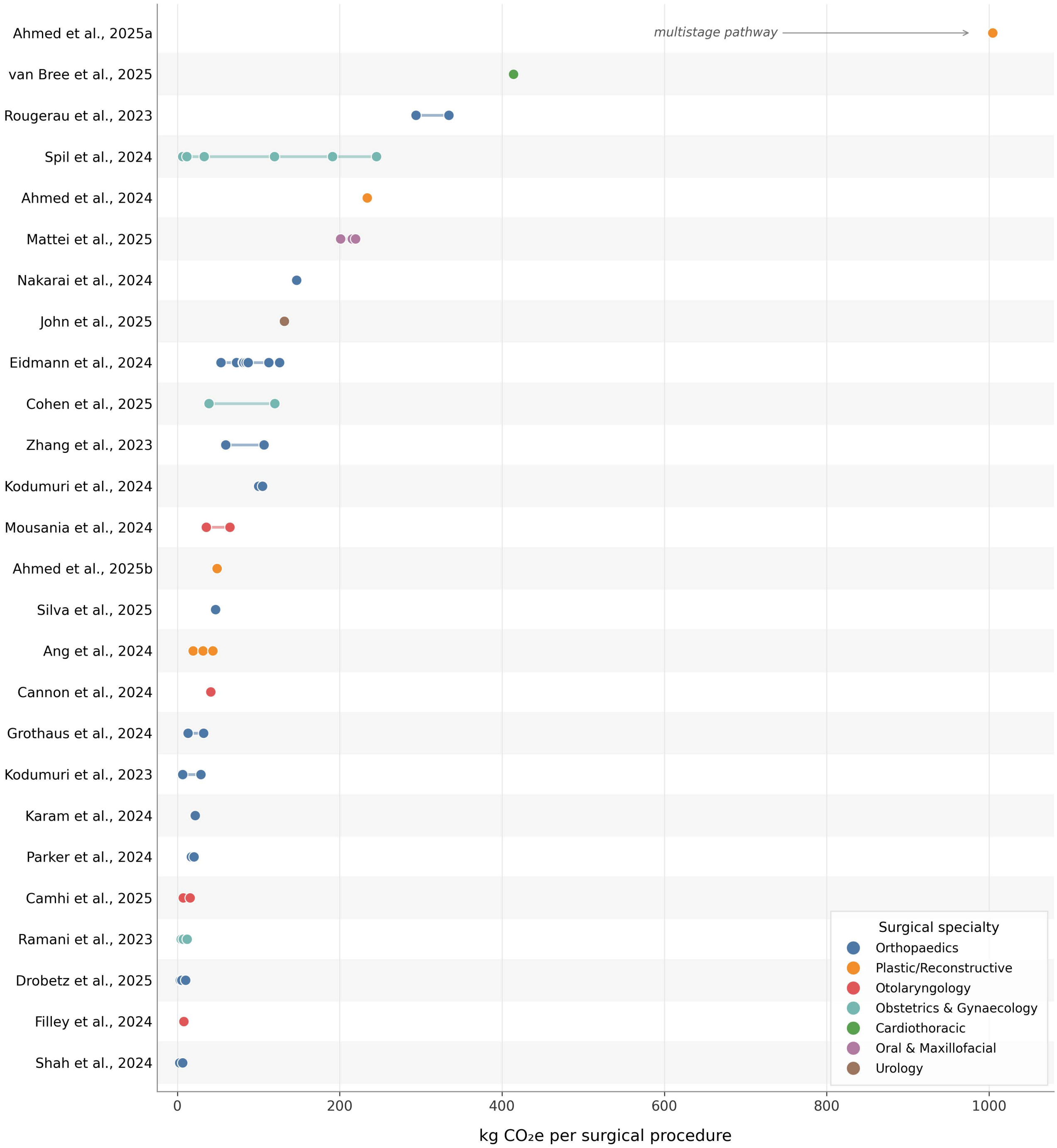


Fig.2. Reported carbon footprints of surgical procedures across the 26 studies included in the systematic review (2023-2025), expressed in kgCO_2e per surgical procedure. Each row corresponds to one study; markers indicate point estimates and connecting lines indicate the range when

multiple values were reported, reflecting comparative arms (e.g., anaesthetic technique, surgical approach) or different procedure variants within the same study. Markers are colour-coded by surgical specialty. Studies are ordered top-to-bottom by their maximum reported value.

https://doi.org/10.1371/journal.pone.0349415.g002

nuclear energy, has a much lower emission factor than in countries with coal or gas-intensive grids. This might explain why, for example, the French tonsil study doesn't mention energy as a factor (likely low impact per case, and they focused on devices) whereas the UK and NL studies do [19–21]. Nonetheless, keeping an OR running (lights, anaesthesia machine, monitors) for a procedure has a non-trivial footprint, and when OR time or efficiency is studied, it connects to this. For instance, endoscopic carpal tunnel release surgery (CTR) had a higher footprint than the open approach largely because of its longer OR time (hence more facility energy use) than open CTR [21]. Facilities-related emissions in that study were a big portion of the 83 $kgCO_2e$ (meaning HVAC, lights, etc.).

Anaesthetic gases and pharmaceuticals. The use of volatile anaesthetic agents (such as desflurane, sevoflurane) and nitrous oxide (N_2O) can be a major GHG contributor because these gases are themselves potent greenhouse gases when released unscavenged [22–24]. However, their impact in the carbon footprint results varies widely depending on if and how studies included them. In several recent studies, anaesthetic gases were purposefully minimized or omitted: one study demonstrated that eliminating volatile gases via regional anaesthesia reduced the footprint by 40.9 $kgCO_2e$ (which we infer largely came from eliminating desflurane) [14]. Another assessment of labour analgesia illustrated the extreme case with nitrous oxide: just that gas usage can dwarf all other sources, adding 230 $kgCO_2e$ per case [19]. In contexts like standard surgery under general anaesthesia, the footprint of anaesthetic gases depends on which agents are used and for how long. Desflurane has a GWP c.a. 2,500 times CO_2 and N_2O c.a. 300, so even a few litres can equal tens of kg of CO_2. Anaesthesia/drugs and associated adjuncts were 27% of TURBT pathway emissions, although they clarify much of that was from consumables in anaesthesia (e.g., disposable breathing circuits, meds) rather than the gases themselves [10]. Indeed, a trend is that many centres have shifted away from high-emission gases: the CABG study mentioned total intravenous anaesthesia (TIVA) was used, so anaesthetic gases didn't feature heavily in that footprint [11]. In contrast, where older practices involved desflurane or N_2O, these agents typically dominated the total emissions profile. Overall, anaesthetic practice remains a controllable hotspot: when high-GWP gases are employed, they can be the largest single contributor to surgical emissions, whereas adoption of low-GWP or gas-free approaches markedly reduces this impact, though drug production and supply chains still contribute residual emissions. A particularly striking example comes from plastic and reconstructive surgery: in DIEP flap breast reconstruction, the induction, maintenance and running of anaesthesia together contributed approximately 67.6% of the total procedural footprint (158 of 234 $kgCO_2e$), reflecting the long operative time (typically 8–10 hours) characteristic of microvascular procedures and the use of nitrous oxide plus oxygen at 5 L/min for maintenance [25]. In contrast, the breast implant reconstruction pathway at the same centre [26] adopted total intravenous anaesthesia (propofol + remifentanil) with no volatile maintenance gases: under this protocol, anaesthesia-related emissions fell to 16.6% of total procedural footprint, illustrating in practice how the choice of anaesthetic technique alone can reduce this hotspot by several-fold within the same clinical setting.

Patient and staff travel. Travel emissions can be significant, especially in studies with broader pathways. In maxillofacial surgeries, patient transportation accounted for 66–70% of total emissions, because patients travelled for multiple consults and follow-ups for their surgery [18]. In an assessment of coronary artery bypass grafting, staff commuting contributed around 9% (36 kg CO_2e) of total emissions, ranking as the third-largest source after consumables and energy use [11]. Patient travel for pre-op was 18.6% of TURBT emissions [10]. In comparative assessments of childbirth in different European countries, travel mode and distance contributed to inter-country variability, although their influence was overshadowed by the dominant impact of nitrous oxide use [19]. Travel didn't feature in some studies that only considered OR time [21,27], but where it is counted, travel often emerges as a major emissions source, especially when the procedure itself has relatively low inherent emissions or when multiple visits are required. This underscores the importance of defining system boundaries clearly: decarbonizing hospital operations alone may not substantially reduce overall emissions if extensive patient or staff travel persists. The integration of telemedicine, consolidation of appointments, and scheduling strategies to minimize round trips have been proposed as practical interventions [28,29]. It is context-dependent: a single outpatient visit might be small, but numerous visits for complex care can add up to more than the surgery itself [18]. Similar findings were reported for autologous breast reconstruction: in the DIEP flap pathway, combined patient and staff travel contributed more than 15% of total emissions [25], and in the autologous microtia reconstruction pathway patient travel alone represented the dominant source when excluding inpatient stay (83.4% of bottom-up calculated emissions), reflecting the geographical centralization of quaternary plastic surgery services [30].

Sterilization and reprocessing. The energy and water needed to sterilize reusable instruments or linens contributes some emissions. In tonsil surgery, instrument decontamination was 5.4% (2 kgCO_2e of the 41 kgCO_2e) [12]. One study specifically tested an alternative to steam sterilization (high-level disinfection) and found it could cut 11% of the procedure's GHG by saving energy [13]. Although sterilization is not typically the dominant contributor, it remains a consistent component of surgical footprints. Transitions from reusable to single-use systems essentially shift emissions from sterilization to manufacturing processes, often increasing overall impacts, though results depend on usage rates and local energy sources. Generally, life cycle analyses favour reusable instruments when reprocessed a sufficient number of times, since the manufacturing of a new disposable item for each procedure tends to be far more carbon-intensive than repeated steam sterilization cycles

It should be noted that sterilization and laundry emissions are frequently approximated in surgical LCAs rather than directly measured. Many studies rely on standardized emission factors from reference assessments [31], which provided baseline energy and water consumption estimates per reprocessing cycle for orthopaedic instruments. This practice, while practical for comparability, introduces some uncertainty that should be considered when interpreting absolute values.

Waste disposal. Paradoxically, disposal of waste (incineration or landfill) was addressed in each article reviewed, but its impact is usually a minor contributor to GHG. In several analyses, waste treatment accounted only 3–5% [11,12]. Evidence from operating room audits confirms that focusing exclusively on waste treatment captures less than 10% of the total footprint [32,33]. Annual waste-related emissions for surgical departments have been measured in the range of a few tonnes of CO_2e, whereas upstream emissions from procurement, manufacturing, and energy use reach tens to hundreds of kilograms per individual procedure. Nevertheless, waste management remains environmentally relevant beyond its carbon impact due to plastic pollution, resource depletion, and the visibility of waste streams within healthcare facilities. Moreover, regulated medical waste incineration carries a substantially higher CO_2 emission factor per kilogram than general waste. Multiple analyses emphasized that improved waste segregation could prevent up to 90% of non-hazardous materials from entering high-energy treatment streams unnecessarily. The hotspot is not the incineration emissions per se, but the choice of disposable vs reusable which affects how much waste is generated in the first place.

The major carbon hotspots identified across studies are: (1) the supply chain of single-use devices and consumables, (2) energy use for OR HVAC/equipment, (3) travel (in broader system-boundary analyses), (4) anaesthetic gases (where used), and (5) to a lesser extent, sterilization processes and waste management. These broadly correspond to what the 2022 Green Theatre Checklist initiatives have targeted and confirmed in 2025: focusing on anaesthetic practices, energy, procurement, and waste segregation. A qualitative systematic review also found anaesthetic gases, sterilization, and habitual practices (like leaving equipment running) as key emission sources, and linked many sustainability measures to structural changes like policy on reusables and recycling [34].

Mitigation strategies and sustainability initiatives

A central goal of these studies, and of this review, is to identify how we can mitigate the carbon emissions of surgical care. The included studies not only quantified footprints but often discussed or even tested interventions to reduce them. The summary of mitigation strategies shown in Table 3 highlights how research into surgical sustainability is gradually evolving

Table 3. Mitigation Strategies Proposed Across Studies.

Category	Mitigation strategy	Description and Evidence	Estimated/ Reported Impact
Anaesthetic practice optimization	Avoid high-GWP gases (N_2O, desflurane) [14]	Elimination of high-GWP agents markedly reduces emissions; N_2O use dominates birth-related procedures.	N_2O adds 230 kg CO_2e per delivery; avoidance reduces > 90% of anaesthesia-related emissions.
	Prefer regional or local anaesthesia [14]	Regional blocks eliminate volatiles and infrastructure demand; maintains outcomes.	12% lower footprint in arthroscopic rotator cuff repair vs general anaesthesia.
	Optimize fresh-gas flows (low-flow) [12]	Low-flow techniques cut volatile agent use by > 70%; recommended in guidelines.	Qualitative reduction in agent consumption.
Rationalization of surgical supplies	"Lean" instrument trays and custom packs [27]	Removing unused items and minimizing kit contents drastically cuts waste and emissions.	−65% waste; −80% CO_2e per CTR case.
	Prefer reusable hardware and linens [12,32,33,81]	Replacing disposables with reusable metal tools, drapes, and gowns reduces supply-chain emissions.	30-50 kgCO_2e saved per case (depending on procedure).
	Optimize material and implant choice [77,81]	Selection of biocompatible, low-energy-manufacture materials for implants and grafts.	10-15% reduction in procedure footprint.
	Limit oversupply/ "open but not used" [10,27]	Customize packs; open only needed items.	5-15% reduction in supply-chain emissions.
Reusables and reprocessing	Reuse of anaesthesia circuits and devices [10]	Substituting disposable with reusable circuits reduces plastic waste.	Qualitative reduction documented.
	Third-party reprocessing of single-use devices [75,79]	Certified reprocessing of high-value devices (e.g., harmonic scalpels).	Up to 50% reduction vs new device.
	Linen reuse optimization [13,32,81]	Smaller drapes/towels; cloth instead of plastic when safe.	28% water saving; less waste volume.
Energy and facilities	Optimize OR HVAC and equipment use [10,15,81]	HVAC is a major hotspot; reduce air exchange when idle and power-down equipment.	10-20% energy savings; proportional CO_2 reduction.
	Transition to renewable energy sources [11,81]	Modelling shows that green electricity significantly lowers hospital footprints.	−13% to −17% overall in modelled scenarios.
Travel and logistics	Reduce staff and patient travel; telehealth [10,18]	Scheduling optimization and virtual consults cut transport emissions.	Patient travel 18–70% of pathway in broad LCAs; savings proportional to visits avoided.
Sterilization and decontamination	Optimize reprocessing cycles and methods [12,15]	High-level disinfection instead of steam can reduce energy demand; review sterilization load per reusable use.	ENT tonsillectomy: 5% of total CO_2e; alternative method cut 11%.
Waste management	Segregation and recycling programs [32,33]	Proper sorting prevents clean plastic from incineration; improves recycling rates.	44% of OR waste potentially recyclable; high CO_2 saving per kg diverted.
	Source reduction > disposal focus [10,12]	Majority of emissions stem from production, not incineration.	> 90% of footprint upstream (materials + energy).
Surgical process optimization	Improve OR list utilization and day-case management [10,20]	Efficient case scheduling reduces per-case overhead; outpatient pathways lower ward energy load.	10-20% per case CO_2e reduction with same day discharge vs inpatient.
Education and cultural change	Staff engagement and training [32,33,81]	Education on waste segregation, lean practice and sustainable choices is key for implementation.	Non quantified but recognized as essential enabler for behavioural change.

https://doi.org/10.1371/journal.pone.0349415.t003

from a purely descriptive approach (quantification of carbon footprint) towards an interventionist approach, geared towards identifying concrete actions. Most of the proposed strategies are behavioural and organisational rather than technological: reducing anaesthetic gases with high global warming potential, rationalising surgical sets and increasing the use of reusable materials are measures that can be implemented within the operating theatre without requiring complex structural or organisational changes.

Systemic measures, such as the energy transition to renewable sources or the reorganisation of the waste cycle, are mostly modelled or discussed in theoretical terms, indicating the need for greater institutional commitment. The growing integration of environmental sustainability into clinical decision-making reflects a cultural shift towards considering environmental impact as an intrinsic dimension of quality of care. The evidence reported in the studies supports a hierarchy of actions for the decarbonisation of surgery in which behavioural and organisational optimisation precedes infrastructural transformation, offering a bottom-up approach.

Quality assessment and risk of bias

The quality scores for each individual study were calculated following the approach adopted in previous studies [6,7], and the results are reported in S1 Table. Four main domains were assessed: completeness, consistency, transparency, and accuracy each comprising specific sub-criteria. These quality domains align with core principles of greenhouse gas accounting which are emphasized in established carbon footprinting standards (e.g., ISO 14040/14044 and the GHG Protocol). For each item, studies were scored on a three-point ordinal scale (2, 1 or 0) according to predefined criteria. Completeness considered the extent to which system boundaries and GHG scopes were fully captured. Consistency evaluated adherence to recognized carbon footprinting guidelines and uniformity of methodological application in comparative analyses. Transparency assessed the clarity of stated hypotheses and objectives, the reporting of included GHGs, assumptions, exclusions, data completeness, and the level of numerical detail in reported results. Accuracy examined the specificity of data sources, and the consideration of both parameter and scenario uncertainty, including whether confidence intervals (CIs) were reported. Each study's total score (maximum = 24, or 22 when items were not applicable) was converted to a percentage to facilitate comparison of relative quality across studies. Higher percentages indicate greater methodological rigor and reporting transparency.

The methodological quality of the 26 included studies varied substantially, with overall quality scores ranging from roughly 38% to 100% of the total criteria. In general, more recently published studies (2024–2025) tended to score higher, reflecting a trend toward improved methodological rigor and adherence to reporting guidelines.

Variability in system boundaries. A major source of heterogeneity was the definition of system boundaries which varied along two distinct dimensions: the breadth of GHG scopes considered, and the temporal extent of the patient pathway included. Considering first the GHG scope dimension, only about half of the studies explicitly accounted for all three scopes of healthcare GHG emissions (see S2Table for details). In contrast, many studies employed truncated boundaries, omitting one or more scopes. These boundary differences pose a significant comparability challenge, a "carbon footprint" of a procedure in one study might encompass a very different set of processes than in another study. As a result, absolute footprint values cannot be directly compared across studies without accounting for what sources were included. Notably, the highest footprint estimates tended to come from studies with the broadest system boundaries, whereas narrowly focused studies reported much smaller carbon totals. This underscores that boundary scope is a key determinant of the reported footprint. It also represents a potential bias: studies that neglect major upstream or downstream processes are likely to underestimate total emissions, sometimes substantially so. Given that 70–80% of healthcare's carbon emissions typically arise indirectly along the supply chain (Scope 3) [35], excluding these components can omit the majority of a surgery's true footprint. Encouragingly, several of the most recent studies did adopt more comprehensive life-cycle boundaries that include supply-chain contributions, aligning with best-practice recommendations to broaden scopes in healthcare sustainability metrics. Variability in system boundaries remains a prominent limitation of the evidence base, and greater standardization is needed to ensure completeness and enable fair comparisons.

A second, equally consequential boundary dimension concerns whether the carbon footprint is estimated for the perioperative phase only (typically from entering to leaving the operating theatre) or for the whole patient care pathway, encompassing preoperative consultations, imaging, travel, inpatient stay and postoperative follow-up. This distinction has profound implications for both the magnitude and the composition of the reported footprint. Narrow-boundary studies focused on operating-theatre activity [21,27] tend to report lower totals dominated by consumables and intraoperative energy use, while whole-pathway assessments [10,11,18,25,26,30,36] capture additional sources such as patient and staff travel, outpatient clinic energy use and inpatient bed-days, which can individually exceed the emissions of the surgical step itself. Recognizing this dichotomy is essential when interpreting comparative figures: whole-pathway assessments are more representative of the true climate burden of surgery, while perioperative-only audits are more suitable for evaluating intraoperative interventions.

Transparency of assumptions and reporting. Most studies were relatively strong in reporting transparency, but there were notable exceptions. Nearly all clearly stated their overarching goals and scope (e.g., defining the surgical procedure and system studied), and 90% explicitly listed which greenhouse gases were counted (typically CO_2, with some also including CH_4 and N_2O in CO_2e) in their calculations. Many also provided detailed breakdowns of results by subprocess or emission source, which enhances interpretability. This level of detail is a strength, as it allows readers to see the major contributors and check consistency with the methods. On the other hand, a minority of studies lacked clarity in important assumptions. In roughly one-third of the papers, the authors did not clearly document the number of data points or measurements underlying each process, for instance, whether energy use was measured directly or estimated, and how many observations informed that estimate. Such omissions make it difficult to judge the reliability of those results. In a few cases, key methodological choices were only vaguely described or buried in supplementary materials (e.g., how equipment utilization was allocated, or why certain items were excluded). The exclusions and assumptions reported by each study (see S3 Table) reveal that while most authors did state their major assumptions and justifications, some provided only limited detail. None of the included studies underwent any external peer audit of their carbon accounting, and only a handful explicitly discussed the completeness of their data or potential gaps. This lack of critical appraisal of data completeness is common in healthcare LCAs, previous work has found that authors often do not assess whether all relevant processes/data were captured [37]. Overall, transparency was one of the stronger areas of quality (reflected in consistently high scoring on this domain), but there remains room for improvement in clearly conveying all assumptions, exclusions, and data collection methods. Clearer reporting would improve reproducibility and allow the research community to more easily identify reasons for differences between studies.

Data sources and quality. The accuracy and reliability of the footprint estimates depend heavily on data quality. In this regard, the studies showed mixed performance. Only 2 out of 26 studies relied exclusively on primary data (i.e., direct measurements specific to the study hospital) for all inputs considered; the vast majority combined primary and secondary data. Commonly, authors measured a few parameters in situ and obtained others from the literature or databases. While using secondary data is often unavoidable, for example, no single hospital can directly measure the embodied emissions of manufactured drugs or devices, it does introduce uncertainty and potential bias if the data are not representative. Many studies assumed literature values or industry averages that may not reflect the local context of their hospital. For instance, several analyses used national conversion factors for waste disposal or energy, sometimes even from other countries due to data availability. Few studies discussed the implications of these choices. In fact, consistency in data representativeness was generally weak: none of the studies formally evaluated how temporally or geographically representative their data were.

Many studies had to assume usage patterns (for equipment, HVAC, etc.) in the absence of direct monitoring. The specificity of data sources was captured in our quality scoring, nearly all studies scored “1” (on a 0–2 scale) for using a mix of primary and secondary data, indicating moderate fidelity. Importantly, the lack of uncertainty analysis means we do not know how much error these data choices might be introducing. In summary, data quality is a concern across the board. Even where primary data were used, sample sizes were often small: some studies based calculations on just 5–15 procedures, which raises questions about statistical reliability. Secondary data, while necessary for life-cycle modelling, were not always transparently sourced or up-to-date. These issues highlight the need for more robust data collection and validation in future studies, as well as for reporting of data uncertainties.

Adherence to LCA standards. About half of the studies explicitly stated that they followed a recognized carbon footprinting or LCA standard, whereas the others did not mention any formal guidance. This split was reflected in the consistency domain scores. Those that did cite a standard (such as the ISO 14040/14044 LCA framework or the GHG Protocol Product Standard) generally showed better methodological coherence. For example, several studies referenced using the GHG Protocol or ISO guidelines to define their scope and inventory, and one study applied a < 1% materiality threshold (cut-off rule) for minor emission sources, which is in line with PAS 2050 and other standards. By contrast, studies that did not reference any guidelines sometimes made ad hoc methodological choices, for instance, defining functional units or impact boundaries in non-standard ways, which could introduce bias. In our sample, there was evidence that newer studies are moving toward accepted norms. Many 2024–2025 studies referenced, at minimum, the inclusion of Scope 1–3 emissions per the GHG Protocol taxonomy or cited performing a life-cycle assessment per ISO protocols. This is a positive development because following established frameworks tends to improve consistency: it ensures, for example, that if two studies both claim to do an LCA, they will at least share common definitions and steps (goal and scope definition, inventory analysis, impact assessment, interpretation). Indeed, among the comparative studies in our review, nearly all applied uniform methods to both comparators, yielding high consistency scores. Only one or two comparative studies had minor consistency issues (e.g., slightly different data sources used between the compared groups), and these were flagged as potential biases. Overall, the use of standard methods is a notable strength for roughly half the studies; the remainder would benefit from closer alignment with published LCA guidance to enhance credibility.

Discussion

Compared with the two prior systematic reviews on this topic, which included 8 and 7 studies respectively [6,7], the present update incorporates 26 eligible works published in just three years (2023–2025), reflecting the rapid growth of the field. Reported footprints now span from under 5 kgCO_2e for minor procedures to over 400 kgCO_2e for complex single-stage operations, with whole multistage patient pathways reaching about 1,000 kgCO_2e. Beyond the larger evidence base, the current corpus differs from the prior reviews in three substantive ways: it covers a markedly broader set of specialties (including cardiothoracic, urologic, obstetric, maxillofacial and plastic/reconstructive surgery), a more diverse geographical distribution, and a larger proportion of studies adopting formal LCA frameworks (ISO 14040/14044, GHG Protocol).

Across procedures and specialties, single-use instruments and consumables consistently emerge as the dominant hotspot, confirming previous evidence that material production and sterilization for disposables represent a substantial proportion of each procedure's footprint. Several recent studies compare the environmental impacts of single-use versus reusable surgical and medical instruments [38–44]. In many cases reusable instruments do offer lower overall emissions, but there are situations where the advantage is marginal or context-dependent, reminding us that "reusable" is not automatically synonymous with "sustainable" without proper implementation. Operating rooms are energy-intensive environments due to ventilation, air conditioning, heating, and specialized equipment, so electricity use and HVAC requirements often make up the next largest share of emissions after materials, underscoring the need for both local efficiency measures and institutional decarbonization through renewable energy sources. This is a central issue not only for operating rooms but for hospital buildings in general: there is a growing concern in other high-intensity departments like diagnostic imaging suites (e.g., MRI and CT scanners) and clinical laboratories as well [45–49].

When included, travel emissions from patients and healthcare staff add a significant layer of impact, highlighting that system-level organization and telehealth integration can reduce emissions beyond the operating room itself. Better coordination of care to minimize unnecessary trips, and the integration of telehealth services, can avoid a great deal of travel-related emissions [28,29,50–52]. Anaesthetic practices also influence results markedly: eliminating desflurane and nitrous oxide, adopting regional techniques, and using low-flow anaesthesia can achieve immediate reductions without compromising safety. The literature in recent years has been rich with papers documenting the outsized climate footprint of anaesthetic gases and highlighting successful interventions, from hospital case studies eliminating desflurane to national policies (the EU's decision to ban desflurane as of 2026) [22–24,53–57].

Reprocessing and waste management, although smaller in relative magnitude, remain critical in the transition from disposable to reusable systems. Effective waste segregation, recycling programs, and reprocessing of medical devices can all help decrease the environmental toll of surgical care and foster a more circular use of materials. In recent literature, an increasing number of studies focus on waste reduction strategies and circular economy principles in surgical contexts, for example, optimizing surgical kits to reduce unused items, recycling polypropylene plastics from instrument trays, or reusing sterilized equipment where feasible [58–63]. These efforts not only cut emissions marginally but also have broader environmental benefits (like reducing landfill waste and pollution) and often yield cost savings for hospitals.

A persistent challenge highlighted by both the present synthesis and the prior reviews is the marked methodological heterogeneity that limits cross-study comparability. Convergence on a small set of shared principles would substantially accelerate cumulative learning in this field. Future studies should explicitly adopt a recognized LCA framework, such as ISO 14040/14044 or the GHG Protocol Product Standard, and report transparently their system boundaries, functional units and data sources, declaring which life-cycle stages are included and which are excluded. Systematic uncertainty analysis should accompany the headline figure, and whole-pathway audits should be preferred over perioperative-only assessments whenever the clinical context allows. Reporting checklists tailored to healthcare LCAs would further support consistency across studies. The three plastic surgery eco-audits [25,26,30] illustrate this replicable approach in practice: by applying the same process-mapping methodology, emission-factor sources and reporting structure to three very different procedures (DIEP flap, breast implant and multistage microtia reconstruction) at a single centre, the team produced internally comparable results that make visible how boundary choices, operative duration and anaesthetic technique drive the total footprint, offering a template that could be extended to other specialties and institutions. Building on these methodological considerations, the CABG study [11] and the minimally invasive gynaecological pathway assessment [36] serve as useful reference points for future work, since both combined process-based bottom-up data collection with broad system boundaries, covered multiple emission scopes including supply chain and travel, applied standardized emission factors and ISO-compliant LCA steps, and explicitly discussed parameter uncertainty.

Beyond the technical agenda, the evidence reviewed reinforces that achieving low-carbon surgery requires coordinated behavioural, organizational and infrastructural strategies, with environmental performance treated as an intrinsic dimension of surgical quality rather than an isolated objective. It's also worth noting that environmental sustainability is becoming an important competitive and reputational concern in the healthcare industry. Hospitals that adopt sustainable methods are increasingly seen favourably by environmentally concerned patients, employees, and investors. In an era of increasing public awareness of climate change, many healthcare providers understand that displaying climate leadership can boost community trust and appeal [3,64–66]. Some healthcare systems increasingly publish sustainability scores or get awards for green activities, and procurement processes are beginning to favour producers of low-carbon items. This means that sustainability is more than just an ethical necessity or a regulatory compliance issue; it is also regarded as a symbol of quality and innovation in healthcare. Real advancement, however, is dependent on culture and mindsets as much as technology and policy [67,68]. Fortunately, various surveys have been undertaken to assess the impression of environmental sustainability among healthcare professionals, and they generally demonstrate a great hunger for change on the ground. When clinicians and hospital workers are taught about the environmental impact of healthcare operations, they strongly support initiatives to decrease waste and emissions [24,69–71]. Many front-line employees are ready to contribute to greener practices if given the opportunity and assistance. This bottom-up engagement is critical: while high-level promises and management initiatives lay the groundwork (the "top-down" part), long-term change frequently occurs only when the workforce is fully aware, engaged, and empowered to act [72–74]. Building environmental awareness into the culture of surgical teams and hospitals, through education, training, and recognition of sustainability achievements, can thereby generate substantial grassroots improvements that eventually transform high climate goals into daily practice. The climate issue in healthcare will be addressed not simply by administrative decisions or new technologies, but also through the collective activities of many people rethinking ordinary practices and challenging what is currently in place.

Despite the advances in knowledge and practice outlined above, there remain notable gaps in the literature that future research needs to address. High-volume or common types of surgery are still under-represented in detailed carbon assessment (e.g., appendectomy, cholecystectomy, neurosurgery, and paediatric surgery). The environmental impact of emerging technologies like robotic surgery has only been partially explored: while waste data and other proxies suggest that robotic procedures have higher footprints, detailed LCAs comparing robotic and conventional surgery are still needed. Similarly, the footprint of implant production (orthopaedic hardware, surgical mesh, etc.) is an area needing deeper analysis; some of our included studies touched on it qualitatively (e.g., spinal implants), but precise data would help target greening efforts in the medical device industry (e.g., using low-carbon materials or recycling metals).

Another knowledge gap is long-term outcome and carbon trade-offs: for instance, if a minimally invasive approach has a higher surgical footprint but leads to fewer complications or re-operations, the net emissions over a patient's episode of illness might favour one or the other. A life-cycle perspective on a patient's treatment course (including potential downstream events) would align carbon accounting with clinical outcome accounting. None of the studies did a full life-cycle cost analysis combining environmental and clinical outcomes (e.g., emissions per quality-adjusted life year, QALY), but that could be a valuable approach for future research, potentially informing policy.

It is worth noting that while individual changes can make significant relative differences, tackling climate change requires systemic action. The cumulative impact of widespread adoption of these changes could be substantial: the healthcare sector is responsible for 4–5% of global GHG emissions, and within that, operating rooms can account for a significant fraction. Thus, understanding the real environmental impact of medical procedures, surgical or otherwise, along a patient's care pathway, and implementing the mitigation measures we have discussed is part of a much bigger picture. It is one of the ways healthcare can help shift the trajectory of its carbon emissions and contribute to broader national and international decarbonization goals.

Limitations

While we attempted to be comprehensive, usual limitations apply. We relied on available published data; some relevant studies may have been in progress or in gray literature (e.g., hospital internal reports) and not captured. We assumed the accuracy of each study's data and did not independently audit their calculations; differences in data quality or errors in original studies would propagate to our synthesis. We also could not meta-analyze quantitatively due to heterogeneity, instead using a narrative approach. Nonetheless, the consistency of themes across independent studies adds robustness to our conclusions.

A further important limitation is the exclusive focus of this review on carbon-equivalent emissions as the environmental endpoint. While greenhouse gas emissions currently represent the most pressing and most widely reported environmental impact of surgical care, other impact categories, including water consumption, eutrophication, toxicity, land use, and plastic and pharmaceutical pollution, are relevant and can diverge from the carbon signal. Mitigation actions optimized solely for carbon may therefore inadvertently shift environmental burdens to other impact categories (the so-called "burden-shifting" problem), for example when reusable devices with a lower carbon footprint entail higher water consumption or chemical emissions during reprocessing. Multi-criteria LCA frameworks and careful interpretation of trade-offs are needed to avoid unintended environmental consequences. As a minor additional limitation, the present review did not include product-level LCAs of medical devices, implants, or pharmaceuticals, which were outside its scope but could provide complementary insight into the upstream drivers of surgical emissions.

Conclusion

Surgical operations contribute significantly to greenhouse gas emissions, but this impact can be dramatically reduced through targeted strategies. The 2023–2025 literature shows that by eliminating unnecessary single-use items, favouring reusable instruments and materials, choosing low-carbon anaesthetic techniques, optimizing operating room energy use, and rethinking care pathways to reduce travel and waste, the carbon footprint of surgery can be lowered by 30–80% in many cases without detriment to patient care. Surgeons, anaesthesiologists, nurses, and administrators all have roles to play: from micro-level decisions (e.g., using a reusable instrument set, turning off equipment, closing the lid on the anaesthetic vaporizer) to macro-level policies (investing in sustainable infrastructure, revising procurement contracts to prioritize low-carbon supplies, and institutionalizing telehealth where appropriate). Incorporating environmental sustainability into routine surgical practice is increasingly recognized as part of delivering high-quality care. Surgical departments can develop data-driven sustainability action plans, and researchers can focus on filling the remaining knowledge gaps, particularly in under-studied procedures and in standardizing assessment methods. Continued innovation, in device reusability, in energy-efficient technologies, and in clinical care models, will further empower the surgical community to reduce its carbon footprint. The studies reviewed provide clear proof that greener surgery is possible now, and the real challenge ahead lies in scaling up these solutions across healthcare systems globally, monitoring progress, and fostering a culture where the surgical team is as attuned to resource stewardship as it is to sterile technique or patient safety checklists. Sustainable surgery is not a distant ideal but an attainable goal.

Supporting information

S1 File. PRISMA 2020 Checklist.
(DOCX)

S2 File. Search strategy.
(DOCX)

S1 Table. Quality Assessment.
(DOCX)

S2 Table. Study inventory boundaries, data collected, and method used to calculate inventory results.
(DOCX)

S3 Table. Stated exclusions, assumptions and other limitations.
(DOCX)

Author contributions

Conceptualization: Beatrice Marchi.

Data curation: Anna Savio, Beatrice Marchi, Andrea Roletto.

Formal analysis: Anna Savio, Beatrice Marchi, Andrea Roletto.

Investigation: Anna Savio, Beatrice Marchi.

Methodology: Anna Savio, Beatrice Marchi.

Supervision: Pierangelo Guizzi, Giuseppe Milano, Lucio Enrico Zavanella, Simone Zanoni.

Validation: Andrea Roletto.

Writing – original draft: Anna Savio, Beatrice Marchi.

Writing – review & editing: Anna Savio, Beatrice Marchi, Andrea Roletto, Pierangelo Guizzi, Giuseppe Milano, Lucio Enrico Zavanella, Simone Zanoni.

PLOS One

References

1. Tennison I, Roschnik S, Ashby B, Boyd R, Hamilton I, Oreszczyn T, et al. Health care's response to climate change: a carbon footprint assessment of the NHS in England. Lancet Planet Health. 2021;5(2):e84–92. https://doi.org/10.1016/S2542-5196(20)30271-0 PMID: 33581070
2. Johnson S, Williams D, Clark B, Stewart Jr E, Peyton C, Johnson C. Perspective chapter: Climate change and health inequities. Health inequality - A comprehensive exploration. IntechOpen. 2024. https://doi.org/10.5772/intechopen.1004280
3. Tee NCH, Yeo JA, Choolani M, Poh KK, Ang TL. Healthcare in the era of climate change and the need for environmental sustainability. Singapore Medical Journal. 2024;:204–10. https://doi.org/10.4103/singaporemedj.SMJ-2024-035
4. Smith JT, Boakye LAT, Ferrone ML, Furie GL. Environmental Sustainability in the Orthopaedic Operating Room. J Am Acad Orthop Surg. 2022;30(21):1039–45. https://doi.org/10.5435/JAAOS-D-22-00247 PMID: 36007200
5. NHS E. Five years of a greener NHS: progress and forward look. London. 2025. https://www.england.nhs.uk/long-read/five-years-greener-nhs-progress-forward-look/
6. Rizan C, Steinbach I, Nicholson R, Lillywhite R, Reed M, Bhutta MF. The Carbon Footprint of Surgical Operations: A Systematic Review. Ann Surg. 2020;272(6):986–95. https://doi.org/10.1097/SLA.0000000000003951 PMID: 32516230
7. Robinson PN, Surendran K, Lim SJ, Robinson M. The carbon footprint of surgical operations: a systematic review update. Ann R Coll Surg Engl. 2023;105(8):692–708. https://doi.org/10.1308/rcsann.2023.0057 PMID: 37906978
8. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;:n71. https://doi.org/10.1136/bmj.n71
9. Drew J, Rizan C. HealthcareLCA Database. HealthcareLCA. https://healthcarelca.com/database. 2025.
10. John JB, Collins M, Eames S, O'Flynn K, Briggs TWR, Gray WK, et al. The carbon footprint of the perioperative transurethral resection of bladder tumour pathway. BJU Int. 2025;135(1):78–87. https://doi.org/10.1111/bju.16477 PMID: 39051536
11. van Bree EM, Stobernack T, Boom T, Geene K, Kooistra EJ, Li W, et al. Assessing the environmental impact of coronary artery bypass grafting to decrease its footprint. Eur J Cardiothorac Surg. 2025;67(2):ezaf054. https://doi.org/10.1093/ejcts/ezaf054 PMID: 39960886
12. Cannon J, Tailor H, Douglas C. Carbon footprint of tonsillectomy. Surgeon. 2024;22(4):242–7. https://doi.org/10.1016/j.surge.2024.06.001 PMID: 38918114
13. Filley GI, Kayastha D, Hayes W, Mehra S, Sherman JD, Eckelman MJ. Environmental Impact of a Direct Laryngoscopy: Opportunities for Pollution Mitigation. Laryngoscope. 2024;134(7):3206–14. https://doi.org/10.1002/lary.31341 PMID: 38379176
14. Rougereau G, Chatelain L, Zadegan F, Conso C. Estimation of the carbon footprint of arthroscopic rotator cuff repairs in France. Orthop Traumatol Surg Res. 2024;110(1):103755. https://doi.org/10.1016/j.otsr.2023.103755 PMID: 37949395
15. Eidmann A, Geiger F, Heinz T, Jakuscheit A, Docheva D, Horas K. Our Impact on Global Warming: A Carbon Footprint Analysis of Orthopaedic Operations. Journal of Bone and Joint Surgery. 2024;106:1971–7. https://doi.org/10.2106/JBJS.24.00212
16. Nakarai H, Kwas C, Mai E, Singh N, Zhang B, Clohisy JC. What is the carbon footprint of adult spinal deformity surgery?. J Clin Med. 2024;13. https://doi.org/10.3390/jcm13133731
17. Ramani S, Hartnett J, Karki S, Gallousis SM, Clark M, Andikyan V. Carbon Dioxide Emissions and Environmental Impact of Different Surgical Modalities of Hysterectomies. JSLS. 2023;27(3):e2023.00021. https://doi.org/10.4293/JSLS.2023.00021 PMID: 37663433
18. Mattei L, Barry F, Al-Badri N, Ferri J, Masson G, Nicot R. Carbon impact of orthognathic surgery. Int J Oral Maxillofac Surg. 2026;55(2):195–201. https://doi.org/10.1016/j.ijom.2025.06.005 PMID: 40562621
19. Spil NA, van Nieuwenhuizen KE, Rowe R, Thornton JG, Murphy E, Verheijen E, et al. The carbon footprint of different modes of birth in the UK and the Netherlands: An exploratory study using life cycle assessment. BJOG. 2024;131(5):568–78. https://doi.org/10.1111/1471-0528.17771 PMID: 38272843
20. Camhi Y, Cerceau S, Didier M, Hernandez J, Leboulanger N. Carbon footprints of various subtotal tonsillectomy techniques. Eur Ann Otorhinolaryngol Head Neck Dis. 2025;142(1):18–20. https://doi.org/10.1016/j.anorl.2024.09.003 PMID: 39304411
21. Zhang D, Dyer GSM, Blazar P, Earp BE. The Environmental Impact of Open Versus Endoscopic Carpal Tunnel Release. J Hand Surg Am. 2023;48(1):46–52. https://doi.org/10.1016/j.jhsa.2021.12.003 PMID: 35123818
22. White SM, Shelton CL, Gelb AW, Lawson C, McGain F, Muret J, et al. Principles of environmentally-sustainable anaesthesia: a global consensus statement from the World Federation of Societies of Anaesthesiologists. Anaesthesia. 2022;77(2):201–12. https://doi.org/10.1111/anae.15598 PMID: 34724710
23. Kampman JM, Sperna Weiland NH. The optimal mode of anaesthesia: are we ready for an evidence-based recommendation?. Br J Anaesth. 2025;134(6):1606–9. https://doi.org/10.1016/j.bja.2025.03.005 PMID: 40355166
24. Flynn FM, Martinsen SS, Øiseth F, Flo J, Leonardsen A-CL. Sustainability in the operating room: a cross-sectional survey of nurse anaesthetists' and operating room nurses' views and practice. BMC Nurs. 2025;24(1):600. https://doi.org/10.1186/s12912-025-03239-x PMID: 40420070
25. Ahmed Z, Zargaran A, Zargaran D, Sousi S, Hakimnia K, Panagiota Glynou S, et al. Sustainability in Reconstructive Breast Surgery: An Eco-audit of the Deep Inferior Epigastric Perforator Flap Pathway. Plast Reconstr Surg Glob Open. 2024;12(12):e6374. https://doi.org/10.1097/GOX.0000000000006374 PMID: 39726822

26. Ahmed Z, Zargaran A, Marudamuthu D, Sousi S, Zargaran D, Hamilton S, et al. Sustainability in breast surgery: An eco-audit of the breast implant pathway. J Plast Reconstr Aesthet Surg. 2025;105:219–29. https://doi.org/10.1016/j.bjps.2025.04.020 PMID: 40318360

27. Kodumuri P, Jesudason EP, Lees V. Reducing the carbon footprint in carpal tunnel surgery inside the operating room with a lean and green model: a comparative study. J Hand Surg Eur Vol. 2023;48(10):1022–9. https://doi.org/10.1177/17531934231176952 PMID: 37226468

28. Savoldelli A, Landi D, Rizzi C. Exploring the Environmental Impact of Telemedicine: A Life Cycle Assessment. dHealth. 2024;:81–6. https://doi.org/10.3233/SHTI240016

29. Thiel CL, Mehta N, Sejo CS, Qureshi L, Moyer M, Valentino V, et al. Telemedicine and the environment: life cycle environmental emissions from in-person and virtual clinic visits. NPJ Digit Med. 2023;6(1):87. https://doi.org/10.1038/s41746-023-00818-7 PMID: 37160996

30. Ahmed Z, Zargaran A, Kamel Y, Sousi S, Tannirandorn P, Zargaran D, et al. Evaluating the Environmental Impact of Quaternary Plastic Surgery: An Eco-audit of the Autologous Microtia Reconstruction Pathway. Plast Reconstr Surg Glob Open. 2025;13(5):e6746. https://doi.org/10.1097/GOX.0000000000006746 PMID: 40330165

31. Rizan C, Lillywhite R, Reed M, Bhutta MF. The carbon footprint of products used in five common surgical operations: identifying contributing products and processes. J R Soc Med. 2023;116(6):199–213. https://doi.org/10.1177/01410768231166135 PMID: 37054734

32. Shah S, Morris H, Nicolaou N, MacInnes S, Haslam P, Shahane S, et al. The carbon footprint of arthroscopic procedures. Ann R Coll Surg Engl. 2024;106(3):256–61. https://doi.org/10.1308/rcsann.2023.0036 PMID: 37381779

33. Drobetz N, Xu J, Chang D, Hazan D, Collins W, Drobetz H. Less trash, more treasure. Waste production and reduction in Orthopaedic surgery. ANZ J Surg. 2025;95(3):539–43. https://doi.org/10.1111/ans.70018 PMID: 39973476

34. Kloevekorn L, Roemeling O, Fakha A, Hage E, Smailhodzic E. Decarbonizing surgical care: a qualitative systematic review guided by the Congruence Model. BMC Health Serv Res. 2024;24(1):1456. https://doi.org/10.1186/s12913-024-11929-6 PMID: 39580403

35. Rodríguez-Jiménez L, Romero-Martín M, Spruell T, Steley Z, Gómez-Salgado J. The carbon footprint of healthcare settings: A systematic review. J Adv Nurs. 2023;79(8):2830–44. https://doi.org/10.1111/jan.15671 PMID: 37198974

36. Cohen ES, Kouwenberg LHJA, Dürager HV, Snijder LE, Lammerts J, van Bodegraven M, et al. Environmental impact of minimally invasive procedures: life cycle assessment of two hospital care pathways. Resour Conserv Recycl. 2025;222. https://doi.org/10.1016/j.resconrec.2025.108441

37. Lange O, Plath J, Dziggel TF, Karpa DF, Keil M, Becker T, et al. A Transparency Checklist for Carbon Footprint Calculations Applied within a Systematic Review of Virtual Care Interventions. Int J Environ Res Public Health. 2022;19(12):7474. https://doi.org/10.3390/ijerph19127474 PMID: 35742724

38. Le NNT, Hernandez LV, Vakil N, Guda N, Patnode C, Jolliet O. Environmental and health outcomes of single-use versus reusable duodenoscopes. Gastrointest Endosc. 2022;96(6):1002–8. https://doi.org/10.1016/j.gie.2022.06.014 PMID: 35718068

39. Boberg L, Singh J, Montgomery A, Bentzer P. Environmental impact of single-use, reusable, and mixed trocar systems used for laparoscopic cholecystectomies. PLoS One. 2022;17(7):e0271601. https://doi.org/10.1371/journal.pone.0271601 PMID: 35839237

40. Leppälä K, Vornanen L, Savinen O. Lifecycle extension of single-use medical device sensors: Case study of an engineering sustainability transition program. J Clean Prod. 2023;423. https://doi.org/10.1016/j.jclepro.2023.138518

41. Demarré L, Huysveld S, Vanderwee K, Duprez V, Cadena E, Dewulf J, et al. Comparison of reusable and single-use specula in Belgian hospitals: an environmental life cycle assessment and economic analysis. Int J Life Cycle Assess. 2024;30(3):429–45. https://doi.org/10.1007/s11367-024-02417-4

42. Feely K, Matthews S, Quilas E, McGain F, Kwek E, Wynne R. Implementation of reusable linen in the intensive care unit: Impact on pressure injury, staff satisfaction, and environmental sustainability. Aust Crit Care. 2025;38(6):101311. https://doi.org/10.1016/j.aucc.2025.101311 PMID: 40819501

43. McCance E, Steinbach I, Morris DS. Comparative carbon footprinting study of reusable vs. disposable instruments in cataract surgery. Eye (Lond). 2025;39(8):1481–5. https://doi.org/10.1038/s41433-025-03656-x PMID: 39948404

44. Rouvière N, Chkair S, Auger F, Cuvillon P, Leguelinel-Blache G, Chasseigne V. Reusable laryngoscope blades: a more eco-responsible and cost-effective alternative. Anaesth Crit Care Pain Med. 2023;42(5):101276. https://doi.org/10.1016/j.accpm.2023.101276 PMID: 37437711

45. Carver DE, Pruthi S, Struk O, Vigil-Garcia M, Meijer C, Gehrels J, et al. Measuring the Environmental Impact of MRI and CT: A Life Cycle Assessment. J Am Coll Radiol. 2026;23(4):507–18. https://doi.org/10.1016/j.jacr.2025.09.030 PMID: 41052702

46. Roletto A, Savio A, Masperi A, Bonfitto GR, Pala F, Migliorisi C, et al. Energy Usage Assessment and Energy Savings Estimation in a Radiology Department in Italy. Energies. 2025;18(8):1936. https://doi.org/10.3390/en18081936

47. Szirt R, Monjur MR, McGovern L, Charlesworth K, O'Connor S, Weaver JC, et al. Environmental Sustainability in the Cardiac Catheter Laboratory. Heart Lung Circ. 2023;32(1):11–5. https://doi.org/10.1016/j.hlc.2022.06.694 PMID: 35965245

48. Alpdemir M, Yurt EF, Şeneş M. Forward steps in green medical laboratory practices for a sustainable future. Turkish Journal of Biochemistry. 2023;49(1):20–3. https://doi.org/10.1515/tjb-2023-0186

49. Béchu C, Rullier A, Lesoin P-E, Gaillot-Durand L, Trecourt A, Gosset P, et al. The carbon footprint of a surgical pathology laboratory in France. Am J Clin Pathol. 2024;162(1):103–9. https://doi.org/10.1093/ajcp/aqae022 PMID: 38470223

50. Qiao Y, Zhai Y, Ma R, Ji M, Lu W. Optimizing teleconsultation scheduling to make healthcare greener. J Clean Prod. 2023;422. https://doi.org/10.1016/j.jclepro.2023.138569

51. Savoldelli A, Landi D, Rizzi C. Environmental and social impacts of a televisit process: Combined qualitative and life cycle assessment. Environmental Impact Assessment Review. 2025;115:108030. https://doi.org/10.1016/j.eiar.2025.108030
52. Silva BVF, Holm-Nielsen JB, Sadrizadeh S, Teles MPR, Kiani-Moghaddam M, Arabkoohsar A. Sustainable, green, or smart? Pathways for energy-efficient healthcare buildings. Sustainable Cities and Society. 2024;100:105013. https://doi.org/10.1016/j.scs.2023.105013
53. Bernat M, Boyer A, Roche M, Richard C, Bouvet L, Remacle A, et al. Reducing the carbon footprint of general anaesthesia: a comparison of total intravenous anaesthesia vs. a mixed anaesthetic strategy in 47,157 adult patients. Anaesthesia. 2024;79(3):309–17. https://doi.org/10.1111/anae.16221 PMID: 38205529
54. Hu X, Pierce JT, Taylor T, Morrissey K. The carbon footprint of general anaesthetics: A case study in the UK. Resour Conserv Recycl. 2021;167:105411. https://doi.org/10.1016/j.resconrec.2021.105411
55. McGain F, Sheridan N, Wickramarachchi K, Yates S, Chan B, McAlister S. Carbon Footprint of General, Regional, and Combined Anesthesia for Total Knee Replacements. Anesthesiology. 2021;135:976–91. https://doi.org/10.1097/ALN.0000000000003967
56. Sherman J, Le C, Lamers V, Eckelman M. Life cycle greenhouse gas emissions of anesthetic drugs. Anesth Analg. 2012;114(5):1086–90. https://doi.org/10.1213/ANE.0b013e31824f6940 PMID: 22492186
57. Narayanan H, Raistrick C, Tom Pierce JM, Shelton C. Carbon footprint of inhalational and total intravenous anaesthesia for paediatric anaesthesia: a modelling study. Br J Anaesth. 2022;129(2):231–43. https://doi.org/10.1016/j.bja.2022.04.022 PMID: 35729012
58. Velicki K, Schultz M, Dy CJ. Saving Money and Reducing Waste With a Tailored Hand Surgery Kit. Qual Manag Health Care. 2023;32(1):35–9. https://doi.org/10.1097/QMH.0000000000000369 PMID: 35802894
59. Labib PL, Ford B, Winfield M, Douie WJ, Kanwar A, Sanders G. Revising a laparoscopic appendicectomy set to reduce reliance on disposable surgical instruments: supporting the transition to sustainable surgical practice. Ann R Coll Surg Engl. 2024;106(2):167–72. https://doi.org/10.1308/rcsann.2023.0015 PMID: 37051744
60. Sathe TS, Sorrentino TA, Wang K, Yap A, Wang JJ, Matthys M, et al. Instrument and Supply Variability: An Opportunity to Reduce the Carbon Footprint of the Operating Room. J Surg Res. 2024;295:732–9. https://doi.org/10.1016/j.jss.2023.11.004 PMID: 38142576
61. Rizan C, Bhutta MF, Reed M, Lillywhite R. The carbon footprint of waste streams in a UK hospital. J Clean Prod. 2021;286:125446. https://doi.org/10.1016/j.jclepro.2020.125446
62. Schluep M, Minheere M, Baus M, Machielse S, Donkers A, Vroman H. Reducing plastic waste in intensive care from longer use of intravenous administration and invasive monitoring sets: A before-and-after study. J Crit Care. 2024;84:154900. https://doi.org/10.1016/j.jcrc.2024.154900 PMID: 39182456
63. van Bodegraven L, van Eenennaam RM, Kouwenberg LHJA, Cohen ES, Sperna Weiland NH, Hehenkamp WJK. Ongbruikte medische disposables in de OK: omvang, klimaatvoetafdruk en kansen voor duurzame zorg. Ned Tijdschr Geneeskd. 2025;169.
64. Barratt AL, Bell KJ, Charlesworth K, McGain F. High value health care is low carbon health care. Med J Aust. 2022;216(2):67–8. https://doi.org/10.5694/mja2.51331 PMID: 34699070
65. Rattan TK, Joshi M, Vesty G, Sharma S. Sustainability indicators in public healthcare: A factor analysis approach. J Clean Prod. 2022;370. https://doi.org/10.1016/j.jclepro.2022.133253
66. Ryan-Fogarty Y, O'Regan B, Moles R. Greening healthcare: systematic implementation of environmental programmes in a university teaching hospital. J Clean Prod. 2016;126:248–59. https://doi.org/10.1016/j.jclepro.2016.03.079
67. Pinzone M, Guerci M, Lettieri E, Redman T. Progressing in the change journey towards sustainability in healthcare: the role of 'Green' HRM. Journal of Cleaner Production. 2016;122:201–11. https://doi.org/10.1016/j.jclepro.2016.02.031
68. Liang R, Orchard JW, Robson SJ. The global surgical triple goal: Surgery must improve health, be equitable, and environmentally sustainable. J Clim Chang Health. 2025;23:100458. https://doi.org/10.1016/j.joclim.2025.100458 PMID: 41647381
69. Roletto A, Catania D, Rainford L, Savio A, Zanardo M, Bonfitto GR, et al. Sustainable radiology departments: A European survey to explore radiographers' perceptions of environmental and energy sustainability issues. Radiography (Lond). 2024;30 Suppl 1:81–90. https://doi.org/10.1016/j.radi.2024.06.022 PMID: 38996669
70. Ikenaga N, Nakamura M, Hirasawa M, Naitoh T, Sakai Y, Habuchi T, et al. Green Surgery Awareness and Challenges: A Survey Among Members of the Japan Society for Endoscopic Surgery. Asian J Endosc Surg. 2025;18(1):e70087. https://doi.org/10.1111/ases.70087 PMID: 40441550
71. Iliopoulou K, Leone M, Hunfeld N, Ferrer R, Baid H, Ostermann M, et al. Environmental sustainability in intensive care: An international survey of intensive care professionals'views, practices and proposals to the European Society of Intensive Care Medicine. J Crit Care. 2025;88:155079. https://doi.org/10.1016/j.jcrc.2025.155079 PMID: 40267551
72. Macpherson CC, Hill J. Are physicians obliged to lead environmental sustainability efforts in health care organizations? Commentary. AMA Journal of Ethics. 2017.
73. Kuiter SG, Herrmann A, Mertz M, Quitmann C, Salloch S. Should healthcare professionals include aspects of environmental sustainability in clinical decision-making? A systematic review of reasons. BMC Med Ethics. 2025;26(1):78. https://doi.org/10.1186/s12910-025-01230-4 PMID: 40611029
74. Huo B, Eussen MMM, Marconi S, Johnson SM, Francis N, Oslock WM, et al. Scoping review for the SAGES EAES joint collaborative on sustainability in surgical practice. Surg Endosc. 2024;38(10):5483–504. https://doi.org/10.1007/s00464-024-11141-x PMID: 39174709

75. Ang K-L, Jovic M, Malin I, Ali SR, Whitaker S, Whitaker IS. Carbon footprint of non-melanoma skin cancer surgery. BJS Open. 2024;8(5):zrae084. https://doi.org/10.1093/bjsopen/zrae084 PMID: 39417641

76. Grothaus O, Jorgensen A, Maughan G, Anto M, Kazmers NH, Garcia BN. Carbon Footprint of Open Carpal Tunnel Release Surgery Performed in the Procedure Room Versus Operating Room Setting. J Hand Surg Am. 2024;49(6):576–82. https://doi.org/10.1016/j.jhsa.2024.03.014 PMID: 38713110

77. Karam KM, Moussa MK, Valentin E, Meyer A, Bohu Y, Gerometta A, et al. Sustainability studies in orthopaedic surgery: The carbon footprint of anterior cruciate ligament reconstruction depends on graft choice. Knee Surg Sports Traumatol Arthrosc. 2024;32(1):124–34. https://doi.org/10.1002/ksa.12035 PMID: 38226676

78. Kodumuri P, Joshi P, Malek I. Assessment of the carbon footprint of total hip arthroplasty and opportunities for emission reduction in a UK hospital setting. 2024. https://doi.org/10.1302/2633-1462

79. Mousania Z, Kayastha D, Rimmer RA, Atkinson JD. A cradle-to-grave life cycle assessment of the endoscopic sinus surgery considering materials, energy, and waste. Int Forum Allergy Rhinol. 2025;15(3):239–49. https://doi.org/10.1002/alr.23474 PMID: 39462253

80. Parker EB, Bluman EM, Chiodo CP, Martin EA, Smith JT. Carbon Footprint of Minor Foot and Ankle Surgery: A Randomized Controlled Trial. Foot Ankle Orthop. 2024;9(1):24730114241238231. https://doi.org/10.1177/24730114241238231 PMID: 38510517

81. Silva de Souza Lima Cano N, Engler ID, Mohammadiziazi R, Geremicca F, Lawson D, Drain N, et al. How Can the Environmental Impact of Orthopaedic Surgery Be Measured and Reduced? Using Anterior Cruciate Ligament Reconstruction as a Test Case. Clin Orthop Relat Res. 2025;483(1):7–19. https://doi.org/10.1097/CORR.0000000000003242 PMID: 39660662

PAPER 2

Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 842–854
https://doi.org/10.2478/rtuect-2024-0064
https://content.sciendo.com

Sustainable Operating Rooms: A Comprehensive Framework for Environmental Impact Analysis

Anna SAVIO[1*], Beatrice MARCHI[2], Andrea ROLETTO[3], Giuseppe MILANO[4], Simone ZANONI[5]

[1–3]*Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy*

[4]*Department of Medical and Surgical Specialties, Radiological Sciences, and Public Health, Università degli Studi di Brescia, Viale Europa 11, 25123, Brescia, Italy*

[5]*Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Via Branze 43, 25123 Brescia, Italy*

Received 15.05.2024; accepted 25.11.2024

***Abstract* – The healthcare sector is responsible for around 4.4 % of worldwide greenhouse gas emissions, according to estimates. Operating rooms are responsible for the greatest rate of resource consumption and overall hospital waste, varying from 20 % to 33 %. Hence, it is essential to fully discover the environmental impact of surgical procedures to obtain insight into the total emissions associated with the healthcare sector. Moreover, the lack of uniformity in data collection and the discrepancy of the data used by researchers makes it challenging, if not ineffective, to conduct a rigorous scientific comparison among the currently available studies on the environmental impacts of surgical procedures. This study aims to provide a practical and standardised framework that can be utilised to evaluate, simply and consistently, the environmental impacts of surgical procedures. To achieve this goal, a comprehensive literature review was conducted to assess the state of the art in environmental impact analyses related to surgical practices. This review highlighted significant variability and heterogeneity in existing methodologies, serving as the foundation for developing a more consistent approach. By simulating three different scenarios based on data availability, a methodology is proposed to conduct an environmental impact analysis tailored to the specific needs of researchers. Adopting a uniform methodology guarantees the inclusion of important variables and factors, preventing any oversights in the evaluation of the entire process.**

***Keywords* – Framework; greenhouse gas (GHG) emissions; healthcare; Life Cycle Assessment (LCA); surgery; waste management.**

1. Introduction

The growing concern for environmental sustainability, accentuated by the ongoing climate crisis, prompted a thorough examination of the primary industries accountable for substantial greenhouse gas emissions and excessive depletion of natural resources. Out of all the sectors, the healthcare industry accounted for approximately 4.4 % of the total global greenhouse gas emissions [1]. Practitioners are now compelled to consider which phases of the care process have the most significant influence on resource consumption as a result of this heightened awareness. Research conducted in both the United States and the United Kingdom reveals

* Corresponding author.
E-mail address: anna.savio@unibs.it

©2024 Author(s). This is an open access article licensed under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0).

that operating rooms contribute to 20–33 % of the overall waste generated by hospitals [2], [3]. Multiple studies concentrate on the generation of waste in surgical theatres, examining waste sorting protocols and measuring the various categories of waste, to identify potential avenues for reducing and recycling waste [4]–[10]. The significant waste generation in operating rooms is associated with the extensive use of disposable instruments. While these instruments ensure complete traceability and patient safety, their usage has a more substantial environmental impact compared to reusable devices [11]–[17].

Additionally, the energy consumption of operating rooms is 2–3 times greater than other sections within healthcare facilities. The structure and arrangement of an operating block are focused on reaching functionality and minimising bacterial and viral contamination. Each facility and technological system must ensure efficiency and safety, adhering to criteria that promote the maintenance of hygienic conditions. This results in significant energy and resource utilisation: the energy consumption linked to HVAC (Heating, Ventilation and Air Conditioning) systems during a surgical procedure is one of the most influential factors [18].

This article aims to present a structured methodological framework that serves as a roadmap for conducting studies on the environmental impacts of surgical procedures. By outlining efficient approaches tailored to data availability and study scope, the framework provides a foundation for advancing research in this field. A comprehensive literature review was carried out to identify and compare previously employed methodologies, highlighting their strengths and limitations. This analysis supports the adoption of a consistent and standardized approach, which can enhance uniformity in research and foster the integration of sustainability principles into surgical practices.

The study underscores the importance of interdisciplinary collaboration, recognizing that combining expertise from fields such as engineering and medicine is essential to ensure the accuracy and reliability of data collection and analysis. Addressing this need, the framework proposes three distinct scenarios, each corresponding to a different level of analytical depth and data availability. These scenarios offer a structured methodology for tackling the issue of environmental sustainability in surgery, bridging disciplines that are crucial for both human and environmental wellbeing.

The results of this study are qualitative, focusing on methodological contributions rather than quantitative data. They include the systematic identification of key factors, such as resource consumption, waste management, and environmental impacts, and the development of scenario-based methodologies to address these factors comprehensively. By offering actionable tools and guidelines, this work equips researchers and practitioners with practical frameworks to integrate sustainability into operating room practices, paving the way for a more environmentally conscious approach to surgical care.

2. METHODS AND METHODOLOGY

The study aims to establish a clear and simple methodological approach for recording operational procedures, identifying necessary data, and choosing the most suitable methodology for environmental impact assessment. A standardised methodological framework is designed to assist and guide researchers in evaluating surgical procedures, considering the various factors that affect their duration, complexity, and outcomes.

A comprehensive review of the literature reveals that the objective of environmental impact analysis and the accessibility of relevant data vary significantly in the surgical setting. Based on these differences, three separate scenarios have been identified. Each scenario sets precise boundaries for analysing the different factors that affect the consumption of resources in the process being studied, ensuring that each evaluation is adapted to its specific needs.

2.1. Literature Review

A literature review was conducted in February 2024 using the Scopus and PubMed databases to identify original articles focused on the environmental impact of surgical procedures performed in operating rooms. The review process started with a preliminary selection, restricting the articles to those written in English and excluding reviews, editorials, and letters. Subsequently, after an initial screening of titles and a detailed review of abstracts, only open-access articles were included, and their full texts were obtained for further analysis. To expand the search, a manual review of references cited in the selected articles and reviews was performed to identify additional studies meeting the eligibility criteria.

Studies that: 1) focused exclusively on single medical devices or equipment used during surgical procedures; 2) evaluated potential eco-friendly initiatives by medical staff or; 3) consisted of abstracts or conference proceedings, were excluded.

The final analysis included only studies that quantified the overall environmental impact associated with the entire process of surgical procedures. For each selected article, data extraction was systematically carried out, collecting information on the year of publication, country of publication, medical field, focus of study and environmental impact assessment approach used.

2.2. Scenarios Identification

The results of the literature review made it possible to identify three potential scenarios, which are useful for effectively representing the different situations that require an environmental impact analysis to be undertaken in the operating room. Each scenario differs in terms of the availability of data to be processed and the type of environmental assessment that can be carried out. The aim of these three scenarios is to provide a clear and structured framework for researchers engaged in this type of analysis.

3. LITERATURE REVIEW

3.1. Study Selection

A comprehensive search conducted using the Scopus and PubMed databases identified a total of 277 research articles addressing the environmental consequences of surgical procedures. However, only a small subset of these studies: 17 articles, accounting for just 6 % of the total, specifically focused on conducting an environmental impact assessment related to the surgical process.

3.2. Characteristics of the Included Articles

Baseline characteristics of articles are summarised in Table 1.

The reviewed literature includes 17 papers examining the environmental effects of surgical procedures. 5/17 (29 %) studies are from the United States, 4/17 (24 %) from France, 3/17 (18 %) from the United Kingdom, and 2/17 (12 %) from India. New Zealand and Ireland provide 1/17 (6 %) respectively. This distribution indicates an increasing concern with the environmental consequences of surgery, particularly in industrialised nations, where resources for sophisticated environmental assessments are more accessible.

An examination of publication years reveals a significant rise in focus on the environmental effects of surgery, with 11/17 (65 %) released in the past three years (2021–2024). This trend signifies an increasing worldwide consciousness regarding climate change and the necessity to alleviate the environmental repercussions of healthcare systems.

TABLE 1. BASELINE CHARACTERISTICS OF ARTICLES

Study (yr)		Country	Medical Specialty	Focus of the Study	Environmental impact assessment approach
[19]	Campion *et al.* (2012)	US	Obstetrics and Gynaecology	Vaginal delivery and caesarean birth	Process-based LCA
[20]	Ditac *et al.* (2023)	France	Cardiology	Atrial fibrillation catheter ablation	Eco-audit
[21]	Ferrero *et al.* (2022)	France	Ophthalmology	Cataract surgery	EIO-LCA
[22]	Grinberg *et al.* (2021)	France	Cardiology	Conventional isolated cardiac surgeries	Eco-audit
[23]	Latta *et al.* (2021)	New Zealand	Ophthalmology	Cataract surgery	Carbon footprint
[24]	Namburar *et al.* (2018)	India	Ophthalmology	Glaucoma surgery	Waste audit
[25]	Power B. *et al.* (2021)	Ireland	Ophthalmology	Intravitreal injection	Hybrid LCA
[26]	Power N. *et al.* (2012)	US	General Surgery	Minimally invasive surgery	Carbon footprint and EEIO
[27]	Prakash *et al.* (2023)	UK	Orthopaedics	Primary hip and knee arthroplasty	Waste audit
[28]	Rizan *et al.* (2023)	UK	General Surgery, Orthopaedics, Otolaryngology	Carpal tunnel decompression, inguinal hernia repair, knee arthroplasty, laparoscopic cholecystectomy, tonsillectomy	Waste audit
[29]	Rougereau *et al.* (2024)	France	Orthopaedics	Arthroscopic rotator cuff repair	Waste audit
[30]	Ryan *et al.* (2023)	US	Otolaryngology	Tonsillectomy, adenoidectomy, sept rhinoplasty, endocrine surgery, tympanoplasty, and hearing implantation surgery	Waste audit
[31]	Stall *et al.* (2013)	UK	Orthopaedics	Total knee arthroplasty	Waste audit
[32]	Thiel *et al.* (2015)	US	Obstetrics and Gynaecology	Abdominal, vaginal, laparoscopic, and robotic hysterectomy	Carbon footprint
[33]	Thiel *et al.* (2017)	India	Ophthalmology	Cataract surgery	Process-based LCA
[34]	Woods *et al.* (2015)	US	Obstetrics and Gynaecology	Robotically-assisted laparoscopy, laparoscopy and laparotomy	Carbon footprint and EEIO
[35]	Zhang *et al.* (2023)	US	Orthopaedics General surgery	Carpal tunnel release	Carbon footprint

From a medical speciality viewpoint, ophthalmology represented 35 % (6/17) of the studies, with research exploring procedures such as cataract surgery, intravitreal injections, and glaucoma surgery. Orthopaedic surgery follows with 29 % (5/17), centred on hip and knee arthroplasties, and rotator cuff repairs. Additional disciplines encompass gynaecology and obstetrics (18 %, 3/17), cardiology (12 %, 2/17) otolaryngology and general surgery (24 %, 4/17) which includes tonsillectomies and carpal tunnel decompressions (10, 17).

The utilised methodological approaches exhibit considerable variation. Life Cycle Assessment (LCA) and its derivatives, including Economic Input-Output LCA (EIO-LCA), constitute 24 % (4/17) of the studies employed to evaluate the complete life cycle of surgical resources from “cradle-to-grave”. Carbon Footprint has been utilised in 24 % (4/17) of the investigations to assess CO_2 emissions. Eco-audits, focused on resource impacts, constitute 12 % (2/17) of the research, whereas Waste audits appear as the most prevalent method, representing 29 % (5/17) of the studies.

The investigated papers reveal a considerable variation in approaches to environmental analysis, which vary significantly based on data availability and the processes examined. 65 % (10/17) of the studies examine the implications related to the acquisition of the examined resources, including electricity and natural gas [19]–[23], [25], [26], [28], [29], [32]. Waste management is a crucial subject, addressed in 65 % (11/17) of the enquiries highlighting the increasing necessity for effective and sustainable waste management regulations [19]–[21], [25]–[29], [32], [34], [35].

The chronological and thematic analysis clearly illustrates how the focus on the environmental impact of surgical operations is fast expanding. The growing interest is directly linked to the imperative of tackling climate change and the substantial influence of the healthcare industry. Despite significant advancements, deficiencies persist in methodological standardisation and the lack of uniformity in the factors considered, such as the specific resources consumed, creates challenges for those looking to enter this field. This inconsistency makes it difficult to establish a clear understanding of how to approach environmental assessments, limiting the ability of researchers and practitioners to adopt standard methodologies or draw reliable comparisons across studies.

4. SCENARIOS CONSIDERED

To clearly and effectively delineate the diverse contexts that necessitate an environmental impact analysis in the field of surgery, three potential scenarios have been identified. These scenarios aim to serve as a structured framework for researchers undertaking such analyses, providing a foundation for selecting the most suitable methodology tailored to the desired outcomes and the available data.

To establish the three scenarios clearly and logically, the temporal representation of the material and resource flows needed for a surgical operation was achieved by dividing the process into three distinct phases.

The pre-operative phase focuses on the processes that facilitate the presence of a resource in the operating rooms. Beginning with the extraction of raw materials and natural resources, we progress to the production and transportation of the necessary instrument/substance/machinery to carry out the procedure. During this stage, the energy provision for the facility is also encompassed.

The intra-operative phase refers to the use and depletion of resources specifically within the confines of the operating room. The energy and material flows vary depending on the specific procedure being carried out. Equipment, air conditioning, and lighting are major contributors to energy consumption, as they are necessary to maintain a climate and environment that meet the required hygiene standards. Materials and instruments can be categorised into two main types: disposables and reusables. Disposables are typically placed in designated containers for disposal, while reusable items are processed for recovery. Substances deemed beneficial encompass pharmaceuticals, anaesthetic gases, and disinfectants.

The post-operative phase involves two primary processes for what is removed from the operating room: waste management and reconditioning process. Consequently, the attention is redirected towards the management and disposal of waste and the processes of sterilising and laundering in hospitals. This stage requires a significant allocation of resources, both from the hospital itself and from external facilities.

The three phases impact the utilisation of natural resources and the release of damaging substances into the atmosphere in different ways. The boundaries of the three proposed scenarios are illustrated in Fig. 1, delineating the phases and processes that are considered in each case.

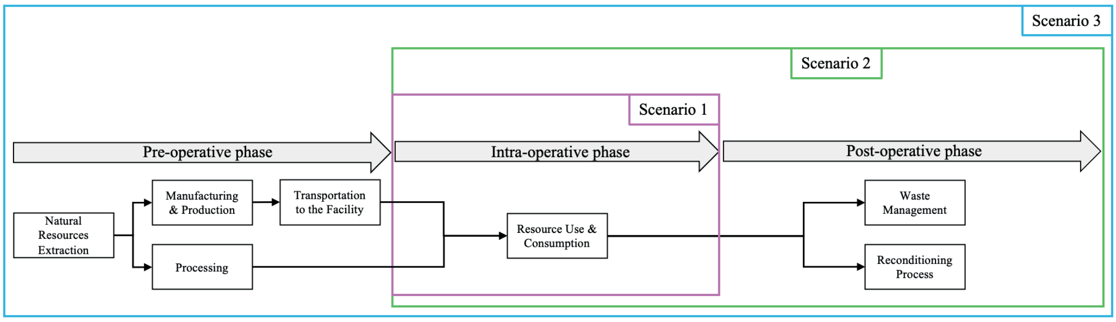


Fig. 1. Phases and processes of surgical operations and boundaries of different scenarios.

4.1. Scenario 1

Scenario 1 outlines a preliminary methodology for assessing the environmental consequences of surgical procedures conducted in the operating rooms. The objective is to offer an initial strategy that can guide the hospital toward a more structured analysis. In this situation, the duration of the surgery establishes the time limit for analysis. The proposed methodology aims to measure the amount of energy and materials used during surgery. Such analysis is highly valuable for comparing various surgical techniques used in performing surgery as it quickly provides a benchmark for comparison with simple data collection.

When there is limited information available on the utilisation of the devices or insufficient data on energy consumption in the operating room, it is possible to quantify the waste generated by conducting a waste audit. While this method of analysis is commonly used, a waste audit provides an even more approximate assessment of the true impact of various techniques because it does not consider a significant portion of consumption factors. In this case, it is crucial to clarify the waste classification policy implemented in the facility where the analysis will take place. The waste classification policy directly affects the quantity of specific waste generated in the operating room. Providing clear and detailed information about where materials are disposed of would enable the comparison of studies conducted in various facilities and countries.

The data collection on the primary factors affecting intra-operative consumption is summarised in Table 2. It is important to acknowledge that this data collection provides a measurement of the resources utilized but does not specify the actual environmental consequences. Nevertheless, it is highly advantageous to easily identify the primary discrepancies between procedures and highlight potential avenues for enhancement.

TABLE 2. PROCESS AND DATA COLLECTION FOR SCENARIO 1 (INTRA-OPERATIVE PHASE)

Phase	Process/Item		Data collection
Intra-operative	Energy and Water	HVAC	Duration of use (h) and energy (kWh)
		Lighting	Duration of use (h) and energy (kWh)
		Medical Equipment	Duration of use (h) and energy (kWh)
		Hot Water	Quantity (m^3)
	Chemicals	Pharmaceuticals	Quantity (mL/mg)
	Materials and Instruments	Disposable devices	Type and quantity (#)
		Reusable devices	Type and quantity (#)
		Linens	Type and quantity (#)
	Waste Audit	Non-recyclables	Quantity (kg)
		Recyclables	Quantity (kg)
		Biohazardous	Quantity (kg)

4.2. Scenario 2

Scenario 2 extends beyond the simple classification and measurement of resources utilised during a surgical procedure. The objective is to comprehend the effects caused by the utilisation of materials in the operating room by expanding the scope of analysis to the post-operative stage. This requires a more structured and complex data collection process compared to Scenario 1. It is important to note that collecting data on post-operative phases allows for the assignment of an emission factor to all the consumed resources in a simple and practical manner, without the need to gather detailed and specific information on every device, material, or substance used during the procedure. In particular, disposable materials and devices, once utilized, inevitably become waste that must be either disposed of or recovered. Therefore, it is sufficient to collect data on the type of waste produced and the applied disposal or recovery method (e.g., incineration, landfill, recycling) to assign the corresponding emission factor.

Emission factors for materials or resources are standardized values that quantify the greenhouse gas emissions (typically expressed in $kgCO_2eq$) associated with a specific quantity of material or resource. These factors are used to estimate the environmental impact of materials and resources in terms of carbon footprint, enabling accurate evaluations and comparisons between products, processes, or sectors. Emission factors for materials or resources are typically provided by international databases (e.g., *Ecoinvent* [36], government reports (e.g., UK GHG Conversion Factors [37], or published LCA studies.

Emission factors for energy consumption are closely linked to the country's energy mix, which reflects the proportions of energy sources like fossil fuels, nuclear, and renewables. Regions with higher reliance on coal or natural gas will have greater emission factors than those using predominantly renewable energy, making it essential to use location-specific data.

In contrast, emission factors for waste depend on the type of waste and its disposal method. Non-recyclable, recyclable, and biohazardous waste have different impacts based on management practices. For example, incineration generates higher emissions than recycling, while landfilling produces methane from organic waste decomposition.

Table 3 provides a concise overview of the factors that need to be considered and examples of emission factors from UK GHG Conversion Factor report are also given. This simplified approach enables the effective quantification of the environmental impact of post-use resources, maintaining analysis precision without requiring an excessive level of detail.

TABLE 3. PROCESS AND DATA COLLECTION FOR SCENARIO 2 (INTRA E POST-OPERATIVE PHASES)

Phase	Process/Item		Data collection	Emission factor
Intra-operative	Energy and Water	HVAC	Duration of use (h) and energy (kWh)	Electricity 0.207 $kgCO_2eq/kWh$ Natural gas 0.183 $kgCO_2eq/kWh$ Water supply 0.177 $kgCO_2eq/m^3$
		Lighting	Duration of use (h) and energy (kWh)	
		Medical Equipment	Duration of use (h) and energy (kWh)	
		Hot Water	Quantity (m^3)	
	Chemicals	Pharmaceuticals	Chemical composition and quantity (mL/mg)	e.g., Sevoflurane 0.130 $kgCO_2eq/mL$
	Materials and Instruments	Disposable devices	Type and quantity (#)	Linked to Waste Management
		Reusable devices	Type and quantity (#)	Linked to Reconditioning Process
		Linens	Type and quantity (#)	Linked to Reconditioning Process
	Waste Audit	Non-recyclables	Quantity (kg) and disposal process	Linked to Waste Management
		Recyclables	Quantity (kg) and disposal process	
		Biohazardous	Quantity (kg) and disposal process	
Post-operative	Waste Management	Landfill	Type of waste and quantity (kg)	Non-recyclables landfill 520.33 $kgCO_2eq/kg$
		Incineration	Type of waste and quantity (kg)	Non-recyclables incineration 21.281 $kgCO_2eq/kg$
		Recycling	Type of waste and quantity (kg)	Plastic recycling 21.281 $kgCO_2eq/kg$
	Reconditioning Process	Laundry	1 cycle duration (h), power (kWh) and quantity of water (m^3)	Electricity 0.207 $kgCO_2eq/kWh$ Natural gas 0.183 $kgCO_2eq/kWh$ Water supply 0.177 $kgCO_2eq/m^3$
		Sterilization	1 cycle duration (h), power (kWh) and quantity of water (m^3)	

4.3. Scenario 3

The goal is to conduct a comprehensive LCA of the entire surgical process. The ISO 14040 series of standards is the internationally recognised reference for conducting LCA studies. The LCA framework consists of four primary steps:

– The objectives and scope of the study include the definition of the products and processes under investigation, the functional unit, system boundaries, assumptions, and limitations, intended application, rationale, and target audience of the study.

– Inventory analysis (LCI) involves the collection and calculation of data to measure the incoming and outgoing flows of a product system, based on the defined objective and scope.
– Life Cycle Impact Assessment (LCIA) is a process that seeks to measure the magnitude of possible environmental effects by utilising the findings of life cycle inventory analysis.
– Interpretation refers to a methodical procedure that involves identifying, assessing, confirming, and evaluating the outcomes of the inventory and impact assessment stages. The goal is to present these findings in a manner that fulfils the requirements of the stated objective and scope and to derive conclusions and recommendations based on them.

To achieve a comprehensive LCA of surgery, it is essential to supplement the information acquired during the intra- and post-operative phases with accurate data on the extraction, manufacturing, and processing cycles of all resources utilised in the operating theatre.

Fig. 2 presents a schematic representation of the resource flows and processes throughout the three stages that need to be considered. The emphasis has been placed on variables that can be measured, compared, and predicted together with a certain level of accuracy. The objective is to assess consumption factors that follow clearly defined cycles while excluding variables that are beyond the control or not directly linked to the surgical procedure (such as patient and medical staff transportation within the hospital).

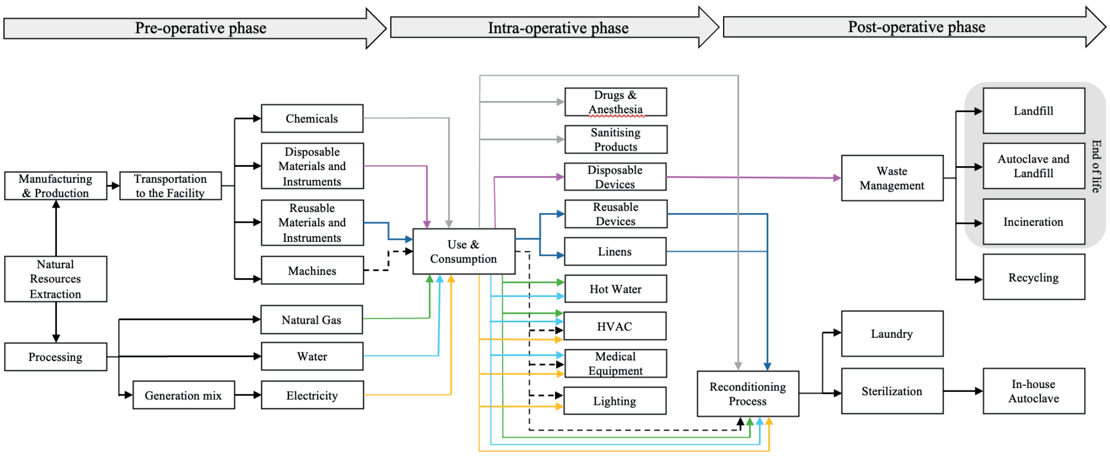


Fig. 2. Life Cycle Assessment main flowchart of resource consumption.

The challenge of conducting a LCA on a process derives from the requirement for precise data, the extensive amount of data that needs to be gathered, and the analysis of the environmental and human health effects of all factors considered [38]. To facilitate this intricate process, the use of specialized LCA software can be invaluable. Tools such as *SimaPro* [39] and *OpenLCA* allow for the systematic analysis of data, from resource extraction to waste management, and incorporate extensive libraries of emission factors and environmental impact categories. However, their effective use requires specialized skills, such as proficiency in data interpretation, environmental modelling, and an understanding of life cycle inventory data. For instance, setting system boundaries, integrating custom datasets, and interpreting the outputs in the context of healthcare require a multidisciplinary approach.

The adoption of such software can significantly enhance the accuracy and depth of LCA studies, enabling researchers to uncover insights that would be difficult to achieve through manual calculations alone. However, institutions embarking on such assessments should invest in training personnel or collaborating with specialists to maximize the potential of these tools.

The integration of life cycle assessment with the health industry is a significant challenge. Nevertheless, we believe that the development of the diagram depicted in Fig. 1 will be useful as a valuable reference and support for researchers seeking to conduct a life cycle analysis of a surgical procedure.

5. DISCUSSION AND CONCLUSION

Analysing the environmental impact of surgical procedures serves several critical purposes. It quantifies key environmental effects, such as carbon emissions, energy consumption, and resource use, while identifying opportunities for optimization. For instance, adopting reusable instruments and refining workflows can significantly reduce the ecological footprint of surgeries. This type of analysis not only raises awareness among healthcare professionals and patients but also supports compliance with sustainability regulations and fosters the development of eco-friendly surgical technologies. Additionally, it establishes measurable benchmarks for continuous improvement, aligning healthcare practices with stakeholder expectations and corporate social responsibility goals.

However, the inherent complexity of surgical procedures and associated challenges in data collection present significant barriers to effective analysis. Issues such as the aggregation of diverse resources, resistance from staff, and privacy concerns complicate the process. Addressing these challenges requires a multidisciplinary approach that combines expertise from healthcare, environmental science, and data management. Advanced technologies and tools are also essential to ensure accurate and actionable insights, allowing for more effective assessments and improvements.

Recognizing these challenges, this study developed a structured framework for assessing the environmental impact of surgical procedures. The framework is divided into three scenarios of increasing complexity, aimed at analysing resource use and material flows. The results highlight significant variability in resource consumption, waste management practices, and methodological approaches, emphasizing the urgent need for standardization. Without uniform assessment methods, it remains difficult to establish common benchmarks or draw reliable comparisons across studies.

The proposed three-scenario framework marks an important step toward promoting sustainability in operating rooms. Scenario 1 focuses on intraoperative resource consumption, providing a simple yet practical method for comparing different surgical techniques. While this approach offers immediate insights, its narrow scope, limited to intraoperative time, restricts its applicability for more comprehensive environmental evaluations. Scenario 2 extends the analysis to include post-operative phases, such as waste management and reconditioning processes, introducing emission factors to quantify the ecological impact of consumed resources. This broader perspective facilitates meaningful cross-sector comparisons but may still oversimplify the full environmental impact of surgical procedures. Finally, Scenario 3 adopts a comprehensive LCA approach, considering all stages from raw material extraction to end-of-life management. While this method delivers detailed and holistic insights, its implementation requires extensive data collection and interdisciplinary collaboration, making it resource-intensive and complex.

Future advancements in these methodologies should focus on establishing centralized databases of emission factors tailored to surgical procedures, which would enhance calculation accuracy and enable consistent assessments across studies. The use of specialized software tools such as *SimaPro* and *OpenLCA* can further streamline data analysis and promote more sophisticated approaches. However, leveraging these tools effectively requires expertise in environmental modelling and data interpretation, underscoring the need for collaboration between healthcare practitioners and environmental experts.

In conclusion, the proposed framework provides a robust foundation for understanding and mitigating the environmental impact of surgical procedures. Its implementation requires sustained efforts to improve data collection and analysis while fostering interdisciplinary collaboration and adopting advanced technologies. This framework not only has the potential to improve current practices but also sets the stage for establishing new standards for environmental sustainability in healthcare. Advancing this field represents a necessary and impactful response to the growing global awareness of climate change and highlights the healthcare sector's pivotal role in addressing this pressing challenge.

Study Limitations

The patient's journey through the healthcare system is not fully covered by this study. A comprehensive investigation of critical phases, such as pre-operative assessments, diagnostics, hospital stay, and post-operative rehabilitation therapies, has not been included in this analysis, even if we are fully aware that these elements may represent an important portion of the overall environmental impact of healthcare [40]. The environmental impact of surgical operations extends far beyond the walls of the operating theatre, reflecting a treatment pathway that includes numerous services and procedures. To obtain a more thorough evaluation of the environmental consequences, future studies should integrate these factors into the entire life cycle of surgical care. This would result in a more extensive and detailed analysis of the environmental impact caused by these procedures.

REFERENCES

[1] Karliner J., Slotterback S., R Boyd., Ashby B., Steele K. Healthcare's climate footprint: How the health sector contributes to the global climate crisis and opportunities for action. *European Journal of Public Health* 2020:30. https://doi.org/10.1093/eurpub/ckaa165.843

[2] Sustainable Development Unit, Public Health England, NHS England. Reducing the use of natural resources in health and social care. Cambridge: Sustainable Development Unit [Online]. [Accessed 30.04.2020]. Available: https://www.sduhealth.org.uk/policy-strategy/reporting/sustainable-development-in-health-and-care-report2018.aspx

[3] Lee B.-K., Ellenbecker M. J., Moure-Eraso R. Analyses of the recycling potential of medical plastic wastes. *Waste Management* 2002:22(5):461–470. https://doi.org/10.1016/S0956-053X(02)00006-5

[4] Deepak A., Sharma V., Kumar D. Life cycle assessment of biomedical waste management for reduced environmental impacts. *J Cleaner Production* 2022:349:131376. https://doi.org/10.1016/j.jclepro.2022.131376

[5] Rammelkamp Z., Dirnberger J., Johnson G., Waisbren S. An Audit of All Waste Leaving the Operating Room: Can the Surgical Suite Be More Environmentally Sustainable? *World Medical and Health Policy* 2021:13(1):126–136. https://doi.org/10.1002/wmh3.397

[6] Kooner S. *et al.* Waste and recycling among orthopedic subspecialties. *Canadian Journal of Surgery* 2020:63(3):E278–E283. https://doi.org/10.1503/cjs.018018

[7] Sullivan G. A., Reiter A. J., Hu A., Shah A. N., Dsida R., Raval M. V. Operating Room Recycling: Opportunities to Reduce Carbon Emissions Without Increases in Cost. *Journal Pediatric Surgery* 2023:58(11):2187–2191. https://doi.org/10.1016/j.jpedsurg.2023.04.011

[8] Lee R. J., Mears S. C. Reducing and Recycling in Joint Arthroplasty. *Journal of Arthroplasty* 2012:27(10):1757–1760. https://doi.org/10.1016/j.arth.2012.04.020

[9] Romano L., Giuliani A., Muselli M., Lupi E., Vistoli F. Toward Environmentally sustainable surgery: Waste recycling in general surgery operating room. Preliminary cognitive audit. *World Journal of Surgery* 2024:48(11):2637–2643. https://doi.org/10.1002/wjs.12237
[10] Zlaugotne B., Pubule J., Gusca J., Kalnins S. N. Quantitative and Qualitative Assessment of Healthcare Waste and Resource Potential Assessment. *Environmental and Climate Technologies* 2022:26(1):64–74. https://doi.org/10.2478/rtuect-2022-0006
[11] Mikusinska M. Comparative Life Cycle Assessment of Surgical Scrub Suits: The Case of Reusable and Disposable Scrubs used in Swedish Healthcare. KTH Royal Institute of Technology, Stocholm, 2012.
[12] Campion N., Thiel C. L., Woods N. C., Swanzy L., Landis A. E., Bilec M. M. Sustainable healthcare and environmental life-cycle impacts of disposable supplies: A focus on disposable custom packs. *Journal of Cleaner Production* 2015:94:46–55. https://doi.org/10.1016/j.jclepro.2015.01.076
[13] Boberg L., Singh J., Montgomery A., Bentzer P. Environmental impact of single-use, reusable, and mixed trocar systems used for laparoscopic cholecystectomies. *PLoS One* 2022:17. https://doi.org/10.1371/journal.pone.0271601
[14] Cohen E. S. *et al*. Environmental Impact Assessment of Reusable and Disposable Surgical Head Covers. *JAMA Surgery* 2023:158(11):1216–1217. https://doi.org/10.1001/jamasurg.2023.3863
[15] Le N. N. T., Hernandez L. V., Vakil N., Guda N., Patnode C., Jolliet O. Environmental and health outcomes of single-use versus reusable duodenoscopes. *Gastrointestinal Endoscopy* 2022:96(6):1002–1008. https://doi.org/10.1016/j.gie.2022.06.014
[16] Eckelman M., Mosher M., Gonzalez A., Sherman J. Comparative life cycle assessment of disposable and reusable laryngeal mask airways. *Anesthesia and Analgesia* 2012:114(5):1067–1072. https://doi.org/10.1213/ANE.0b013e31824f6959
[17] Vozzola E., Overcash M., Griffing E. An Environmental Analysis of Reusable and Disposable Surgical Gowns. *AORN Journal* 2020:111(3):315–325. https://doi.org/10.1002/aorn.12885
[18] MacNeill A. J., Lillywhite R., Brown C. J. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *The Lancet Planet Health* 2017:1(9):e360–367. https://doi.org/10.1016/S2542-5196(17)30162-6
[19] Campion N., Thiel C. L., DeBlois J., Woods N. C., Landis A. E., Bilec M. M. Life cycle assessment perspectives on delivering an infant in the US. *Science of the Total Environment* 2012:425:191–198. https://doi.org/10.1016/j.scitotenv.2012.03.006
[20] Ditac G. *et al*. Carbon footprint of atrial fibrillation catheter ablation. *EP Europace* 2023:25(2):331–340. https://doi.org/10.1093/europace/euac160
[21] Ferrero A., Thouvenin R., Hoogewoud F., Marcireau I., Offret O., Louison P., et al. The carbon footprint of cataract surgery in a French University Hospital. *Journal Français d'Ophtalmologie* 2021:45(1):57–64. https://doi.org/10.1016/j.jfo.2021.08.004
[22] Grinberg D. *et al*. Eco-audit of conventional heart surgery procedures. *European Journal of Cardio-Thoracic Surgery* 2021:60(6):1325–1331. https://doi.org/10.1093/ejcts/ezab320
[23] Latta M., Shaw C., Gale J. The carbon footprint of cataract surgery in Wellington. *The New Zealand medical Journal* 2021:134:1541.
[24] Namburar S., Pillai M., Varghese G., Thiel C., Robin A. L. Waste generated during glaucoma surgery: A comparison of two global facilities. *American Journal of Ophthalmology Case Reports* 2018:12:87–90. https://doi.org/10.1016/j.ajoc.2018.10.002
[25] Power B., Brady R., Connell P. Analyzing the carbon footprint of an intravitreal injection. *Journal of Ophthalmic and Vision Research* 2021:16(3):367–376. https://doi.org/10.18502/jovr.v16i3.9433
[26] Power N. E., Silberstein J. L., Ghoneim T. P., Guillonneau B., Touijer K. A. Environmental impact of minimally invasive surgery in the United States: An estimate of the carbon dioxide footprint. *Journal of Endourology* 2012:26(12):1639–1644. https://doi.org/10.1089/end.2012.0298
[27] Prakash R., Abid H., Wasim A., Sharma A., Agrawal Y. The Environmental Impact and Sustainability of Total Hip and Knee Arthroplasty. *Arthroplasty Today* 2023:24. https://doi.org/10.1016/j.artd.2023.101254
[28] Rizan C., Lillywhite R., Reed M., Bhutta M. F. The carbon footprint of products used in five common surgical operations: identifying contributing products and processes. *Journal of the Royal Society of Medicine* 2023:116(6):199–213. https://doi.org/10.1177/01410768231166135
[29] Rougereau G., Chatelain L., Zadegan F., Conso C. Estimation of the carbon footprint of arthroscopic rotator cuff repairs in France. *Orthopaedics and Traumatology: Surgery and Research* 2024:110(1):103755. https://doi.org/10.1016/j.otsr.2023.103755
[30] Ryan M. T., Malmrose J., Riley C. A., Tolisano A. M. Operating Room Waste Generated Across Otolaryngology Cases. *Military Medicine* 2023:188(7–8):E1697–E1700. https://doi.org/10.1093/milmed/usab548
[31] Stall N. M., Kagoma Y. K., Bondy J. N., Naudie D. Surgical waste audit of 5 total knee arthroplasties. *Canadian Journal of Surgery* 2013:56(2):97–102. https://doi.org/10.1503/cjs.015711
[32] Thiel C. L., Eckelman M., Guido R., Huddleston M., Landis A. E., Sherman J., et al. Environmental impacts of surgical procedures: Life cycle assessment of hysterectomy in the United States. *Environmental Science and Technology* 2015:49(3):1779–1786. https://doi.org/10.1021/es504719g

[33] Thiel C. L. *et al.* Cataract surgery and environmental sustainability: Waste and lifecycle assessment of phacoemulsification at a private healthcare facility. *Journal of Cataract and Refractive Surgery* 2017:43(11):1391–1398. https://doi.org/10.1016/j.jcrs.2017.08.017
[34] Woods D. L., McAndrew T., Nevadunsky N., Hou J. Y., Goldberg G., Kuo D. Y.-S., Isani S. Carbon footprint of robotically-assisted laparoscopy, laparoscopy and laparotomy: A comparison. *International Journal of Medical Robotics and Computer Assisted Surgery*. 2015:11(4):406–412. https://doi.org/10.1002/rcs.1640
[35] Zhang D., Dyer G. S. M., Blazar P., Earp B. E. The Environmental Impact of Open Versus Endoscopic Carpal Tunnel Release. *Journal of Hand Surgery* 2023:48(1):46–52. https://doi.org/10.1016/j.jhsa.2021.12.003
[36] Wernet G., Bauer C., Steubing B., Reinhard J., Moreno-Ruiz E., Weidema B. The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* 2016:21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8
[37] UK Government GHG Conversion Factors for Company Reporting. *Department for Environment, Food and Rural Affairs/ Department for Business, Energy & Industrial Strategy, London*, 2023 [Online]. [Accessed 16.08.2024]. Available: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
[38] Heijungs R. Ecodesign – Carbon Footprint – Life Cycle Assessment - Life Cycle Sustainability Analysis. A Flexible Framework for a Continuum of Tools. *Environmental and Climate Technologies* 2010:4(1):42–46. https://doi.org/10.2478/v10145-010-0016-5
[39] SimaPro: LCA Software 2023, *PRé Sustainability* [Online]. [Accessed 16.08.2024]. Available: https://simapro.com/
[40] Roletto A., Savio A., Marchi B., Zanoni S. Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging. *Environmental and Climate Technologies* 2024:28(1):303–311. https://doi.org/10.2478/rtuect-2024-0024

PAPER 3

Greening Healthcare: An Approach to Assess the Environmental Impact of Medical Procedures

Anna Savio*, Andrea Roletto*, Beatrice Marchi*, Giuseppe Milano, Simone Zanoni*****

**Department of Mechanical and Industrial Engineering, University of Brescia, Brescia, Italy (anna.savio@unibs.it, andrea.roletto@unibs.it, beatrice.marchi@unibs.it)*
***Department of Medical and Surgical Specialties, Radiological Sciences, and Public Health, University of Brescia, Brescia, Italy (giuseppe.milano@unibs.it)*
****Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy (simone.zanoni@unibs.it)*

Abstract: There is an increasing awareness of how human activities, such as waste generation, resource consumption, and greenhouse gas emissions, affect the environment. Among these activities, healthcare facilities stand out as significant consumers of resources and generators of waste, leading to growing attention. However, transitioning to more sustainable practices necessitates a detailed comprehension of the factors influencing resource consumption and waste generation to facilitate the creation of effective, enduring solutions. The medical care process can be complex and multifaceted. Starting from an initial diagnosis, a patient may go through various phases, such as surgical interventions and recovery periods, each involving specific consumption and impacts. This study proposes a model for schematizing the care process that highlights the interconnections between the various phases of care. This model serves not only to visualise the real journey of the patient but also to investigate the impact of procedures, assessing both environmental effects and effects on patient well-being. In this context, the patient is not just a passive recipient of care but plays an active role in the healing process. Adopting a holistic approach thus allows for the integration of considerations on resource consumption with the effectiveness of treatments and patient outcomes, creating a comprehensive view that embraces both environmental and social sustainability. Exploring these themes underscores the urgency of healthcare policies that holistically promote sustainability, addressing environmental challenges without neglecting the human and clinical aspects of the healthcare system. Through the promotion of sustainable practices, it is possible not only to reduce the environmental impact of healthcare facilities but also to improve the quality and efficacy of the care provided. Healthcare providers can establish a healing environment that promotes the well-being of both the planet and individuals by incorporating sustainability into their daily operations.

Keywords: Healthcare Sustainability; Care Process Mapping; Environmental Impact; Patient Well-Being.

1. Introduction

The healthcare sector is an essential component of the general public's well-being. Nonetheless, it is at the core of a convoluted paradox: maintaining health comes at a significant environmental cost. Hospitals are held accountable for their substantial ecological footprint, second only to the hotel industry in terms of energy and resource consumption (Karliner et al., 2019). They are in a unique position because of their continuous and vital operations: they must be ready to protect people's health at all times, but they also urgently need to reevaluate their methods in light of sustainability. One of the biggest optimisation challenges the sector faces is the choice to maintain medical devices in a state of stand-by, which results in significant energy expenditure (Benmamoun et al., 2023). This choice is made to achieve maximum operational efficiency. The inevitable and unquestionable need to adhere to hygienic standards also results in significant use of chemicals and disposable materials (Campion et al., 2015; Snigdha et al., 2023). Although necessary for infection control, these become special/hazardous waste, accounting for most of the sector's waste production. This phenomenon is especially noticeable in operating rooms, which account for roughly 20% to 30% of all hospital waste (MacNeill et al., 2017). Research on how medical care affects the environment primarily concentrates on pinpointing the areas or systems that use the greatest amounts of energy and materials to identify hotspots and offer suggestions for improvement (Keller et al., 2021). In particular, the patient is thought of as a passive beneficiary of care when evaluating the ecological effects of medical procedures. Sustainability is primarily evaluated from an environmental standpoint, which is also intimately related to the healthcare facility's finances: cutting back on resource consumption will almost certainly have a positive financial effect. Indeed, multiple studies demonstrate that the adoption of environmental sustainability strategies not only has positive effects on the environment but also leads to cost reduction (McAleese et al., 2023; Thiel et al., 2019). However, it is restrictive and reductive to conduct sustainability analyses in the healthcare industry, whose main goal is to protect people's health, without considering how medical procedures affect patients' quality of life. Evaluating optimisation strategies on factors that impact both human well-being and the environment is made possible by taking a holistic approach to the care process. This study suggests using an innovative model to assess medical procedures, incorporating them into the patient's care process, and trying to represent the pathway to recovery in a clear, sequential manner. With the help of this method, it is possible to comprehend that each interaction with the patient, from the initial diagnostic appointments until their complete recovery, represents not just a time for medical intervention but also a crucial stage in a longer process of transformation. Every medical procedure affects the patient's health and well-being in addition to the environment. Careful examination of the various stages of the care process can show how sustainable practices can be successfully incorporated, helping to significantly reduce the ecological footprint without compromising the standard of care. The existing literature on this subject is extremely limited, and to the best of our knowledge, no current study adopts the comprehensive approach that is critically needed in the health sector. This study aims to address this significant gap by proposing a perspective that encompasses both an analysis focused on maximizing patient well-being and an analysis dedicated to minimizing environmental impacts. Adopting a holistic approach is essential because the goals of innovation in the medical field often neglect other vital factors, such as the reduction of resource consumption and the mitigation of harmful emissions. By integrating these considerations, our approach ensures that advancements in medical procedures not only enhance patient outcomes but also promote environmental sustainability. The article begins by outlining a standardized care process, divided into several distinct phases, each emphasizing crucial medical activities. It then explores the significant social and environmental impacts of these medical procedures, stressing the importance of incorporating patient quality of life into assessments of environmental sustainability.

2. Methodology

The methodology is divided into two stages. First, an analysis of the existing literature was conducted to establish a foundation for scientific advancement. This phase highlighted that multiple studies investigate the issue of environmental sustainability in the healthcare industry, with a specific focus on resource consumption. These studies highlight the operating theatre as the area with the highest level of wasteful resource consumption (MacNeill et al., 2017).

Furthermore, in many cases is crucial to determine which technique is the most sustainable due to the possibility of accomplishing the same operation using different techniques that require different surgical time and a different number of resources, such as endoscopic surgery or robot-assisted surgery (Campion et al., 2012; Thiel et al., 2018; Zhang et al., 2023). It is important to note that carrying out a surgical procedure entails a set of pre- and post-operative activities that vary depending on the specific type of operation and impact the utilisation of resources. Also, the type of anaesthesia given to the patient has a significant impact on the overall environmental impact of a surgical procedure. Recent research indicates that the choice of anaesthetic gas has a significant impact on total GHG emissions into the atmosphere: desflurane, which is still widely used in medicine, is 20 times more pollutant than sevoflurane and isoflurane (Sherman et al., 2012). To accurately compare various surgical procedures, it is

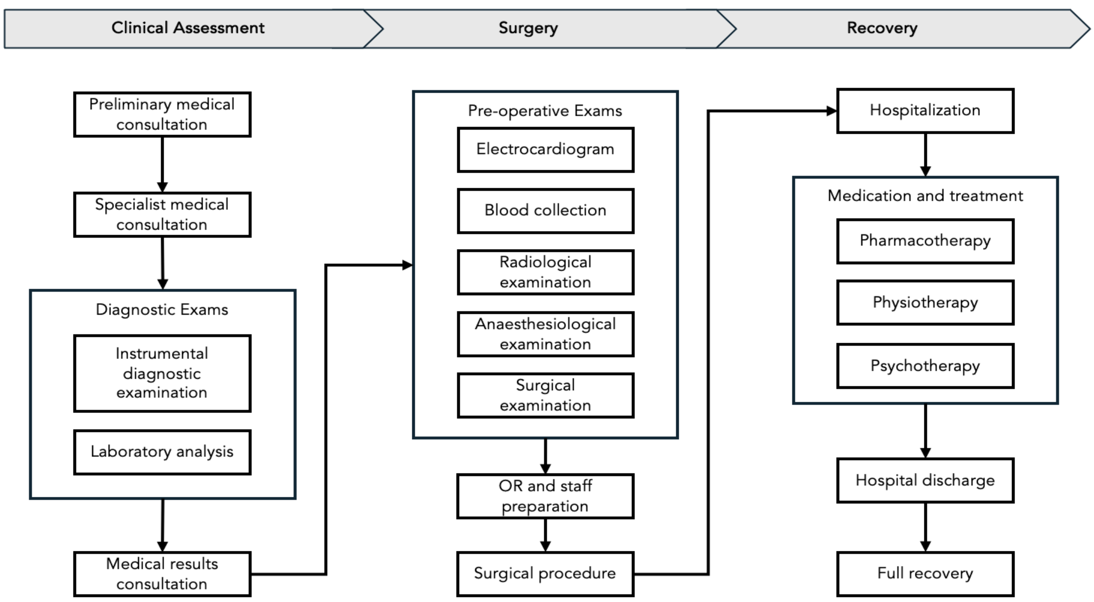


Figure 1: Generic Care Process Map

essential to employ a methodology that considers the complete care process faced by the patient.

Secondly, the study proposes a method for identifying the activities that comprise the care process for a patient undergoing surgery, with an emphasis on the sequential identification of the stages involved in achieving well-being. Three fundamental temporal phases were identified: clinical assessment, surgery, and recovery. Each of them is associated with several activities. By extending the research boundaries to all activities before and after surgery, it is possible to evaluate, in parallel with the environmental analysis, a series of factors affecting the patient's state of well-being, considering both the approach to surgery and the rehabilitation process. In this way, it is possible to place not only the environmental but also the social impact at the centre of the debate. Both impacts are part of the concept of sustainability, which complements the primary aim of healthcare: to improve people's health, effectively and efficiently.

3. Care Process Mapping

The different phases of the care process were subdivided and summarised using a logical map of activities, as shown in Figure 1.

The diagram illustrates the activities sequentially, simplifying the patient's journey to recovery to the greatest extent possible. The mapping should function as a reference for identifying the specific pathway experienced by the patient.

3.1 Clinical Assessment

During this phase, the hospital carries out activities aimed at providing the patient with an accurate diagnosis. This involves determining the location and nature of the health problem by assessing symptoms and the patient's physical condition. The primary activities include:

- Medical consultations: involve patients going to a healthcare facility to consult medical specialists to determine the cause of their symptoms or to undergo routine checkups.
- Diagnostic examinations: following the medical instructions, the patient may need to undergo a range of diagnostic instrumental examinations (such as radiology, nuclear medicine, echography, electrocardiogram, etc.) and laboratory tests to confirm the patient's condition and identify the location of the illness.

3.2 Surgery

Surgery activities are categorised into two separate stages:

- Pre-operative exams: further diagnostic examinations are conducted to assess the patient's eligibility for the surgery. After confirming the patient's condition, the medical team arranges the operating room, and the hospital staff gets ready for the surgical procedure.
- Surgical procedure: it includes the precise duration of the surgery, starting from the moment the patient enters the operating room until the patient's departure. The instruments, equipment, supplies, duration, and operators vary significantly based on the specific surgery being conducted.

3.3 Recovery

During this phase, the activities are focused on returning the patient to a condition of optimal physical and mental health. The patient who has received surgical intervention will subsequently experience a period of hospitalisation of varying duration and will be required to undergo specific treatments, including physical, pharmacological, and psychotherapeutic interventions. After being released from the hospital, he will go through a period to reach a full recovery either at home or in specialised clinics.

4. Discussion

The purpose of schematizing the patient care process flow is to expand the application of analysing the environmental impact associated with medical procedures. Every stage of the care process involves the proper utilisation of resources, leading to the release of pollutants and the generation of waste. These processes can be associated with related greenhouse gas emissions, which can be categorised according to the activity carried out. According to the Greenhouse Gas Protocol (GHGP), the three categories into which to classify emissions according to their origin are: Scope 1 for "Direct GHG emissions"; Scope 2 for "Electricity indirect GHG emissions"; and Scope 3 for "Other indirect GHG emissions" (Ranganathan et al, 2004). This subdivision helps to understand the nature of the environmental impact of hospital activities, and which of them form part of the patient care pathway. In particular, the processes with the greatest environmental impact associated with hospital activities all fall under Scope 2 (Health Care Without Harm, 2019). Dividing the care process into time phases (clinical assessment, surgery, and recovery) helps identify the interconnected and essential activities involved in a patient's rehabilitation.

Clinical assessment includes diagnostic activities, of which diagnostic imaging covers a large part of the health care activities that a patient receives in his or her medical care. The energy consumption of imaging equipment has a significant impact on the environmental footprint of healthcare facilities. Equipment such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and Positron Emission Tomography (PET) account for approximately 10% of a hospital's energy consumption. (Picano et al, 2022). In addition, diagnostic imaging activities also result in the use of a considerable amount of consumable material, which increases the amount of waste produced by the hospital (McAlister et al, 2022). A careful analysis of this essential phase in the patient care process therefore appears necessary, considering all the phases that, within a structured model, prove to be interconnected with the other phases of the patient care pathway.

The surgical procedure is considered the focal point of the treatment process, as the literature examining the environmental consequences of these procedures raises inquiries about what should be the beginning and conclusion points for assessments. Various disparities exist in the studies that conduct these types of assessments, in which research boundaries depend on distinct objectives and the feasibility of data collection. The article presents an innovative perspective in which the patient's care can be seen as a transformative procedure that not only aids healing but also actively engages the patient. Undoubtedly, he is not simply a passive recipient of treatment, but an active participant in his process of care. By adopting this analytical perspective, it is possible not only to improve current practices but also to innovate responsibly in the medical field, considering the environmental impact and the overall well-being of the patient. Within the assessment of environmental impact in medical practices, it is crucial to also extend the investigation to factors that influence the overall physical and mental condition of the patient. This approach aligns with the concept of social sustainability, which recognises the patient not only as a beneficiary of medical care, but also as an integral part of a broader system that includes his or her quality of life. Consider endoscopic surgery as an example: minimally invasive surgery, by definition, provides multiple benefits compared to conventional surgical methods.

Furthermore, the utilisation of advanced imaging systems not only enhances the accuracy of the procedure but also minimises blood loss during the operation. The advantages of endoscopic surgery primarily manifest on the patient's side, as it entails smaller incisions that minimise tissue trauma and the likelihood of infection. Consequently, there is a reduced requirement for pain-relieving medications and the resulting scars are less noticeable. Patients typically undergo a more rapid recovery, enabling faster restoration of daily activities and a reduced duration of hospitalisation, resulting in decreased financial and resource costs for the hospital. Nevertheless, when examining consumption during operation, the utilisation of endoscopic techniques leads to a more significant ecological footprint compared to conventional techniques (Campion et al., 2012; Zhang et al., 2023). The primary reason for this is the employment of sophisticated instruments and machinery, as well as the requirement for additional time to execute the procedure.

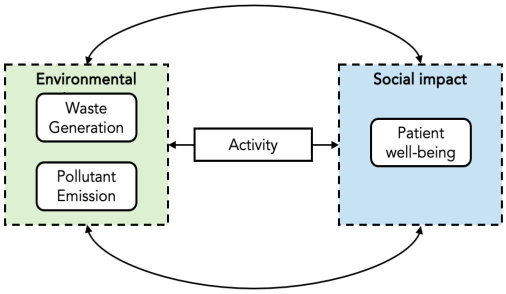


Figure 2: Environmental and Social Impact of Medical Activity

Therefore, simply evaluating the environmental consequences of a specific surgical procedure will not result in comprehensive conclusions that help determine the most efficient technique to use. To ensure proper consideration, it is crucial to give equal importance to the effect of each activity on both the environment and the well-being of the patient (Fig.2).

Key determinants that can influence the patient's overall well-being during the care process include:

- Length of hospital stay: prolonged periods of hospitalisation can negatively affect the patient's mental health and increase the risk of infection.
- Total recovery time: the length of recovery affects the patient's daily life and ability to return to normal activities. A faster and more effective recovery has a positive impact on the patient's perception of the quality of care received.
- Pharmacological treatments: the side effects of drugs can impair the patient's quality of life. The choice of treatments with fewer adverse effects or the use of innovative therapies can significantly improve the patient's well-being.
- Effectiveness of treatment: effective treatment not only cures the disease but also improves the patient's mood and boosts his or her confidence.

In addition to these, other factors such as emotional support during treatment, the accessibility and quality of information provided to the patient, and the patient's involvement in treatment decisions play a key role in his or her recovery and overall well-being. It is essential that, when analysing the sustainability of treatment processes, not only the environmental effects but also the impacts on the patient's well-being are disclosed. This means transparently reporting the results of treatment effectiveness, side effects, recovery times, and any other factors that may affect the patient's quality of life. This not only assists patients in making well-informed decisions but also motivates healthcare institutions to consistently enhance care protocols to achieve a balance between treatment effectiveness and reducing inconvenience to the patient's life. Incorporating these measurements into the concept of social sustainability within the healthcare sector not only enriches the understanding of the overall impact of medical care but also promotes a holistic approach that evaluates treatment success not only in terms of medical outcomes but also in terms of improved quality of life and patient well-being.

5. Conclusions

The proposed innovative method of analysis that emerges from this study emphasises the need to evaluate each phase of the patient care pathway under the lens of sustainability. Such a model proposes to examine the interactions and mutual influence between the various phases, intending to identify points of inefficiency and outline opportunities for improvement. This method would not only facilitate the identification of strategies to minimise environmental impact but also provide the tools to assess the operational efficiency of healthcare facilities and the overall well-being of the patient. It is essential to promote medical practice that is oriented towards sustainability, not only in ecological terms but also in human/social terms, recognising that the health of the patient and that of the environment are intrinsically linked.

6. Study Limitations

The model proposed in the study provides a streamlined visualization of the essential steps in a patient's recovery pathway. However, it is important to note that not every factor influencing the patient during the care process is examined by this model. In practice, each activity within the care cycle may repeat multiple times until the desired medical outcome is achieved. The generic care process can be optimized by analyzing the probability of each activity occurring, allowing for a revision and improvement of the process's logical map. This cyclical nature of medical interventions reflects the complexities and iterative adjustments often required in personalized care plans. Moreover, while the study emphasizes the importance of integrating each assessment with social considerations, particularly concerning the patient's well-being, it stops short of delving into the various methods available for assessing environmental impacts in healthcare settings. A comprehensive approach would benefit from including a broader range of environmental assessment techniques, such as Life Cycle Assessment (LCA), which can systematically and carefully examine multiple impacts associated with all stages of a product's life from cradle to grave.

References

Benmamoun, Z., Fethallah, W., Bouazza, S., Abdo, A. A., Serrou, D., & Benchekroun, H. (2023). A framework for sustainability evaluation and improvement of radiology service. *Journal of Cleaner Production*, *401*.

Campion, N., Thiel, C. L., DeBlois, J., Woods, N. C., Landis, A. E., & Bilec, M. M. (2012). Life cycle assessment perspectives on delivering an infant in the US. *Science of the Total Environment*, *425*, 191–198.

Campion, N., Thiel, C. L., Woods, N. C., Swanzy, L., Landis, A. E., & Bilec, M. M. (2015). Sustainable healthcare and environmental life-cycle impacts of disposable supplies: A focus on disposable custom packs. *Journal of Cleaner Production*, *94*, 46–55.

Health Care Without Harm (2019) Health care's climate footprint - How the Health Sector Contributes to the Global Climate Crisis and Opportunities for Action

Karliner, J., Slotterback, S., Boyd, R., Ashby, B., & Steele, K. (2019). *Healthcare's climate footprint: How the health sector contributes to the global climate crisis and opportunities for action*.

Keller, R. L., Muir, K., Roth, F., Jattke, M., & Stucki, M. (2021). From bandages to buildings: Identifying the environmental hotspots of hospitals. *Journal of Cleaner Production*, *319*.

McAleese, T., Jagiella-Lodise, O., Roopnarinesingh, R., Cleary, M., & Rowan, F. (2023). Sustainable orthopaedic surgery: Initiatives to improve our environmental, social and economic impact. In *Surgeon*. Elsevier Ltd.

McAlister S, McGain F, Petersen M, et al (2022) The carbon footprint of hospital diagnostic imaging in Australia. Lancet Reg Health West Pac 24:100459.

MacNeill, A. J., Lillywhite, R., & Brown, C. J. (2017). The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *The Lancet Planetary Health*, *1*(9), e360–e367.

Picano E, Mangia C, D'Andrea A (2022) Climate Change, Carbon Dioxide Emissions, and Medical Imaging Contribution. J Clin Med 12:215.

Sherman, J., Le, C., Lamers, V., & Eckelman, M. (2012). Life cycle greenhouse gas emissions of anesthetic drugs. *Anesthesia and Analgesia*, *114*(5), 1086–1090.

Snigdha, Hiloidhari, M., & Bandyopadhyay, S. (2023). Environmental footprints of disposable and reusable personal protective equipment – a product life cycle approach for body coveralls. *Journal of Cleaner Production*, *394*.

Thiel, C. L., Woods, N. C., & Bilec, M. M. (2018). Strategies to Reduce Greenhouse Gas Emissions from Laparoscopic Surgery. *American Journal of Public Health*, *108*, S158–S164.

Zhang, D., Dyer, G. S. M., Blazar, P., & Earp, B. E. (2023). The Environmental Impact of Open Versus Endoscopic Carpal Tunnel Release. *Journal of Hand Surgery*, *48*(1), 46–52.

Ranganathan J, Corbier L, Bhatia P, et al (2004) The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. WBCSD/WRI 2004; World Resources Institute.

PAPER 4

Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 303–311
https://doi.org/10.2478/rtuect-2024-0024
https://content.sciendo.com

Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging

Andrea ROLETTO[1*], Anna SAVIO[2], Beatrice MARCHI[3], Simone ZANONI[4]

[1–3]*Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy*

[4]*Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Via Branze 43, 25123 Brescia, Italy*

Received 02.04.2024; accepted 23.07.2024

***Abstract* – The increasing focus on environmental sustainability is becoming essential in the radiology sector, which is accredited for about 10 % of the healthcare industry's carbon footprint. A multitude of research initiatives investigated the environmental impacts of diagnostic imaging. Life Cycle Assessment (LCA) stands as a prominent method for structural assessment of environmental impacts, offering a tool for examining the environmental consequences of specific processes. The aim of this study includes analysing existing LCA approaches in the literature to identify their limitations and to suggest a comprehensive LCA framework for diagnostic imaging. Of the original articles on environmental sustainability in radiology published since 2014, five have described an LCA approach. About the boundaries of their systems, all studies considered the electricity consumption of imaging equipment. Usage of consumables was included in 80 % (4/5) of the studies, as well as energy consumption of auxiliary equipment and Heating, Ventilation and Air Conditioning (HVAC) systems. Only 40 % (2/5) of articles considered waste generation, cleaning and disposal of products used during imaging activities. The articles also varied in their LCA approach, with different life cycle assessment methods. Insights from this analysis led to the identification of differences in LCA methodological approaches in imaging found in the literature. In addition, a new LCA framework designed to overcome the limitations observed in existing research was proposed, offering a more comprehensive analysis. The objective may be the development of more targeted strategies to reduce Greenhouse Gas (GHG) emissions associated with diagnostic procedures.**

***Keywords* – Electricity consumption; Environmental sustainability; Greenhouse Gas (GHG) emissions; Healthcare sector; Radiology; Research methodology.**

1. INTRODUCTION

The increasing focus on environmental sustainability within the diagnostic imaging sector reflects a broader understanding of healthcare's significant environmental footprint [1]. This sector, which includes technologies such as X-ray, Magnetic Resonance Imaging (MRI), Computer Tomography (CT) and ultrasound scanners, is recognized for contributing about 10 % to the healthcare industry's overall carbon footprint [2], [3]. This awareness has

* Corresponding author.
E-mail address: andrea.roletto@unibs.it

©2024 Author(s). This is an open access article licensed under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0).

stimulated numerous research initiatives aimed at comprehensively understanding and mitigating the environmental impacts associated with diagnostic imaging [4].

These impacts are multifaceted. One of the primary concerns is the substantial electricity consumption required to power the equipment used in diagnostic imaging. The operation of MRI, CT scanners, and other imaging technologies demands significant energy, contributing indirectly to the sector's carbon emissions [5]–[10]. This energy consumption not only exacerbates the healthcare industry's carbon footprint but also increases operational costs, pushing for more energy-efficient innovations in medical technology [11]. Furthermore, the environmental impact associated with the electricity used differs depending on the country in which the equipment is located, as it is necessary to consider the emission factors for electricity consumption which varies from country to country [12].

Another critical environmental issue is the carbon emissions resulting from the use of diagnostic imaging. These emissions are not only associated with the energy used during the operation of the equipment but also with the lifecycle of the imaging technologies, including their manufacture, transportation, maintenance, repair operations and disposal [13]. The healthcare sector's reliance on fossil fuels for energy contributes significantly to its carbon emissions, highlighting the need for a shift towards renewable energy sources and more sustainable practices within the sector.

Waste generation is also a significant concern. Diagnostic imaging procedures can produce a variety of wastes, including single-use plastics, contrast media and the disposal of obsolete or outdated equipment [13], [14]. The management and disposal of this waste present challenges in terms of both environmental sustainability and public health as underlined in different studies [15]–[19].

In response to these challenges, there is a growing push in the diagnostic imaging industry towards studying the environmental impact of radiological activities and proposing greener practices [11]. This includes efforts to reduce energy consumption during equipment idle-period [6], the choice of diagnostic examinations with less environmental impact for the same clinical utility [20], and initiatives to reduce waste and promote recycling and resource recovery [21]. In addition, there is a growing interest in assessing the full environmental impact of diagnostic imaging procedures through life cycle assessment (LCA) studies, already used in other areas of the healthcare system [22]. LCA is a method used to assess the environmental consequences associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling [23]. These methods help identify key areas where improvements can be made, promoting a more sustainable approach to healthcare.

When evaluating the environmental impact of a diagnostic imaging activity through LCA, it is essential to consider various aspects that span the entire diagnostic pathway of a patient. These aspects also align with the three scopes outlined in the GHG Emissions Protocol Corporate Standard (Fig. 1) [24].

The main purpose of this study was to establish a novel framework for quantifying the environmental impact of diagnostic imaging processes through an LCA study. This involved a thorough review of existing literature to identify previously employed methodologies, comparing these approaches to highlight their merits and limitations. Through an analysis of these studies, the research aimed to identify the strengths and gaps in the current literature.

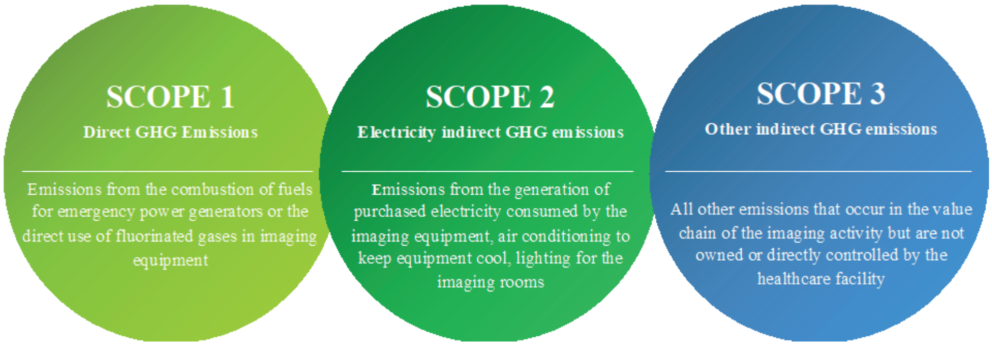


Fig. 1. Scope 1, 2 and 3 emissions in diagnostic imaging department according to the GHG protocol.

2. Methods and Methodology

The study was structured in two distinct segments. Initially, a literature review was conducted to analyse existing publications on environmental sustainability in the field of radiology. The aim was to identify articles that addressed LCA specifically. The search was limited to original studies written in English, published in peer-reviewed journals, with an available abstract.

In the subsequent phase of the study, the focus shifted towards developing a detailed framework designed for the application of LCA within medical imaging practices. This segment sought to bridge the gap between theoretical sustainability concepts and practical application in radiology, emphasising how LCA can be effectively integrated to assess and minimise the environmental footprint of imaging technologies and procedures. It proposed a systematic approach to evaluate the entire lifecycle of imaging equipment – from manufacture and daily use to disposal and recycling – thereby providing insights into potential environmental impacts and offering guidelines to implement these practices effectively. No ethics committee approval was needed to perform this study.

2.1. Literature review and data extraction

In February 2024, a literature review was conducted on Medline (PubMed), Embase (Elsevier) and Web of Science to find original articles on environmental sustainability in diagnostic imaging. Initially, a preliminary review of the collected articles was conducted, during which reviews, case reports, and studies solely relying on automated computer analysis were omitted. Following this, for all studies that passed this initial phase, the complete texts were acquired for further examination. Lastly, a manual search of the references within the selected articles and reviews was performed to identify any further studies that met the eligibility criteria.

Studies were excluded if: 1) focused on hospitals in general or in a setting different from diagnostic imaging department, 2) reviews, editorials, and viewpoints; 3) Abstracts or conference proceedings.

Studies were included in the final analysis if they were focused on the LCA approach on diagnostic imaging.

For all articles included at the final selection, a data extraction was performed. For each study the extracted data (when present) were: year of publication; country of publication; aim of the study; diagnostic imaging technique considered; functional unit of the analysis; LCA methods; LCA software; LCA characteristics.

2.2. Framework design

Through the results of the literature review, a comprehensive framework for a new LCA methodology adapted to imaging technologies was proposed. This framework was created to address shortcomings identified in previous studies by providing a more holistic assessment. By drawing on examples from various sectors beyond healthcare, this new approach improves the methodological foundations.

The key to improving the LCA framework is the identification of all imaging steps with a substantial environmental impact. This allows the associated carbon emissions to be accurately calculated, ensuring a more accurate and complete environmental assessment.

3. RESULTS

3.1. Literature Review

3.1.1. Study selection

From a search conducted on Medline, Embase, and Web of Science, a total of 17 original research articles focused on environmental sustainability within the field of radiology, published from 2014 onwards, were identified. Among these, only 5 articles, which represent 29.4 % of the total, described a LCA approach in the context of diagnostic imaging.

3.1.2. Characteristics of the included articles

Baseline characteristics of articles are summarised in Table 1.

TABLE 1. BASELINE CHARACTERISTICS OF ARTICLES

Study	Year	Country	Imaging technique	Aim/objective
Leapman [25]	2023	USA	MRI, Ultrasound	Estimate the environmental impact associated with prostate MRI examinations and prostate biopsy
McAlister [26]	2022	Australia	Chest X-ray, Mobile Chest X-ray, CT, MRI, Ultrasound	Estimate the carbon footprint of five different diagnostic imaging modalities
Esmaeili [27]	2018	USA	MRI	Estimate the environmental impact of MRI examinations
Martin [28]	2018	USA	CT, MRI, Ultrasound	Estimate environmental impacts of various abdominal imaging examinations
Esmaeili [29]	2015	USA	CT	Estimate the environmental impact of CT examinations

Four articles originated from the United States and one from Australia. The imaging techniques evaluated across the articles include MRI, which was analysed in all articles, CT and Ultrasound, each discussed in 3/5 articles, and Chest X-ray as well as Mobile Chest X-ray, each mentioned in 1/5 articles. Regarding the aims of the identified studies, three articles were focused on assessing the environmental impact of diagnostic imaging broadly, without specifying the clinical inquiries being addressed [26], [27], [29]. Conversely, two studies concentrated on evaluating the environmental footprint of diagnostic imaging tailored to specific anatomical regions, specifically targeting the abdomen [28] and prostate [25]. The study on prostate imaging also encompassed the environmental considerations of an associated interventional procedure, namely a biopsy.

3.1.3. Characteristics of Life Cycle Assessments

The specific characteristics regarding the Life Cycle Assessment method of the articles are described in Table 2.

In the studies reviewed, 3/5 articles adopt the complete patient examination, defined as the sequence of scans necessary for a diagnostic evaluation, as the functional unit for study, correlating it with a specific carbon footprint [25], [27], [28]. Conversely, 2/5 articles focus on the environmental impact of individual scans, treating each scan as the functional unit for analysis [26], [29].

Among the system boundaries adopted, one study exclusively adopted a Cradle-to-grave approach [28], two studies adopted a Gate-to-gate approach for energy consumed by imaging equipment and a Cradle-to-gate approach for consumable use [27], [29], two studies set Cradle-to-grave system boundaries [25], [26]. Two articles specified the use of life cycle inventory database *Ecoinvent* [25], [26]. Life Cycle impact assessment model also varied: two studies [25], [28] utilised the Tool for the Reduction and Assessment of Chemical and other environmental Impact (TRACI) 2.1, while one study utilised *ReCiPe* 2016 model [25].

TABLE 2. SPECIFIC CHARACTERISTICS OF LCA

Study	Functional Unit	System boundary	LC inventory database	LC Impact assessment model
Leapman [25]	Examination	Cradle-to-grave	*Ecoinvent* 3.3	TRACI 2.1 version 1.04
McAlister [26]	Scan	Cradle-to-grave	*Ecoinvent* 3.5	*ReCiPe* 2016
Esmaeili [27]	Examination	Gate-to-gate Cradle-to-gate	n/a	n/a
Martin [28]	Examination	Cradle-to-gate	n/a	TRACI 2.1 version 1.03
Esmaeili [29]	Scan	Gate-to-gate Cradle-to-gate	n/a	n/a

An LCA analysis considers various processes associated with a specific production activity in their system boundaries. The same can apply to healthcare and diagnostic activities as well. In the selected articles, in addition to different types of LCA, various processes that contribute to a diagnostic activity were considered. The processes considered by the selected articles for their respective LCA analyses are described in Table 3.

Seven processes that contribute to the ecological footprint associated with diagnostic imaging procedures are considered in the selected articles:

- Energy consumption of auxiliary equipment, such as contrast media injectors, computers and workstations;
- Electricity consumption of imaging equipment;
- Heating, ventilation and air conditioning (HVAC) systems;
- Manufacture of capital equipment, including imaging devices;
- Staff and patient travel to and from the healthcare facility;
- Usage of consumables, such as paper towel, gloves, contrast agent;
- Waste generation, cleaning, disposal of all products and equipment used during diagnostic activities.

All selected studies [25]–[29] considered the energy consumption of imaging equipment in their LCA analysis, related to the amount of carbon emissions (CO_2-eq). In this analysis, all phases of energy consumption for the radiological equipment were considered, including the production phase, the idle-period (when the device is on but not in use), the standby phase, and the periods when the equipment is switched off.

The energy consumption of auxiliary equipment was considered in 4/5 studies, [25]–[29], counting the energy consumption associated with the contrast medium injectors and computer stations required to perform the diagnostic examination and produce the report, as well as heating, ventilation and air conditioning systems [25], [27]–[29], and usage of consumables [25]–[27], [29], such as paper towel, gloves, contrast agent and syringes. Waste generation, cleaning and disposal were analysed in 2/5 studies [25], [26]. Factors like manufacture of capital equipment and staff and patient travel to and from the healthcare facility, were each covered in only 20 % of the studies.

TABLE 3. PROCESSES INCLUDED IN SYSTEM BOUNDARIES

Study	Energy consumption of auxiliary equipment	Electricity consumption of imaging equipment	Heating, ventilation and air conditioning	Manufacture of capital equipment	Staff and patient travel	Usage of consumables	Waste generation, cleaning, disposal
Leapman [25]	Yes	Yes	Yes	–	Yes	Yes	Yes
McAlister [26]	Yes	Yes	–	–	–	Yes	Yes
Esmaeili [27]	Yes	Yes	Yes	–	–	Yes	–
Martin [28]	–	Yes	Yes	Yes	–	–	–
Esmaeili [29]	Yes	Yes	Yes	–	–	Yes	–

3.2. LCA Framework

Through the results of the literature review, the LCA framework, depicted in Fig. 2, was designed to overcome the limitations of the studies currently in the literature by covering all aspects that can be included in the three phases: preclinical, clinical, post-clinical.

- Preclinical Phase: The production and transportation of imaging equipment and consumables, including the manufacture of components and the delivery of contrast agents or radioactive materials used in diagnostic tests.
- Clinical Phase: The patients and staff travel to and from healthcare facilities [30], which includes emissions from transportation. It can also consider the use of disposable items during the imaging process, such as gowns or syringes for contrast administration.
- Post-clinical Phase: The disposal, maintenance and repair operations of imaging equipment, the disposal or recycling of consumables, management of hazardous waste (like used contrast materials or radioactive waste), and data storage and management for the images produced

The next stage in the sustainability assessment framework is the system approach. Only two articles considered a Cradle-to-grave system approach. This reveals that there are currently no studies that have outlined a comprehensive LCA framework in diagnostic imaging. When analysing LCA interface software, Life Cycle inventory database and Life Cycle impact assessment model, not in all articles are specified. For example, only two articles specify which inventory database was used (*Ecoinvent*). There is no common approach in using the LC impact assessment model, where two studies utilised the TRACI 2.1, while one study utilised *ReCiPe* 2016 model. Therefore, it becomes evident that there is a need for a common inclusive LCA framework within diagnostic imaging. Such a framework should integrate the attributes of existing studies in the literature and aim to cover in the system boundary, as comprehensively as possible, all factors contributing to the carbon footprint associated with diagnostic imaging practices.

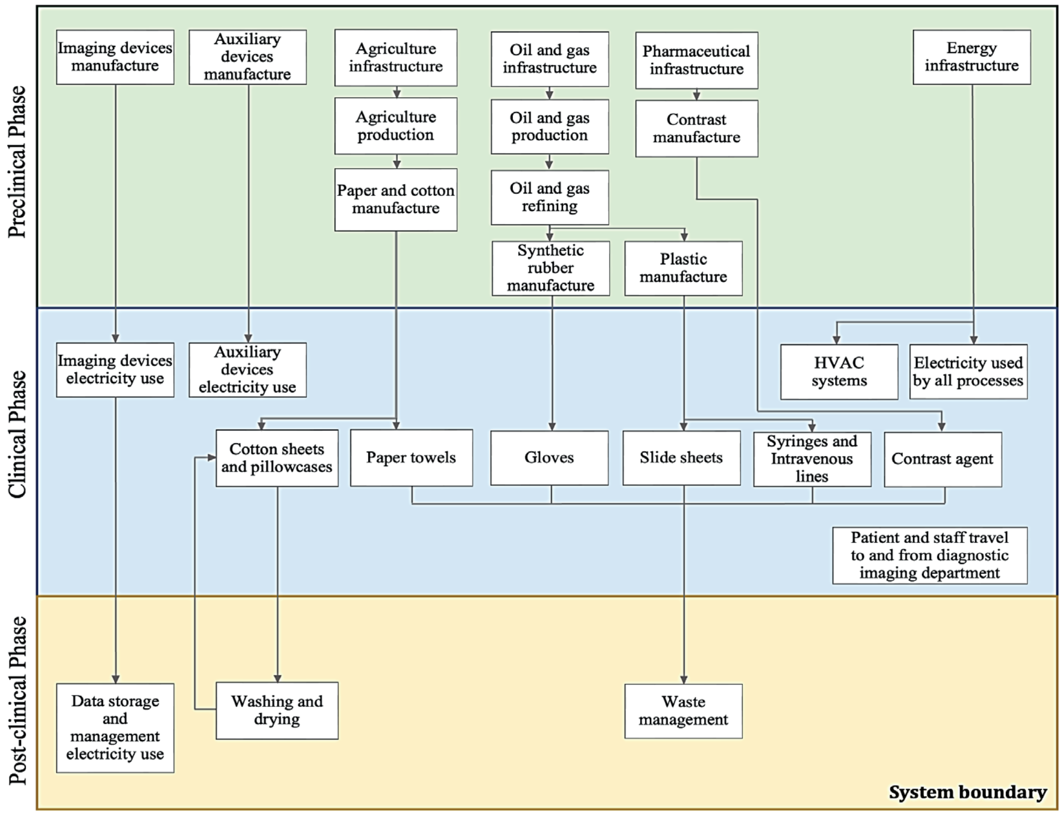


Fig. 2. Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging.

The choice of methodology can be determined according to the geographical location of the study. Finally, in the interpretation phase, the results of the LCA are analysed, particularly regarding inherent uncertainty. To understand the impact of uncertainty on the results, sensitivity analysis can be used to discover the impact that variations in parameter values may have on the results of the study. The use of this model to implement an LCA methodology may make it possible to overcome the limitations of LCA studies implemented in the radiological area and to follow the characteristics of other models described in other scientific areas [31]–[34].

The feasibility of implementing the proposed framework in real healthcare settings depends on various factors such as the existing technological infrastructure, the skills of the staff and the availability of financial resources. The main challenges include data collection, protection of patient privacy, and the need for training and awareness-raising of healthcare personnel.

3.3. Study limitations

Despite the valuable insights provided by the considered studies, this proposal for a new Life Cycle Assessment framework for diagnostic imaging is also based on data collected during the literature review. This literature review has some limitations that should be considered. Firstly, the scope of this review is limited to the studies available within the selected timeframe and databases. Although efforts were made to include a wide range of articles, it is possible that some relevant studies were inadvertently excluded, including those not published in the English language. Secondly, the generalizability of the findings from the included studies may be limited due to variability in study designs, contexts, and geographic locations. The included studies were conducted in various countries, with variations in healthcare systems, infrastructures and energy sources. These contextual factors can influence energy consumption patterns and practices in diagnostic imaging departments, making it difficult to draw universal conclusions. Furthermore, the heterogeneity of the data collected across studies poses a challenge for direct comparisons and synthesis.

4. CONCLUSION

This literature review offers an in-depth examination of various studies focused on employing LCA methodology to assess the environmental impact of diagnostic imaging procedures routinely conducted by healthcare facilities in different countries. The findings from this research have culminated in the creation of a comprehensive framework for a novel LCA methodology designed for diagnostic imaging in radiology. This new approach aims to address and overcome the limitations identified in literature by providing a complete analysis that takes the entirety of the environmental footprint of imaging modalities, including CT, MRI, and ultrasound procedures. By refining the LCA framework, it will be possible to identify the phases in diagnostic imaging that have the most substantial environmental impact. Consequently, this enables the formulation of precise strategies aimed at minimising the greenhouse gas emissions linked to diagnostic imaging processes.

REFERENCES

[1] Brown M., Schoen J. H., Gross J., Omary R. A., Hanneman K. Climate Change and Radiology: Impetus for Change and a Toolkit for Action. *Radiology* 2023:307:4. https://doi.org/10.1148/radiol.230229

[2] Malik A., *et al.* Environmental impacts of Australia's largest health system. *Resources, Conservation and Recycling* 2021:169:105556. https://doi.org/10.1016/j.resconrec.2021.105556

[3] Picano E., Mangia C., D'Andrea C. A. Climate Change, Carbon Dioxide Emissions, and Medical Imaging Contribution. *J Clin Med*icine 2022:12(1):215. https://doi.org/10.3390/jcm12010215

[4] Roletto A., Zanardo M., Bonfitto G. R., Catania D., Sardanelli F., Zanoni S. The environmental impact of energy consumption and carbon emissions in radiology departments: a systematic review. *European Radiology Experimental* 2024:8(1):35. https://doi.org/10.1186/s41747-024-00424-6

[5] Woolen S. A., *et al.* Ecodesign and Operational Strategies to Reduce the Carbon Footprint of MRI for Energy Cost Savings. *Radiology* 2023:307(4):230441. https://doi.org/10.1148/radiol.230441

[6] Heye T., *et al.* The Energy Consumption of Radiology: Energy-and Cost-saving Opportunities for CT and MRI Operation. *Radiology* 2020:295(3):593–605. https://doi.org/10.1148/radiol.2020192084

[7] Doo F. X., *et al.* Environmental Sustainability and AI in Radiology: A Double-Edged Sword. *Radiology* 2024:310(2). https://doi.org/10.1148/radiol.232030

[8] Hainc N., Brantner P., Zaehringer C., Hohmann J. Green Fingerprint' Project: Evaluation of the Power Consumption of Reporting Stations in a Radiology Department. *Academic Radiology* 2020:27(11):1594–1600. https://doi.org/10.1016/j.acra.2019.11.011

[9] Büttner L., *et al.* Switching off for future—Cost estimate and a simple approach to improving the ecological footprint of radiological departments. *European Journal of Radiology Open* 2021:8. https://doi.org/10.1016/j.ejro.2020.100320

[10] Brown M., Snelling E., De Alba M., Ebrahimi G., Forster B. B. Quantitative Assessment of Computed Tomography Energy Use and Cost Savings Through Overnight and Weekend Power Down in a Radiology Department. *Canadian Association of Radiologists Journal* 2022:74(2). https://doi.org/10.1177/08465371221133074

[11] Mariampillai J., *et al.* The green and sustainable radiology department. *Die Radiologie* 2023:63:21–26. https://doi.org/10.1007/s00117-023-01189-6

[12] Bastos J., Monforti-Ferrario F., Melica G. GHG Emission Factors for Electricity Consumption 2024 [Online]. Available: https://data.jrc.ec.europa.eu/dataset/919df040-0252-4e4e-ad82-c054896e1641
[13] Woolen S. A., *et al.* Radiology Environmental Impact: What Is Known and How Can We Improve? *Academic Radiology* 2023:30(4):625–630. https://doi.org/10.1016/j.acra.2022.10.021
[14] Shum P. L., *et al.* Environmental sustainability in neurointerventional procedures: A waste audit. *Journal of Neurointerventional Surgery* 2020:12(11):1053–1057. https://doi.org/10.1136/neurintsurg-2020-016380
[15] Zlaugotne B., Pubule J., Gusca J., Kalnins S. N. Quantitative and Qualitative Assessment of Healthcare Waste and Resource Potential Assessment. *Environmental and Climate Technologies* 2022:26(1):64–74. https://doi.org/10.2478/rtuect-2022-0006
[16] Sabour M. R., Amron R. A systematic analysis of research trends on healthcare waste management during 1995–2022. *International Journal of Environmental Science and Technology* 2024. https://doi.org/10.1007/s13762-024-05770-x
[17] Kaposi A., Nagy A., Gomori G., Kocsis D. Analysis of healthcare waste and factors affecting the amount of hazardous healthcare waste in a university hospital. *Journal of Material Cycles and Waste Management* 2024:26(2):1169–1180. https://doi.org/10.1007/s10163-024-01890-1
[18] Voudrias E. A. Healthcare waste management from the point of view of circular economy. *Waste Management* 2018:75:1–2 https://doi.org/10.1016/j.wasman.2018.04.020
[19] Soares A. L. *et al.* A Review of the Applicability of Current Green Practices in Healthcare Facilities. *International Journal of Health Policy and Management* 2023:12(1):6947. https://doi.org/10.34172/ijhpm.2023.6947
[20] Alshqaqeeq F., McGuire C., Overcash M., Ali K., Twomey J. Choosing radiology imaging modalities to meet patient needs with lower environmental impact. *Resources, Conservation and Recycling* 2020:155. https://doi.org/10.1016/j.resconrec.2019.104657
[21] Shum P. L., *et al.* Sustainability in interventional radiology: are we doing enough to save the environment? *CVIR Endovascular* 2022:5(1):60. https://doi.org/10.1186/s42155-022-00336-9
[22] McGain F., Muret J., Lawson C., Sherman J. D. Environmental sustainability in anaesthesia and critical care. *British Journal of Anaesthesia* 2020:125(5):680–692. https://doi.org/10.1016/j.bja.2020.06.055
[23] The International Organization for Standardization, ISO 14040:2006 Life cycle assessment - Principles and framework, 2006 [Online]. [Accessed: 14.03.2024.] Available: https://www.iso.org/standard/37456.html
[24] Ranganathan J., *et al.* WBCSD/WRI 2004. Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. *World Resources Institute* 2004. https://doi.org/10.13140/RG.2.2.34895.33443
[25] Leapman M. S., *et al.* Environmental Impact of Prostate Magnetic Resonance Imaging and Transrectal Ultrasound Guided Prostate Biopsy. *European Urology* 2023:83(5):463–471. https://doi.org/10.1016/j.eururo.2022.12.008
[26] McAlister S., *et al.* The carbon footprint of hospital diagnostic imaging in Australia. *The Lancet Regional Health - Western Pacific* 2022:24:100459. https://doi.org/10.1016/j.lanwpc.2022.100459
[27] Esmaeili A., McGuire C., Overcash M., Ali K., Soltani S., Twomey J. Environmental impact reduction as a new dimension for quality measurement of healthcare services: The case of magnetic resonance imaging. *International Journal of Health Care Quality Assurance* 2018:31(8):910–922. https://doi.org/10.1108/IJHCQA-10-2016-0153
[28] Martin M., Mohnke A., Lewis G. M., Dunnick N. R., Keoleian G., Maturen K. E. Environmental Impacts of Abdominal Imaging: A Pilot Investigation. *Journal of the American College of Radiology* 2018:15(10):1385–1393. https://doi.org/10.1016/j.jacr.2018.07.015
[29] Esmaeili A., Twomey J. M., Overcash M. R., Soltani S. A., McGuire C., Ali K. Scope for energy improvement for hospital imaging services in the USA. *Journal of Health Services Research & Policy* 2015:20(2):67–73. https://doi.org/10.1177/1355819614554845
[30] Andrews E., Pearson D., Kelly C., Stroud L., Rivas Perez M. Carbon footprint of patient journeys through primary care: a mixed methods approach. *British Journal of General Practice* 2013:63(614):e595–e603. https://doi.org/10.3399/bjgp13X671579
[31] Schneider F., Parsons S., Clift S., Stolte A., Krüger M., McManus M. Life cycle assessment (LCA) on waste management options for derelict fishing gear. *The International Journal of Life Cycle Assessment* 2023:28(3):274–290. https://doi.org/10.1007/s11367-022-02132-y
[32] Wu M., Sadhukhan J., Murphy R., Bharadwaj U., Cui X. A novel life cycle assessment and life cycle costing framework for carbon fibre-reinforced composite materials in the aviation industry. *The International Journal of Life Cycle Assessment* 2023:28(5):566–589. https://doi.org/10.1007/s11367-023-02164-y
[33] Sartori T., Drogemuller R., Omrani S., Lamari F. A schematic framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS). *Journal of Building Engineering* 2021:38:102180. https://doi.org/10.1016/j.jobe.2021.102180
[34] Gardezi S. S. S., Shafiq N., Hassan I., Arshid M. U. Life Cycle Carbon Footprint Assessments, Case Study of Malaysian Housing Sector. *Environmental and Climate Technologies* 2021:25(1):1003–1017. https://doi.org/10.2478/rtuect-2021-0076

PAPER 5

energies

MDPI

Article

Assessing Energy and Waste Impacts in Orthopaedic Departments: A Case Study from an Italian Public Hospital †

Anna Savio [1,*], Beatrice Marchi [1], Andrea Roletto [1], Pierangelo Guizzi [2], Giuseppe Milano [3], Lucio Enrico Zavanella [1] and Simone Zanoni [4]

[1] Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, 25123 Brescia, Italy; beatrice.marchi@unibs.it (B.M.); andrea.roletto@unibs.it (A.R.); lucio.zavanella@unibs.it (L.E.Z.)
[2] Department of Orthopaedic Surgery, Ospedale di Gardone Val Trompia, 25063 Brescia, Italy; pierangelo.guizzi@asst-spedalicivili.it
[3] Department of Medical and Surgical Specialties, Radiological Sciences and Public Health, Università degli Studi di Brescia, 25123 Brescia, Italy; giuseppe.milano@unibs.it
[4] Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, 25123 Brescia, Italy; simone.zanoni@unibs.it
* Correspondence: anna.savio@unibs.it

† This paper is an extended version of our paper published in 20th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, 5–10 October 2025.

Abstract

Hospitals are major consumers of natural resources, and their continuous 24/7 demands exert significant environmental repercussions. Notably, energy utilization and waste generation constitute primary determinants of the ecological footprint associated with healthcare facilities. This study aims to provide a replicable framework for estimating operational carbon account of orthopedic hospital operations using readily available data, without requiring expert-level life cycle assessment tools. A three-level analysis was applied to a case study in a large Italian public hospital, focusing on CO_2e emissions from energy consumption and hazardous waste generation. Operational data from the hospital and detailed audits of orthopedic procedures were used to estimate energy consumption, ventilation loads, and waste volumes. Results showed that HVAC systems dominated energy-related emissions, while surgical waste was a major contributor at the meso- and micro-levels. Several mitigation strategies were proposed, including reducing off-hours air exchange rates and improving waste segregation, leading to potential emission reductions. The study highlights that even a simplified carbon accounting approach can generate valuable insights for healthcare managers, supporting internal benchmarking and sustainability action.

Keywords: healthcare; GHG emission; waste management; energy consumption; environmental assessment

Check for updates

Academic Editors: Francesco Calise, Qiuwang Wang, Poul Alberg Østergaard, Maria Vicidomini and Wenxiao Chu

Received: 24 December 2025
Revised: 25 January 2026
Accepted: 31 January 2026
Published: 5 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

The healthcare sector presents a fundamental paradox: its primary mission of safeguarding and enhancing human health stands in contrast to its increasing recognition as a significant contributor to environmental degradation, notably climate change, which poses an escalating and direct threat to global public health. As the adverse health consequences of climate disruption intensify, manifested through extreme weather events, air pollution, and the proliferation of vector-borne diseases, the sector functions both as a critical first responder and an unintended driver of these crises. This dual role has spurred considerable research focused on quantifying the environmental footprint of healthcare systems worldwide. The management of healthcare waste is particularly challenging due to the presence of complex and heterogeneous waste streams, often composed of mixed materials and subject to contamination risks. These characteristics make effective segregation comparable to other complex systems such as municipal or packaging waste streams, where improper sorting can significantly increase environmental impacts [1]. Recent studies have highlighted the critical role of energy systems and energy efficiency measures in healthcare facilities, emphasizing the contribution of hospital buildings, HVAC systems, and energy supply strategies to overall carbon emissions and operational sustainability [2].

A seminal global analysis [3] estimated that the healthcare sector accounts for approximately 4.4% of total global greenhouse gas (GHG) emissions, thereby ranking it among the most carbon-intensive service industries. National-level studies from Europe, North America, Asia, and Oceania consistently show that the healthcare sector represents a non-negligible share of national greenhouse gas emissions, although with substantial variability depending on energy mixes, healthcare organization, and service intensity. In Australia, healthcare accounts for 7% of national emissions [4]; in the United States, estimates range from 8 to 10% [5], in Canada, 5% [6], while in Japan and China, healthcare contributes 4.6% and 2.7%, respectively [7,8].

In the Netherlands, a study [9] broadened the scope of analysis beyond climate change to encompass other environmental stressors, including material extraction, blue water consumption, and land use. Similarly, the healthcare sector's "extinction-risk footprint" was quantified in the Netherlands and across Europe [10], revealing that food supply chains, rather than pharmaceuticals or energy consumption, are disproportionately responsible for threats to biodiversity.

Hospitals consistently emerge as major sources of emissions within national healthcare systems. Building infrastructure and catering were identified as primary environmental hotspots across 33 Swiss hospitals [11], while the emissions of a German hospital using a hybrid financial model were quantified [12], demonstrating the dominance of indirect (Scope 3) emissions in the carbon footprint.

Indeed, supply chain emissions, classified as Scope 3 under the GHG Protocol [13], represent a recurrent theme. A hybrid assessment approach employed at Erasmus MC [14] in the Netherlands found that 72% of the institution's emissions stemmed from Scope 3 activities, particularly pharmaceuticals and medical devices. Similarly, another study [15] reported that medicines and devices accounted for nearly 60% of Geneva's healthcare carbon footprint, followed by hospital operations and patient transport. In England, ref. [16] reported that 62% of the entire National Health Service's (NHS) emissions in 2019 originated from its supply chain, further emphasizing the central role of indirect emissions.

The environmental impact of anesthetic gases and pharmaceuticals has also garnered increasing attention. Several studies [17–19] have demonstrated substantial carbon intensities associated with desflurane and single-use medical devices. Within operating rooms, the emissions per surgical procedure exhibit considerable variability, influenced by energy consumption and the choice of anesthetic agents, with reported differences exceeding an order of magnitude across institutions [20]. In Japan [7], those patients aged 65 and older account for over half of the nation's healthcare emissions, primarily due to hospitalization and pharmaceutical consumption. Similar trends have been observed in Austria, where overall healthcare emissions have decreased over a decade due to increased use of renewable energy sources, although emissions from patient travel have increased [21].

Significantly, methodological approaches have evolved to more accurately capture these dynamics. Hybrid models, integrating bottom-up Life Cycle Assessment (LCA) with top-down environmentally extended input–output (EEIO) methods, have been widely adopted [4,16], enabling enhanced granularity and system-level insights. While EEIO

https://doi.org/10.3390/en19030836

methods capture broad systemic flows, LCA remains indispensable for assessing individual products or procedures, a complementarity that several authors emphasize as essential for policy-relevant analysis [9,19].

Despite this expanding body of research, notable knowledge gaps persist, particularly within national contexts characterized by regionally decentralized healthcare systems or a lack of standardized environmental reporting frameworks. Italy represents such a context. Although research addressing the environmental impact of Italian healthcare is emerging, comprehensive studies remain limited, especially those examining environmental performance at the departmental or procedural level. A preliminary assessment of energy and waste impacts in an orthopaedic department of an Italian public hospital was presented in a conference proceeding [22], laying the groundwork for the comprehensive multilevel analysis developed in this study.

Recent studies have begun to quantify the environmental burdens associated with Italian hospitals, providing valuable insights into sustainability challenges and potential interventions. A significant area of investigation concerns hospital food services, which contribute substantially to both waste generation and GHG emissions. One study revealed that meals with lower carbon footprints were often discarded more frequently, thereby negating their ecological benefit [23]. Weekly per-patient emissions were estimated to be as high as 11.5 kg of carbon dioxide equivalent ($kgCO_2e$) at lunch and 7.0 $kgCO_2e$ at dinner.

At a systemic level, a national study identified deficiencies in energy governance across 1062 hospitals, with an estimated annual energy consumption of 1062 kilotons of oil equivalent (ktep) [24]. Other energy-intensive domains, such as diagnostic imaging, have also been assessed: in diagnostic imaging, up to 91% of the energy consumption of computed tomography (CT) and magnetic resonance imaging (MRI) scanners was found to be wasted during idle periods [25].

Emerging technologies, such as telemedicine, demonstrate promise for reducing patient transport emissions. Remote consultations reduced per-visit emissions from 9.77 kg to 0.41 $kgCO_2e$ [26]. Similarly, inappropriate endoscopic examinations alone could account for over 4100 tons of CO_2 annually [27]. Collectively, these studies underscore the pressing need for data-driven strategies to mitigate the environmental footprint of the Italian healthcare sector. Among clinical specialties, Orthopedics and Trauma stands out as one of the most resource-intensive. Recent research indicates that orthopedic surgeries are responsible for up to 57.5% of the total carbon footprint of a surgical procedure, with energy consumption and waste disposal procedures being the primary factors. Further, the average quantity of waste generated per orthopedic procedure can be as high as 14–16.5 kg, with a substantial proportion of this waste consisting of single-use plastics and potentially recyclable materials. These figures emphasize the significance of focusing on orthopedic departments in environmental performance assessments, as they present significant opportunities for operational optimization and carbon reduction [28,29].

Despite the growing number of studies addressing the environmental impact of orthopedic surgery, existing research predominantly adopts either a full life cycle perspective at the level of individual procedures or a hospital-wide perspective without specialty-level resolution. As a result, the interaction between hospital energy systems, departmental organization, and procedure-level waste generation remains insufficiently explored. In particular, multiscale frameworks capable of linking hospital-wide energy consumption, departmental performance, and operating-room-level impacts within a single clinical specialty are still lacking, especially in national contexts such as Italy where standardized environmental reporting in healthcare is limited. This study addresses this gap by proposing a replicable, multilevel assessment framework focusing on operational energy use

https://doi.org/10.3390/en19030836

and infectious waste management within an orthopedic department of a large Italian public hospital.

2. Materials and Methods

This study investigates the environmental impacts in terms of carbon dioxide equivalent (CO_2e) associated with orthopedic surgical interventions at a major public hospital in Italy, situated in the Lombardy region. This extensive healthcare facility encompasses over 1200 beds and more than 130,000 m^2 of functional space. Given the complexity of this healthcare infrastructure, the study adopts a multiscale framework to assess system-wide resource flows, departmental consumption, and procedure-level performance.

2.1. Study Design

The analysis is structured across three distinct levels:

- Macro-level, representing hospital-wide resource consumption and waste generation;
- Meso-level, focusing specifically on the Orthopedic and Trauma (O&T) department;
- Micro-level, assessing the environmental burden of operating rooms (Ors) and individual orthopedic surgical procedures.

This layered methodological approach facilitates both top-down allocation and bottom-up measurement strategies, thereby capturing variations in resource intensity across functional domains.

2.2. Data Collection and Sources

2.2.1. Macro-Level: Hospital-Wide Data

Annual energy consumption data for the year 2023, encompassing electricity, district heating, and district cooling, were retrieved from institutional utility records. These values were normalized to kilowatt-hours (kWh) to enable aggregation and comparison. The hospital's total floor area (132,816 m^2) and the total number of installed beds (1294) were used to calculate intensity indicators. Bed occupancy rates were not explicitly considered, as intensity indicators based on installed beds and floor area are commonly adopted to represent the structural and operational capacity of healthcare facilities. This approach allows comparability across hospitals and time periods, independently of short-term fluctuations in patient occupancy. GHG emissions were estimated based on vector-specific conversion factors. Waste data were sourced from official disposal records and included detailed breakdowns according to the European Waste Catalogue (CER) code. Total waste mass and the proportion of hazardous waste were calculated. Per-bed and per-square-meter values were used for benchmarking purpose.

2.2.2. Meso-Level: Orthopedic and Trauma Department

The orthopedic and trauma department includes two 20-bed inpatient wards and a surgical suite containing four ORs. Surface area measurements were extracted from facility floor plans. In the absence of sub-metering, departmental energy consumption was estimated via surface-based allocation, applying the hospital's average kWh/m^2 intensity. The total volume of infectious healthcare waste generated over the study period was obtained from hospital waste management logs and recorded in liters. To estimate the corresponding waste mass, a reference density value for solid infectious healthcare waste was applied. Based on the national and international literature, reported density values typically range between 120 and 150 kg per cubic meter. For this study, an intermediate reference value of 135 kg/m^3 was adopted, consistent with national guidelines [30].

https://doi.org/10.3390/en19030836

2.2.3. Micro-Level: Operating Rooms and Surgical Procedures

Prospective data collection was conducted in two of the four orthopedic ORs. Direct electricity consumption was recorded over two weeks using power quality analyzer GSC59 (HT Instruments, Faenza, Italy). Waste audits were performed over two surgical days. The operational procedures included in the waste audit were selected based on predefined criteria aimed at representativeness rather than exhaustiveness. Specifically, procedures were chosen to reflect typical orthopedic surgical activity in terms of duration, surgical complexity, and resource use, and were limited to elective procedures performed in standard operating rooms under routine conditions. All generated waste was sorted, weighed, and categorized. The number of annual orthopedic procedures (2186 in 2023) was used to extrapolate Micro-level impacts. HVAC energy was not directly metered at the room level, and it was modelled separately

No inferential statistical analysis was performed on the collected data. The study adopts a descriptive case-study approach, focusing on the quantification of energy use and waste generation under routine operating conditions

2.3. Environmental Impact Analysis

2.3.1. CO_2e Emission Factors for Energy Sources

Official data from the local energy provider specify the CO_2e emission factors for three main energy sources used in hospitals: electricity, district heating, and district cooling. These emission factors are expressed in kgCO_2e/kWh, with a breakdown of fossil, biogenic, and other greenhouse gas components where available [31]. For electricity, the local energy provider reports a CO_2e emission factor of approximately 0.258 kgCO_2e/kWh for 2023, reflecting a decrease from 0.307 kgCO_2e/kWh in 2022. This reduction is attributed to an increased integration of renewable energy sources. The projected fossil CO_2 intensity for 2024 is approximately 0.215 kgCO_2e/kWh, representing a 17% reduction compared to 2023 [26,32]. Emissions of methane (CH_4) and nitrous oxide (N_2O) are considered negligible, with emissions from the Italian national grid estimated at 0.0176 gCH_4/kWh and 0.0028 gN_2O/kWh, values consistent with the local provider's energy mix [33]. Regarding district heating, the CO_2e emission factor reported by the local energy provider is 0.12 kgCO_2e/kWh, based on 2021 certification data. This represents one of the lowest emission factors in Italy, largely due to the use of heat generated from waste-to-energy plants and industrial heat recovery processes, thereby minimizing reliance on fossil fuels. Previously, the emission factor was 0.24 but was halved due to the increased use of renewable energy sources [34]. The fossil CO_2 component accounts for 0.12 kgCO_2/kWh, while the biogenic share contributes 0.11 kgCO_2/kWh, resulting in a total emission of about 0.23 kgCO_2 per kWh of heat distributed. Emissions of other greenhouse gases, such as CH_4 and N_2O, are considered negligible.

District cooling in the study area is currently produced by electrically driven compression chillers. Since no certified emission factor is published by the local provider, the CO_2 emission factor for district cooling was calculated based on the electricity emission factor and an average coefficient of performance (COP). Assuming a conservative average COP of 2.5, consistent with large-scale district cooling plants, the resulting emission factor for district cooling was estimated as the electricity emission factor divided by the COP. This approach reflects the actual energy conversion process and ensures consistency with the fossil CO_2 accounting applied to electricity. Accordingly, a fossil CO_2 emission factor of approximately 0.10 kgCO_2e/kWh was adopted for district cooling.

In conclusion, the following fossil CO_2 emission factors have been selected for the study, consistent with the GHG Protocol, which excludes biogenic emissions:

https://doi.org/10.3390/en19030836

- Electricity: The emission factor is 0.258 $kgCO_2e/kWh$ for 2023, reflecting the renewable energy mix, and representing the fossil CO_2 component after the reduction from 2022.
- District Heating: The emission factor for fossil CO_2 is 0.12 $kgCO_2e/kWh$, excluding biogenic emissions, which are considered carbon neutral.
- District Cooling: The emission factor for fossil CO_2 is estimated at 0.10 $kgCO_2e/kWh$, with the total cooling emissions adjusted to exclude biogenic emissions, which are also considered carbon neutral.

2.3.2. Emission Factors in Infectious Waste Management

Italian laws regulate the management of infectious medical waste (CER 180103) [35], requiring treatment through high-temperature incineration or sterilization (autoclaving). Depending on the method employed, these processes have varying impacts on CO_2 emissions.

The collection and transport of infectious waste contribute a relatively minor proportion to overall CO_2 emissions compared to the subsequent treatment process. This phase involves the use of sealed containers and specialized vehicles for transport. The associated emissions are relatively low, as the waste is usually conveyed to regional treatment plants, thereby limiting transport distances and fuel consumption. Furthermore, local waste management operators complement route optimization strategies and invest in renewable energy sources to achieve further emissions reduction. The primary treatment methods and their associated emissions are as follows:

- Incineration: Waste-to-energy plants employ high-temperatures combustion (>1000 °C) to incinerate waste, with the concurrent recovery of energy in the form of electricity and heat. The principal source of emissions is the fossil content in the waste stream (such as plastics and synthetic materials). On average, the incineration of one ton of waste generates about 500–1200 kg CO_2e. However, when energy recovery is considered, the net emission factor ranges from 500 to 700 $kgCO_2e$ per ton of treated waste. This method partially offsets emissions by generating renewable energy, thus decreasing reliance on fossil fuels [30].
- Sterilization: Autoclaving, a sterilization method, uses high-temperature, high-pressure steam to render waste non-hazardous. This process results in significantly lower emissions compared to incineration, with an emission factor ranging from 100–200 kg CO_2e per ton of waste. The reduced environmental impact is attributed to the absence of direct combustion of carbon-based materials, positioning sterilization as a more environmentally friendly option, particularly when coupled with energy recovery in waste-to-energy plants for the disposal of post-treatment residues [36].

Following treatment, the waste is either incinerated in municipal waste plants or disposed of in landfills. Emissions from sterilized waste are lower than those from incinerated waste; however, some CO_2 is still released, particularly from any remaining fossil content if incineration is the final disposal method. Landfill disposal can lead to the generation of biogenic CO_2 and methane emissions over time [36].

The total CO_2 emissions associated with infectious waste management are largely determined by the chosen treatment method. Incineration with energy recovery offers a significant reduction in net emissions due to the energy produced, while sterilization, although inherently less emissive, still incurs an environmental impact due to energy consumption. Local waste management operators are adopting renewable energy sources and energy-efficient practices to minimize their carbon footprint. According to the IPCC Guidelines for National Greenhouse Gas Inventories, gross CO_2 emissions from waste incineration are typically in the order of 0.7–1.2 $kgCO_2$ per kg of waste [37]. Conversely, Italian technical documentation based on ENEA sources reports lower average values

https://doi.org/10.3390/en19030836

for municipal waste incineration, around 0.29 kgCO_2 per kg, reflecting national plant performance and energy recovery practices [38].

Given the higher fossil carbon content of healthcare-related infectious waste compared to municipal solid waste, and considering the presence of energy recovery systems in local waste management operators, this study adopts a representative net emission factor in the range of 0.5–0.7 kgCO_2e per kg of waste treated. This interval reflects a conservative compromise between gross incineration emissions and national average values and is consistent with common life cycle and operational carbon accounting practices.

3. Results

3.1. Macro-Level Analysis

At the Macro scale, the public hospital under investigation registered a total energy consumption of 113,604,273 kWh in the year 2023. This consumption was distributed across electricity (31,476,237 kWh, 28%), district heating (46,656,036 kWh, 41%), and district cooling (35,472,000 kWh, 31%). When normalized by the facility's functional area of 132,816 m^2, this yields an average energy intensity of 855.4 kWh/m^2/year. Considering the specific regional emission factor applicable in Italy, the results of the Macro-level analysis are reported in Table 1.

Table 1. Energy consumption at Macro-level.

Energy Vector	kWh/Year	kgCO_2e/kWh	kgCO_2e/Year
Electrical Energy	31,476,237	0.258	8,120,869
District Heating	46,656,036	0.120	5,598,724
District Cooling	35,472,000	0.10	3,547,200
Total	113,604,273	/	17,266,793

Regarding waste management at the hospital level, official disposal records for 2023 indicated a total of 833,415 kg, with 65% (approx. 541,719 kg) classified as hazardous waste. Assuming standard incineration treatment with an average emission factor of 0.6 kgCO_2e/kg, the associated emissions are:

$$\textit{Hospital Hazardous Waste } CO_2\text{e: } 541{,}719\,\frac{\text{kg}}{\text{year}} \cdot 0.6\,\frac{\text{kgCO}_2\text{e}}{\text{kg}} = 325{,}031\,\frac{\text{kgCO}_2\text{e}}{\text{year}} \quad (1)$$

This estimation highlights the carbon burden associated with infectious waste streams at the hospital level.

3.2. Meso-Level Analysis

The Orthopedics and Traumatology department encompasses a total area of 2425.3 m^2, including both inpatient wards and an operating suite. Based on hospital-wide average intensities and proportional allocations by surface area, the estimated total annual consumption for the department is detailed in Table 2.

Table 2. Energy consumption at Meso-level.

Energy Vector	kWh/Year	kgCO_2e/kWh	kgCO_2e/Year
Electrical Energy	574,776	0.258	148,292
District Heating	851,969	0.120	102,236
District Cooling	647,742	0.10	64,774
Total	2,074,487	/	315,303

https://doi.org/10.3390/en19030836

Waste generation from the Orthopedics and Traumatology department was assessed using departmental waste consignment records and data on the utilization of various waste containers throughout 2023. The analysis considered the quantity and capacity of containers designated for infectious and potentially infectious materials.

A total volume of 258,977 liters (corresponding to 258.977 m^3) of waste was collected during the year. The corresponding waste mass was estimated by applying the reference density value for solid infectious healthcare waste described in the Methods section.

Applying this density factor, the total annual mass of waste was estimated as follows:

$$\textit{O\&T Hazardous Waste Mass}: 258.977\frac{\text{m}^3}{\text{year}} \cdot 135\frac{\text{kg}}{\text{m}^3} = 34{,}462\frac{\text{kg}}{\text{year}}(34.5\text{ tonnes}) \quad (2)$$

The composition of this waste primarily includes solid infectious materials (e.g., surgical drapes, gloves, absorbent pads), sharps and cutting instruments, organic fluids captured via suction systems, and sealed containers.

Assuming that all waste underwent high-temperature incineration with energy recovery, the associated greenhouse gas (GHG) emissions were calculated:

$$\textit{O\&T Hazardous Waste CO}_2\textit{e}: 34{,}462\frac{\text{kg}}{\text{year}} \cdot 0.6\frac{\text{kgCO}_2\text{e}}{\text{kg}} = 20{,}677.2\frac{\text{kgCO}_2\text{e}}{\text{year}} \quad (3)$$

Although representing a small fraction of the hospital's total waste mass, the intensive nature of surgical activities and the widespread use of single-use items amplify the environmental burden per unit of clinical output.

3.3. Micro-Level Analysis

At the Micro-level, a high-resolution analysis was conducted to assess both direct and indirect energy consumption associated with individual orthopedic surgical procedures. Energy use was quantified through a dual-channel approach: direct measurement of electrical demand from the operating theater's dedicated circuit and modelling of heating, ventilation and air conditioning (HVAC) requirements based on volumetric parameters. Each operating theater had an area of 42 m^2 and a volume of 126 m^3. HVAC consumption was estimated using a standard energy model based on 20 air changes per hour, a maintained internal temperature of 17 °C, and a unit energy load for air handling of 0.6 Wh/m^3 [39]. The temperature value corresponds to the set-point recorded on the operating room thermostat at the time of the audit, reflecting the operational conditions of the orthopaedic operating room during routine surgical activity.

Using portable metering systems connected to the electrical panels supplying two orthopedic operating rooms, an average daily consumption of 26 kWh per room was recorded. Assuming 312 active surgical days per year, the annual energy use for all the operating rooms was calculated (Table 3).

The combined direct electrical consumption and HVAC loads for the operating rooms amount to:

$$\text{OR Annual Energy Consumption: } 32{,}448\frac{\text{kWh}}{\text{year}} + 45{,}290\frac{\text{kWh}}{\text{year}} = 77{,}738\frac{\text{kWh}}{\text{year}} \quad (4)$$

$$\text{OR Annual Energy CO}_2\text{e: } 77{,}738\frac{\text{kWh}}{\text{year}} \cdot 0.258\frac{\text{kgCO}_2\text{e}}{\text{kWh}} = 20{,}057\frac{\text{kgCO}_2\text{e}}{\text{year}} \quad (5)$$

https://doi.org/10.3390/en19030836

Table 3. HVAC energy consumption in the operating rooms.

Electricity Consumption		HVAC	
Daily	26 kWh/day/room	Volume	126 m^3
Annual surgical days	312 days/year	Parameters	17 °C
			20 ACH
			0.6 Wh/m^3
Annual energy consumption	8112 kWh/year/room	Demand per room	36.29 kWh/day/room
N°rooms	4 rooms	Annual	11,322 kWh/year/room
Total	32,448 kWh/year	Total	45,290 kWh/year

Considering the 2186 surgical procedures performed annually, the average energy consumption and associated emissions per procedure are:

$$\text{Single Surgery Energy Consumption: } \frac{77{,}738\,\frac{\text{kWh}}{\text{year}}}{2186\,\frac{\text{surgeries}}{\text{year}}} = 35.56\,\frac{\text{kWh}}{\text{surgery}} \quad (6)$$

$$\text{Single Surgery } \mathit{Energy}\ \mathit{CO}_2\text{e: } \frac{20{,}057\,\frac{\text{kgCO}_2\text{e}}{\text{year}}}{2186\,\frac{\text{surgeries}}{\text{year}}} = 9.17\,\frac{\text{kgCO}_2\text{e}}{\text{surgery}} \quad (7)$$

To assess the waste profile associated with typical orthopedic interventions, a dedicated waste audit was conducted over two surgical days. Thirteen surgeries were audited, encompassing a representative range of procedures, including total joint replacements, ligament repairs, and tissue biopsies (Table 4). Using the data from this audit, the average waste generation per surgical procedure was determined, and the greenhouse gas emissions associated with hazardous waste generation were calculated to ascertain their impact at the Micro-level.

Table 4. Operating rooms waste audit.

Surgery Procedure	Hazardous Waste [kg]	Organic Fluids [kg]	Paper [kg]	Plastic [kg]	Non-Recyclable [kg]	Total [kg]
Medial Patellofemoral Ligament Reconstruction	7.6	1	0.4	0.4	1	10.4
Total Knee Arthroplasty	11.9	0.6	0.8	1.1	1.6	16
Rotator Cuff Tendon Repair	9.8	1.6	0.5	0.5	0.6	13
Anterior Cruciate Ligament Repair	7.5	0.8	0.2	0.2	0.8	9.5
Knee Tissue Biopsy	6.7	1	0.2	0.4	2.5	10.8
Total Knee Arthroplasty	11.1	1.5	0.8	1.1	4.7	19.2
Multiligamentous Knee Reconstruction	10.2	8.9	1.2	2.1	2.2	24.6
Rotator Cuff Tendon Repair	8.4	1.6	0.9	0.7	1.1	12.7
Rotator Cuff Tendon Repair	7.6	0.8	0.6	0.6	0.9	10.5
Rotator Cuff Tendon Repair	6.6	1.4	0.4	0.5	0.3	9.2
Bankart Repair	10.2	1	0.7	0.7	1.8	14.4
Total Shoulder Arthroplasty	8.9	2.1	1	1.1	1.4	14.5
Total Shoulder Arthroplasty	10.6	2	1.1	0.9	2.4	17

Table 4. *Cont.*

Surgery Procedure	Hazardous Waste [kg]	Organic Fluids [kg]	Paper [kg]	Plastic [kg]	Non-Recyclable [kg]	Total [kg]
Avg	9.0	1.9	0.7	0.8	1.6	14.0
Annual production	19,674	4153	1530	1749	3498	30,604
Avg %	64%	14%	5%	6%	11%	100%

Notes: Each row is one surgery case. "Hazardous Waste" is infectious/biological waste destined for incineration. "Organic Fluids" includes suctioned liquids (with and without solidifying containers). "Non-Recyclable" includes miscellaneous materials not suitable for recycling (textiles, mixed material items).

Assuming all hazardous waste undergoes high-temperature incineration with energy recovery, the associated greenhouse gas (GHG) emissions were calculated as follows:

$$\text{Single Surgery Hazardous Waste } CO_2\text{e: } 9.0\frac{\text{kg}}{\text{surgery}} \cdot 0.6\frac{\text{kgCO}_2\text{e}}{\text{kg}} = 5.4\frac{\text{kgCO}_2\text{e}}{\text{surgery}} \quad (8)$$

$$\text{Annual Hazardous Waste } CO_2\text{e: } 5.4\frac{\text{kgCO}_2\text{e}}{\text{surgery}} \cdot 2186\frac{\text{surgeries}}{\text{year}} = 11{,}804\frac{\text{kgCO}_2\text{e}}{\text{year}} \quad (9)$$

This equates to 11.8 metric tons of CO_2e annually attributable solely to the incineration of infectious surgical waste. When compared to the total energy-related emissions from the department (315,303 kgCO_2e), surgical waste incineration represents approximately 3.7% of the total.

4. Discussion

4.1. Key Metrics for Energy and Environmental Comparison

4.1.1. Energy Intensity per Surface Area (kWh/m^2)

It is the most common metric indicating annual energy use per unit of surface area. However, this indicator alone does not capture the level of healthcare activity or operational efficiency. Hospitals with similar kWh/m^2 can have vastly different services and patient loads. Furthermore, this metric does not distinguish between the mix of energy sources used.

4.1.2. Energy Intensity per Capacity (kWh/Bed)

Relating energy to bed capacity provides an indicator linked to the hospital's care provision capacity. This metric is often considered an output measure of the healthcare service delivered. For example, a lower kWh/bed value with the same level of services indicates greater energy efficiency per hospitalized patient. It offers an intuitive way to compare hospitals of varying sizes, although it also has limitations as it does not consider outpatient activities or laboratory functions.

4.1.3. Carbon Emission Intensity (kgCO_2e/m^2)

This indicator quantifies the greenhouse gas emissions associated with energy consumption per square meter. It is crucial as it incorporates the environmental impact of the energy mix used. Two hospitals with identical kWh/m^2 consumption can have significantly different carbon footprints if one relies on renewable energy sources while the other uses fossil fuels. For example, studies in Spain have estimated 100 kg CO_2-equivalent emitted per m^2 of hospital per year. The use of kgCO_2e/m^2 thus allows for the comparison of the effectiveness of decarbonization and energy efficiency measures, providing a direct indication of the climate impact of healthcare facilities.

https://doi.org/10.3390/en19030836

Combining these indicators provides a more comprehensive picture of performance. The kWh/m^2 alone can be misleading as it does not reflect the intensity of hospital use or the associated CO_2 emissions. Instead, the kWh/bed normalizes consumption based on the care capacity, while the kgCO_2e/m^2 normalizes by surface area but weighs the carbon content of the energy sources. These metrics facilitate a more meaningful comparison of hospitals across different countries (where energy mixes and bed capacity vary) than the simple kWh/m^2. In summary, kWh/bed measures energy efficiency relative to the healthcare service provided, and kgCO_2e/m^2 measures the carbon efficiency of the energy used: two complementary perspectives for evaluating the sustainability of hospitals.

These indicators provide the reference framework used in the following subsection to contextualize the energy and carbon performance of the analyzed hospital and orthopedic department.

4.2. Global Comparison of Energy Consumption and Emissions by Geographic Area

Scientific literature indicates notable geographical differences in hospital energy consumption and associated emissions. Table 5 presents a comparison between the results obtained in this study and typical values of energy consumption (in kWh/m^2/year and kWh/bed/year) and CO_2 emissions (kgCO_2e/m^2/year) across major geographic regions, where data are available. These are indicative average values, as significant variability exists within each region based on factors such as facility size, climate, and the specialization of services. Values reported for the literature studies were derived from the original publications. Where necessary, unit conversions were performed to ensure consistency across indicators; however, original system boundaries and methodological assumptions were preserved.

Table 5. Energy and environmental indicators among different countries.

Geographical Area	kWh/m^2/Year	kWh/Bed/Year	kgCO_2e/m^2/Year
Europe [40–42]	250–300	20,000–60,000	100
North America [43,44]	738	80,000–120,000	200–250
Asia [45–48]	180–400	5000–15,000	50–150
Oceania [49]	393–460	40,000	180–200
Macro-level	855	87,793	130

Energy consumption in European hospitals exhibits an average profile on a global scale. Comparative studies indicate a mean intensity ranging from 270 to 333 kWh/m^2/year across EU countries. In Spain, energy audits have revealed diverse hospital consumption levels, spanning from 150 kWh/m^2/year for efficient facilities to over 500 kWh/m^2/year for those with high energy demands. In terms of bed capacity in Spain, this translates to an annual consumption of 20 to 60 MWh per bed [40]. Research conducted in Germany suggests an average energy intensity of 270 kWh/m^2, a figure consistent with other EU countries [42]. The average CO_2 emissions in Europe are 100 kgCO_2e/m^2/year, a relatively lower value attributed to the region's cleaner energy mix. Hospitals in Northern Europe tend to exhibit less energy consumption per m^2 due to colder climates and superior building insulation, while those in Southern Europe may require more energy for air conditioning during warmer months. The healthcare sector in Europe accounts for up to 5% of national energy consumption [41].

https://doi.org/10.3390/en19030836

North American hospitals, particularly in the United States, exhibit the highest energy intensities worldwide, with values around 740 kWh/m^2/year, approximately double the European average [42]. This is largely driven by larger floor areas per bed, continuous operation of energy-intensive HVAC systems, and extensive use of advanced medical equipment. In combination with a fossil-fuel-dominated energy mix, these factors result in high carbon intensities, often exceeding 200 kgCO_2e/m^2/year [43,44].

In Asia, hospital energy consumption is highly heterogeneous [45–47]. Facilities in lower-income contexts, such as public hospitals in India, show relatively low energy intensities (typically below 250 kWh/m^2/year), reflecting lower technological endowment and reduced cooling demand [45]. Conversely, modern hospitals in hot or humid climates, or those designed as large, high-tech complexes, can reach energy intensities comparable to North American facilities (>500 kWh/m^2/year) [46]. Across the region, climatic conditions and the carbon intensity of national electricity systems play a decisive role, with coal-based grids leading to disproportionately high emissions even at moderate energy consumption levels [47].

Hospitals in Oceania, particularly in Australia, display energy intensities comparable to those observed in North America, with values around 400–460 kWh/m^2/year for large facilities [49]. Factors such as warm climates, aging building stock, and reliance on coal-based electricity contribute to carbon intensities significantly higher than European benchmarks. At the same time, national programs promoting energy efficiency and on-site renewable generation indicate growing efforts to mitigate operational emissions [48].

Overall, these comparisons highlight that hospital energy and carbon intensity are not solely determined by healthcare activity levels, but are strongly influenced by structural characteristics, climate, and the energy system context, underscoring the importance of region-specific benchmarking and mitigation strategies.

In this study, the Macro-level energy intensity of the investigated Italian public hospital is 855 kWh/m^2/year, placing it significantly above both national and international benchmarks. The facility analyzed is an academic medical center with over 1200 beds, providing highly specialized and research-intensive care. Within the national context, ENEA (the Italian National Agency for New Technologies, Energy and Sustainable Economic Development) reports typical energy intensity values of 300–500 kWh/m^2 and annual consumption per bed of 60,000–70,000 kWh/bed/year for public hospitals, with very large teaching hospitals occasionally reaching 89,000 kWh/bed/year [50]. Our case hospital records 87,793 kWh/bed/year, approach the upper limit of this category despite already benefitting from scale-related efficiency (Figure 1). These figures highlight the burden imposed by both clinical complexity and infrastructural inertia.

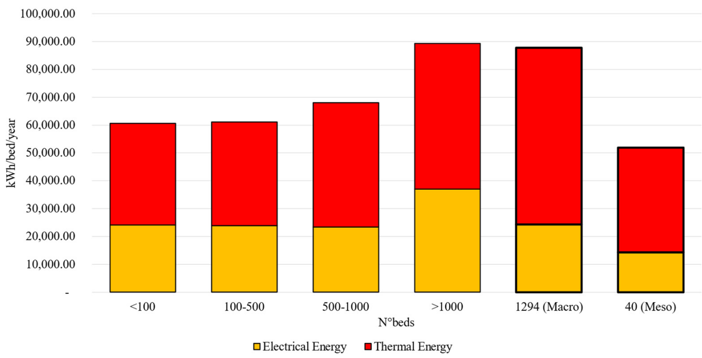


Figure 1. Comparison of the annual energy consumption per bed in Italian hospitals.

https://doi.org/10.3390/en19030836

On an international scale, the energy consumption and emissions performance of this hospital more closely resemble that of large academic centers in the U.S. rather than typical EU facilities. Its intensity metrics align with the North American model, characterized by extensive operations, advanced diagnostics, and high technological load.

As an academic institution, the hospital under study encompasses not only inpatient and surgical services, but also teaching spaces, research laboratories, and administrative offices. These non-clinical areas tend to increase total surface area without a proportional increase in the number of beds, which partially accounts for the elevated kWh/m^2 values. Nonetheless, the per-bed consumption remains high, indicating an urgent need for energy efficiency measures even at the operational level.

Our results show that the carbon intensity at both the Macro- and Meso-levels reaches 130 $kgCO_2e/m^2/year$ (Table 5), substantially exceeding the European average of 100 $kgCO_2e/m^2/year$. The primary factors contributing to these high values are the substantial reliance on fossil fuels, the potentially outdated building envelopes and HVAC systems.

Figure 2 provides a concise, yet powerful visual summary of the annual CO_2e emissions at the three analytical levels of the study: Macro-level (entire hospital), Meso-level (O&T department), and Micro-level (OR). This visual representation reinforces the key findings, particularly the elevated carbon intensity observed at the Macro-level, which significantly exceeds the European average. The Meso-level data highlight that, although the orthopedic department accounts for a relatively limited portion of the hospital's total surface area and energy use, it nonetheless contributes disproportionately to the institution's environmental emissions. This is primarily due to high HVAC demands and the volume of infectious waste generated. At the Micro-level, emissions per surgical procedure (9.17 $kgCO_2e$ from energy use and 5.4 $kgCO_2e$ from waste incineration) further illustrate how individual interventions cumulatively exert a substantial climate impact.

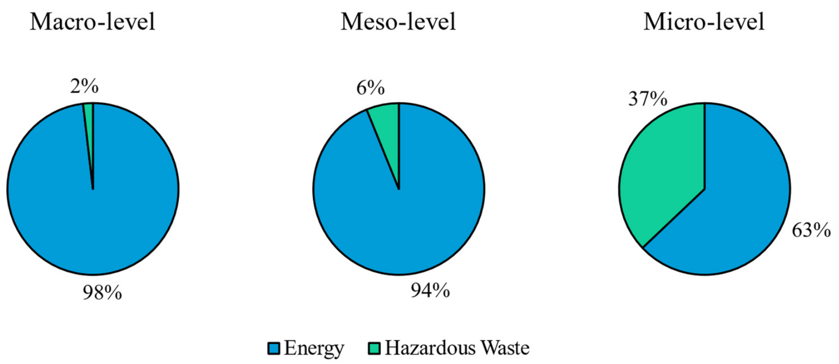


Figure 2. $kgCO_2e$ annual distribution at Macro- (hospital), Meso- (O&T department) and Micro- (OR) Level.

As shown in Table 6, when compared with recent orthopedic-specific studies adopting comprehensive life cycle assessment boundaries, the per-procedure emission value estimated in this study is substantially lower. This difference is primarily attributable to the intentionally limited system boundaries applied. While several orthopedic carbon footprint studies include upstream emissions related to implants, pharmaceuticals, single-use medical devices, sterilization processes, and broader supply chains [51,52], the present analysis is restricted to operational energy consumption and hazardous waste treatment.

https://doi.org/10.3390/en19030836

Table 6. Comparison with recent orthopedic surgery environmental impact studies.

Study	Country	System Boundary	Metric	Key Results	Notes on Comparability
[51]	Germany	Full LCA (Scope 1–3)	$kgCO_2e$/procedure	53–126 $kgCO_2e$	Includes implants, anesthetics, supply chain
[52]	Australia	Full LCA	$kgCO_2e$/TKR	~130 $kgCO_2e$	Includes prosthesis, sterilization, single-use devices
[53]	France	Waste-focused	$kgCO_2e$/procedure	Median 4.3 $kgCO_2e$	Waste only
[54]	Netherlands	Waste LCA	kg CO_2-eq	19–24 kg CO_2e	Full material LCA
[55]	Australia	Waste audit	kg waste/procedure	Avg 8.2 kg	Mass-based, not CO_2
This study	Italy	Energy consumption + hazardous waste	$kgCO_2e$/procedure	14.6 $kgCO_2e$	Partial operational account

Despite these boundary differences, the waste-related component estimated in this study (5.4 $kgCO_2e$ per procedure) is consistent with values reported in studies specifically focusing on intraoperative waste. For example, median waste-related footprints of approximately 4–5 $kgCO_2e$ per orthopedic procedure have been reported in the literature [53], while other analyses indicate that waste streams alone can exceed 19 kg CO_2-equivalent per procedure when evaluated using full life cycle approaches [54,55].

This consistency supports the validity of the waste incineration estimates adopted here and suggests that they provide a reasonable order-of-magnitude representation of downstream waste-related emissions within the defined system boundaries.

Collectively, these findings underscore the urgency of targeted energy efficiency and waste reduction strategies, particularly in high-intensity zones such as orthopedic operating theaters.

Figure 3 illustrates the impact of the O&T department on the hospital's energy- and waste-related emissions, representing about 1.91% of overall CO_2 equivalent emissions. In examining the internal structure of the O&T department, operating rooms are identified as a critical area, contributing 9.48% to the department's overall environmental effect. This assessment exclusively evaluated emissions associated with energy use and hazardous waste generation. According to this narrow focus, targeted interventions, especially in high-intensity regions like operating rooms, may present significant chances for emission reductions, even within departments with a marginal overall impact.

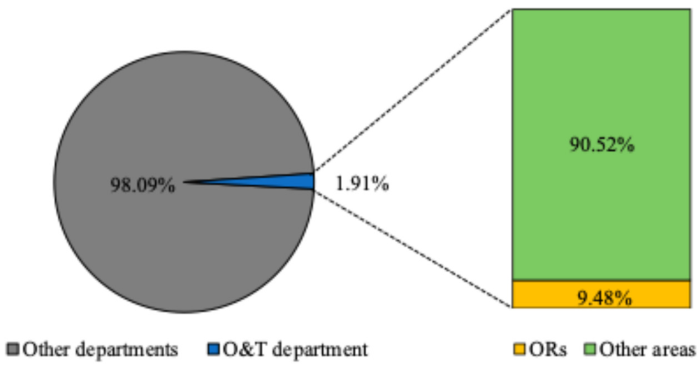


Figure 3. Environmental impact of O&T department and the contribution of ORs [$kgCO_2e$].

https://doi.org/10.3390/en19030836

4.3. Scalable Mitigation Strategies for Environmental Impact Reduction in Hospitals

Environmental sustainability in hospitals can be pursued through interventions at the three levels, analyzed (Macro, Meso, and Micro). Below, we present various environmental impact mitigation strategies for each level, along with scientific evidence quantifying the potential CO_2 emission savings.

4.3.1. Macro-Level

- Energy optimization and renewable sources: at the hospital level, a key lever is the reduction of energy-related emissions. Energy efficiency measures (e.g., smart building management systems, LED lighting, cogeneration) combined with the transition to a renewable energy mix can drastically reduce this footprint [56]. A notable example is the Boston Medical Center (USA), which has undertaken a sustainability plan involving facility renovation. As a result, the hospital has reduced its energy consumption-related CO_2 emissions by 91% (from 2011 to date), with annual operational savings exceeding $40 million reinvested in patient care [57]. This demonstrates the enormous potential of renewable sources on a macro scale. Other facilities have also achieved similar results: for example, some Chinese clinics that have installed photovoltaic systems report a reduction of over 1000 tons of CO_2 per year thanks to 2 GWh of solar electricity produced [58]. These structural interventions, while requiring initial investments, have a large-scale impact and guaranty permanent emission reductions.
- Hospital waste management policies: studies indicate that hazardous waste should typically constitute 10% of the total, but in practice, this proportion is often much higher due to excessive caution [59]. Adequate staff training and clear guidelines can prevent the "over-classification" of waste. Beyond the environmental advantages of minimizing hazardous waste, there exists an economic benefit, since the disposal of hazardous waste can be up to five times more expensive than conventional waste disposal. A hospital intervention showed that proper segregation of healthcare waste led to a reduction of approximately 85% in CO_2 emissions related to that waste [60]. In absolute terms, the carbon footprint of waste treatment in the operating room block decreased from approximately 527 kg CO_2eq to just 79.1 kg CO_2eq per week after the recycling program. This is equivalent to over 23 tons of CO_2 avoided per year, simply by improving waste management at the hospital/department level.

4.3.2. Meso-Level

- Intelligent ventilation management in the operating room: operating rooms (ORs) have stringent air exchange and filtration requirements to ensure sterility. An effective strategy to reduce the HVAC energy consumption is to implement "setback" modes during off-peak hours, reducing the number of air changes when the rooms are not in use (e.g., at night). The literature confirms that reducing the ventilation flow in the operating room outside of surgical hours does not compromise air quality or increase the risk of infection, provided the systems are brought back to full operation before use [61]. A case was documented where reduced mode was extended to 19 out of 22 operating rooms during nights and weekends (leaving three active for emergencies), resulting in a 50% reduction in HVAC energy consumption compared to the baseline [20]. Other simulations indicate that reducing the air changes per hour from 30 to 6 in rest rooms can cut ventilation energy costs by up to 70%, without a significant increase in microbial contamination [62]. In a Spanish study of a surgical block, optimizing microclimate parameters during downtime resulted in an annual energy saving of 70% compared to traditional management [63]. Additionally, new "smart" systems like RFID sensors to automatically detect room occupancy can dy-

https://doi.org/10.3390/en19030836

namically adjust ventilation, with pilot studies estimating a further energy saving of 50% compared to constant ventilation [64].

- Reusable materials: implementing programs to replace single-use materials with reusable and sterilizable alternatives at the ward level is a key strategy. Numerous comparisons in the literature highlight the environmental benefits of reusables without compromising safety. For example, a comparative study on single-use vs. reusable anesthesia devices found that switching to reusable can reduce CO_2 emissions by 84% in Europe (thanks also to a cleaner energy mix), by 48% in the USA, and, conversely, could slightly increase them in Australia (+9%) where the electricity mix was more carbon-intensive [61]. This highlights the importance of both choosing reusable items and powering sterilization centers with renewable energy. Another study analyzed the impact of reusable vs. disposable surgical gowns: reusable gowns showed a carbon footprint approximately 60% lower than their disposable equivalents. Similarly, reusable surgical caps have significantly lower carbon footprints and other impact categories compared to single-use TNT caps [65]. At the ward level, the systematic adoption of reusable linens, clothing, and instruments (in line with infection prevention guidelines) can therefore avoid several tons of CO_2 per year. It should be noted that in many hospitals, there has been a shift towards single-use items in recent decades for perceived reasons of convenience or reduced infection risk, but evidence indicates that well-sterilized reusable devices do not increase surgical infections. Therefore, reversing this trend where possible represents a significant sustainability opportunity at the Meso-level.

4.3.3. Micro-Level

- Optimization of surgical kits and reduction of unused open materials: "streamlining" procedural sets to eliminate non-essential tools or materials can reduce both waste and embodied emissions. An exemplary case comes from ophthalmic surgery [66] in which a recent study calculated the carbon footprint of cataract surgery and evaluated two Micro-level-level interventions: removing unnecessary items from single-use kits and replacing some single-use instruments with reusable equivalents. The result was a saving of 935 kg CO_2/year thanks to the streamlining kit and an additional 309 kg CO_2/year thanks to the switch to reusable items. In total, for the volume of cataracts considered, approximately 1.24 tons of CO_2 per year were avoided. Additionally, the study found that for the devices considered, single-use items had a footprint 27 times greater than reusable versions: this means that reusing a device about 20 times is enough for a reusable device to become advantageous in terms of net emissions compared to 20 equivalent single-use devices. This type of analysis can be extended to other procedures (e.g., arthroplasty kits, laparoscopy sets, etc.), identifying the highest-impact items for each intervention and acting on them (eliminating them if unused, or introducing reusable alternatives). For example, in orthopedic surgery, optimizing open screws and plates for synthesis procedures can avoid costly waste. Similarly, customizing instrument trays (modular instrumentation instead of standard complete sets) reduces the number of materials that need to be sterilely reprocessed after surgery, saving energy and CO_2.
- Sustainable practices in the operating room: there are micro-organizational measures that, although not always quantified in kg of CO_2, contribute to reducing waste and emissions. For example, turning off or putting unnecessary electrical equipment into standby mode during the procedure (or between procedures) reduces the room's energy consumption without impacting care [67]. Similarly, carefully preparing sterile materials before surgery and opening only what is truly needed can prevent many

https://doi.org/10.3390/en19030836

new items from being unnecessarily contaminated and then discarded. "Lean surgery" projects in the literature have shown that by involving the surgical team in systematically identifying and removing waste, not only is there cost savings, but also a significant reduction in waste per procedure (up to −30%) and consequently in the emissions associated with their life cycle [68,69]. In hand surgery, for example, the adoption of "lean" techniques has allowed for a reduction in the number of instruments opened but not used, resulting in a decrease in the carbon footprint per procedure without compromising clinical outcomes [70]. Although the benefits of these punctual changes may seem small, their sum across thousands of annual procedures makes them significant.

From an implementation perspective, the mitigation strategies discussed above differ substantially in terms of feasibility, time horizon, and potential impact within the analyzed hospital. Measures related to operational optimization, such as improved scheduling of operating rooms, enhanced waste segregation, and behavioral interventions targeting staff practices, represent low-cost and low-barrier options that could be implemented in the short term. These strategies do not require major infrastructural changes and could yield immediate reductions in energy use and waste generation.

Conversely, strategies involving HVAC system retrofitting, electrification of thermal energy supply, or on-site renewable energy generation are associated with higher mitigation potential but face significant implementation barriers in the analyzed unit. These include high upfront investment costs, constraints related to existing building infrastructure, and the need to ensure uninterrupted clinical operations in critical areas such as operating theaters. As a result, while these measures could substantially reduce operational emissions, their deployment is more likely to occur over a medium- to long-term planning horizon.

5. Conclusions

This study provides a comprehensive, multiscale environmental assessment of an orthopedic department within a major Italian public hospital, examining energy consumption and waste generation at Macro-, Meso-, and Micro-levels. The findings reveal that the hospital's energy intensity (855 kWh/m^2/year and 87,793 kWh/bed/year) significantly exceeds both national and international benchmarks, exhibiting a closer alignment with North American academic medical centers rather than European counterparts. Despite its size and complexity, the institution demonstrates considerable potential for enhancing energy efficiency and reducing emissions. At the Meso-level, the Orthopedic and Trauma department emerged as a disproportionate contributor to the hospital's energy- and waste-related emissions, primarily driven by energy consumption related to HVAC systems and the generation of infectious waste. Micro-level analysis of operating rooms revealed average emissions of 14.6 kgCO_2e per surgical procedure, 9.17 kg from energy use, and 5.4 kg from hazardous waste incineration, highlighting the environmental impact of individual clinical activities.

This study underscores the utility of a multilevel analytical framework for pinpointing specific hotspots and inefficiencies that may be overlooked in aggregated assessments. This approach facilitates the implementation of targeted interventions in high-impact areas, such as surgical theaters, HVAC systems, and waste management protocols. It also emphasizes the importance of integrating sustainability considerations into hospital operations and clinical decision-making processes.

Overall, the proposed methodology offers a replicable and policy-relevant instrument for monitoring environmental performance within healthcare settings. While not intended to represent the full carbon footprint of orthopedic care, the approach lowers the barrier to engagement with sustainability for hospital managers and clinicians. Future research

https://doi.org/10.3390/en19030836

should extend this framework to other departments and institutions, incorporate real-time metering and Scope 3 emissions, and evaluate the effectiveness of mitigation strategies. By doing so, healthcare systems can better align clinical excellence with environmental stewardship, ultimately advancing both public and planetary health.

6. Limitation

This study does not represent the total carbon footprint of orthopedic care, but a partial operational carbon account limited to energy consumption (electricity, district heating and cooling) and infectious waste treatment. Upstream Scope 3 emissions related to pharmaceuticals, medical implants, consumables, food services, and patient or staff transportation were not included. As widely documented in the literature, these omitted sources may account for most healthcare-related emissions; therefore, the results presented here should not be interpreted as the overall carbon footprint of an orthopedic department.

A further limitation concerns data availability and system boundaries. Energy consumption at the departmental and operating-room level was partially estimated through allocation and modelling approaches due to the absence of sub-metering. Similarly, waste-related emissions were calculated using average emission factors for high-temperature incineration with energy recovery, which introduces uncertainty related to treatment efficiency and fossil carbon content.

The Micro-level analysis was based on direct measurements conducted in two operating rooms over a limited observation period. Although the monitored days were selected to be representative of typical surgical activity, the resulting values should be interpreted as order-of-magnitude estimates rather than statistically exhaustive measurements. No inferential statistical analysis was performed due to the exploratory nature of the study and the limited sample size.

Despite these limitations, the proposed framework offers a transparent and replicable approach that can support internal benchmarking and identify priority areas for mitigation. Future research should expand the system boundaries to include upstream Scope 3 emissions, integrate real-time metering, and apply the methodology across multiple hospitals and clinical specialties.

Author Contributions: Conceptualization, A.S., B.M. and A.R.; methodology, A.S., B.M. and A.R.; validation, A.S., B.M., A.R., P.G. and G.M.; formal analysis, A.S. and B.M.; investigation, A.S., B.M. and A.R.; resources, P.G. and G.M.; data curation, P.G. and G.M.; writing—original draft preparation, A.S., B.M. and A.R.; writing—review and editing, P.G., G.M., S.Z. and L.E.Z.; visualization, A.S. and B.M.; supervision, S.Z. and L.E.Z.; project administration, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Marfe, G.; Perna, S.; Hermann, A. Challenges in Healthcare Waste Management of the UN 2030 Agenda in the COVID-19 Era. *Am. J. Environ. Sci.* **2022**, *18*, 20–41. [CrossRef]
2. Mazzeo, D.; Baglivo, C.; Panico, S.; Manieri, M.; Matera, N.; Congedo, P.M. Eco-Sustainable Energy Production in Healthcare: Trends and Challenges in Renewable Energy Systems. *Energies* **2023**, *16*, 7285. [CrossRef]
3. Lenzen, M.; Malik, A.; Li, M.; Fry, J.; Weisz, H.; Pichler, P.-P.; Chaves, L.S.M.; Capon, A.; Pencheon, D. The Environmental Footprint of Health Care: A Global Assessment. *Lancet Planet. Health* **2020**, *4*, e271–e279. [CrossRef] [PubMed]

https://doi.org/10.3390/en19030836

4. Malik, A.; Lenzen, M.; McAlister, S.; McGain, F. The Carbon Footprint of Australian Health Care. *Lancet Planet. Health* **2018**, *2*, e27–e35. [CrossRef] [PubMed]
5. Eckelman, M.J.; Sherman, J. Environmental Impacts of the U.S. Health Care System and Effects on Public Health. *PLoS ONE* **2016**, *11*, e0157014. [CrossRef]
6. Eckelman, M.J.; Sherman, J.D.; MacNeill, A.J. Life Cycle Environmental Emissions and Health Damages from the Canadian Healthcare System: An Economic-Environmental-Epidemiological Analysis. *PLoS Med.* **2018**, *15*, e1002623. [CrossRef]
7. Nansai, K.; Fry, J.; Malik, A.; Takayanagi, W.; Kondo, N. Carbon Footprint of Japanese Health Care Services from 2011 to 2015. *Resour. Conserv. Recycl.* **2020**, *152*, 104525. [CrossRef]
8. Wu, R. The Carbon Footprint of the Chinese Health-Care System: An Environmentally Extended Input–Output and Structural Path Analysis Study. *Lancet Planet. Health* **2019**, *3*, e413–e419. [CrossRef]
9. Steenmeijer, M.A.; Rodrigues, J.F.D.; Zijp, M.C.; Waaijers-van der Loop, S.L. The Environmental Impact of the Dutch Health-Care Sector beyond Climate Change: An Input–Output Analysis. *Lancet Planet. Health* **2022**, *6*, e949–e957. [CrossRef]
10. Irwin, A.; Geschke, A.; Mackenbach, J.P. The Biodiversity Impact of Health Care: Quantifying the Extinction-Risk Footprint of Health Care in The Netherlands and Other European Countries. *Sustainability* **2024**, *16*, 1343. [CrossRef]
11. Keller, R.L.; Muir, K.; Roth, F.; Jattke, M.; Stucki, M. From Bandages to Buildings: Identifying the Environmental Hotspots of Hospitals. *J. Clean. Prod.* **2021**, *319*, 128479. [CrossRef]
12. Keil, M. The Greenhouse Gas Emissions of a German Hospital—A Case Study of an Easy-to-Use Approach Based on Financial Data. *Clean. Environ. Syst.* **2023**, *11*, 100140. [CrossRef]
13. *The Greenhouse Gas Protocol: The GHG Protocol for Project Accounting*; World Business Council for Sustainable Development: Genève, Switzerland; World Resources Institute: Washington, DC, USA, 2005; ISBN 1569735980.
14. Lau, I.; Burdorf, A.; Hesseling, S.; Wijk, L.; Tauber, M.; Hunfeld, N. The Carbon Footprint of a Dutch Academic Hospital—Using a Hybrid Assessment Method to Identify Driving Activities and Departments. *Front. Public Health* **2024**, *12*, 1380400. [CrossRef] [PubMed]
15. Mermillod, B.; Tornare, R.; Jochum, B.; Ray, N.; Flahault, A. Estimating the Carbon Footprint of Healthcare in the Canton of Geneva and Reduction Scenarios for 2030 and 2040. *Int. J. Environ. Res. Public Health* **2024**, *21*, 690. [CrossRef]
16. Tennison, I.; Roschnik, S.; Ashby, B.; Boyd, R.; Hamilton, I.; Oreszczyn, T.; Owen, A.; Romanello, M.; Ruyssevelt, P.; Sherman, J.D.; et al. Health Care's Response to Climate Change: A Carbon Footprint Assessment of the NHS in England. *Lancet Planet. Health* **2021**, *5*, e84–e92. [CrossRef]
17. Sherman, J.; Le, C.; Lamers, V.; Eckelman, M. Life Cycle Greenhouse Gas Emissions of Anesthetic Drugs. *Anesth. Analg.* **2012**, *114*, 1086–1090. [CrossRef]
18. Cimprich, A.; Young, S.B. Environmental Footprinting of Hospitals: Organizational Life Cycle Assessment of a Canadian Hospital. *J. Ind. Ecol.* **2023**, *27*, 1335–1353. [CrossRef]
19. Hernandez, C.; Rodrigues, C.; Marques, P.; Freire, F. Life Cycle Assessment of a Large Volume Parenteral for Hospital Use. *Resour. Conserv. Recycl.* **2023**, *198*, 107120. [CrossRef]
20. MacNeill, A.J.; Lillywhite, R.; Brown, C.J. The Impact of Surgery on Global Climate: A Carbon Footprinting Study of Operating Theatres in Three Health Systems. *Lancet Planet. Health* **2017**, *1*, e381–e388. [CrossRef]
21. Weisz, U.; Pichler, P.-P.; Jaccard, I.S.; Haas, W.; Matej, S.; Bachner, F.; Nowak, P.; Weisz, H. Carbon Emission Trends and Sustainability Options in Austrian Health Care. *Resour. Conserv. Recycl.* **2020**, *160*, 104862. [CrossRef]
22. Savio, A.; Marchi, B.; Roletto, A.; Guizzi, P.; Milano, G.; Zavanella, L.E.; Zanoni, S. Assessing Energy and Waste Impacts in Orthopaedic Departments: A Case Study from an Italian Public Hospital. In Proceedings of the 20th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, 5–10 October 2025.
23. Cook, N.; Goodwin, D.; Porter, J.; Collins, J. Food and Food-related Waste Management Strategies in Hospital Food Services: A Systematic Review. *Nutr. Diet.* **2023**, *80*, 116–142. [CrossRef]
24. Marino, A.; Pariso, P. Digital Innovation Government: Organizational and Energy Analysis in Italian Hospitals. *Entrep. Sustain. Issues* **2023**, *10*, 214–230. [CrossRef]
25. Roletto, A.; Savio, A.; Masperi, A.; Bonfitto, G.R.; Pala, F.; Migliorisi, C.; Zanoni, S. Energy Usage Assessment and Energy Savings Estimation in a Radiology Department in Italy. *Energies* **2025**, *18*, 1936. [CrossRef]
26. Savoldelli, A.; Landi, D.; Rizzi, C. Exploring the Environmental Impact of Telemedicine: A Life Cycle Assessment. In *dHealth 2024*; IOS Press: Amsterdam, The Netherlands, 2024; Volume 313, pp. 81–86.
27. Elli, L.; La Mura, S.; Rimondi, A.; Scaramella, L.; Tontini, G.E.; Monica, F.; Soncini, M.; Topa, M.; Bortoluzzi, F.; Sorge, A.; et al. The Carbon Cost of Inappropriate Endoscopy. *Gastrointest. Endosc.* **2024**, *99*, 137–145.e3. [CrossRef]
28. Shah, S.; Morris, H.; Thiagarajah, S.; Gordon, A.; Sharma, S.; Haslam, P.; Garcia, J.; Ali, F. Handling 'Carbon Footprint' in Orthopaedics. *Ann. R. Coll. Surg. Engl.* **2024**, *106*, 498–503. [CrossRef]
29. Eidmann, A.; Stratos, I.; Scarlat, M.; Rudert, M. Sustainability in Orthopaedic Hospitals—Urgent Actions for a Changing Climate. Can We Make Orthopaedics Climate Smart? *Int. Orthop.* **2025**, *49*, 311–313. [CrossRef]

https://doi.org/10.3390/en19030836

30. Cusano, G.; Roudier, S.; Neuwahl, F.; Holbrook, S.; Gómez Benavides, J. *Best Available Techniques (BAT) Reference Document for Waste Incineration—Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)*; Publications Office: Luxembourg, 2019.
31. A2A. *A2A ESG Highlights 2023*; A2A S.p.A.: Milan, Italy, 2023. Available online: https://www.gruppoa2a.it/en/sustainability (accessed on 15 October 2024).
32. ISPRA—Istituto Superiore per la Protezione e la Ricerca Ambientale. *Le Emissioni Di CO_2 Nel Settore Elettrico Nazionale e Regionale*; ISPRA: Rome, Italy, 2025; ISBN 978-88-448-1256-0.
33. ISPRA—Istituto Superiore per la Protezione e la Ricerca Ambientale. Italian Greenhouse Gas Inventory 1990–2022. National Inventory Report 2024. Available online: https://www.isprambiente.gov.it/en/publications/reports (accessed on 8 January 2025).
34. Legambiente Brescia. *Legambiente Brescia Il Teleriscaldamento Urbano: Il Caso Brescia E Considerazioni Generali*; Audizione presso ARERA, "Crisi energia: Prospettive e proposte settoriali"; Legambiente Brescia: Brescia, Italy, 2022. Available online: https://www.arera.it/fileadmin/allegati/audizioni/pubbliche/22/Legambiente%20Brescia_aud22.pdf (accessed on 15 October 2024).
35. Italian Republic. *D.P.R. 15 Luglio 2003 n. 254*; Gazzetta Ufficiale della Repubblica Italiana: Rome, Italy, 2003. Available online: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.del.presidente.della.repubblica:2003-07-15;254 (accessed on 15 October 2024).
36. Ministero dell'Ambiente e della Sicurezza Energetica Recycling and Waste Management. Available online: https://www.mase.gov.it/pagina/recycling-and-waste-management#rifiuti_pericolosi (accessed on 5 May 2025).
37. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Waste: Geneva, Switzerland, 2019; Volume 5.
38. Comune di Reggio Emilia. *CarbonZERO—Relazione Tecnica*; Comune di Reggio Emilia: Reggio Emilia, Italy, 2015. Available online: https://rigenerazione-strumenti.comune.re.it/carbonzero/ (accessed on 15 October 2024).
39. CIBSE—Chartered Institution of Building Services Engineers. *Guide A: Environmental Design*; CISBE: London, UK, 2015; ISBN 9781906846541.
40. García-Sanz-Calcedo, J. Study of CO_2 Emissions from Energy Consumption in Spanish Hospitals. *Vibroeng. Procedia* **2019**, *26*, 46–51. [CrossRef]
41. Sustainability and Environmental Protection in Hospitals. Available online: https://www.etkho.com/en/sustainability-and-environmental-protection-in-hospitals/#:~:text=Let%E2%80%99s%20put%20it%20in%20figures,lighting%20and%20hot%20water%20supply (accessed on 5 May 2025).
42. González González, A.; García-Sanz-Calcedo, J.; Rodríguez Salgado, D. Evaluation of Energy Consumption in German Hospitals: Benchmarking in the Public Sector. *Energies* **2018**, *11*, 2279. [CrossRef]
43. Chung, J.W.; Meltzer, D.O. Estimate of the Carbon Footprint of the US Health Care Sector. *JAMA* **2009**, *302*, 1970. [CrossRef] [PubMed]
44. Bawaneh, K.; Ghazi Nezami, F.; Rasheduzzaman, M.; Deken, B. Energy Consumption Analysis and Characterization of Healthcare Facilities in the United States. *Energies* **2019**, *12*, 3775. [CrossRef]
45. Kumar, S.; Yadav, N.; Singh, M.; Kachhawa, S. Estimating India's Commercial Building Stock to Address the Energy Data Challenge. *Build. Res. Inf.* **2019**, *47*, 24–37. [CrossRef]
46. De Masi, R.F.; Del Regno, N.; Gigante, A.; Ruggiero, S.; Russo, A.; Tariello, F.; Vanoli, G.P. The Importance of Investing in the Energy Refurbishment of Hospitals: Results of a Case Study in a Mediterranean Climate. *Sustainability* **2023**, *15*, 11450. [CrossRef]
47. Hu, S.-C.; Chuah, Y.; Hu, S.C.; Chen, J.D.; Chuah, Y.K. Energy Cost and Consumption in a Large Acute Hospital. *Int. J. Archit. Sci.* **2004**, *5*, 11–19.
48. Brown, L.H.; Buettner, P.G.; Canyon, D.V. The Energy Burden and Environmental Impact of Health Services. *Am. J. Public Health* **2012**, *102*, e76–e82. [CrossRef]
49. Miller, W.F.; Liu, A.; Crompton, G.; Ma, Y. *Healthcare Sector Energy Baseline and Key Performance Indicators*; Queensland University of Technology: Brisbane, QLD, Australia, 2020. Available online: https://ihub.org.au/wp-content/uploads/LLHC1_Healthcare_Sector_Baseline_Energy_Report_V01.pdf (accessed on 25 October 2024).
50. Baldazzi, A.S.; Beltrone, E.; Mostacci, A.A.; Mura, A.; Napoleoni, D.; Pasquino, F.; Santangelo, A.; Stemperini, A.; Toso, F. *Rapporto Sulla Raccolta Dati per la Determinazione e Caratterizzazione Delle Tipologie di Impianto per Il Condizionamento Invernale ed Estivo Negli Edifici ad uso Ospedaliero*; ENEA—Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile: Rome, Italy, 2013; Report RdS/2013/141. Available online: https://www.ricercasistemaelettrico.enea.it/archivio-documenti.html?task=download.send&id=4900:rapporto-sulla-raccolta-dati-per-la-determinazione-e-caratterizzazione-delle-tipologie-di-impianto-per-il-condizionamento-invernale-ed-estivo-negli-edifici-destinati-a-scuole-e-uffici&catid=460 (accessed on 30 October 2024).
51. Eidmann, A.; Geiger, F.; Heinz, T.; Jakuscheit, A.; Docheva, D.; Horas, K.; Stratos, I.; Rudert, M. Our Impact on Global Warming. *J. Bone Jt. Surg.* **2024**, *106*, 1971–1977. [CrossRef] [PubMed]

https://doi.org/10.3390/en19030836

52. McGain, F.; Wickramarachchi, K.; Aye, L.; Chan, B.G.; Sheridan, N.; Tran, P.; McAlister, S. The Carbon Footprint of Total Knee Replacements. *Aust. Health Rev.* **2024**, *48*, 664–672. [CrossRef]
53. Ogeron, P.; Boukebous, B.; Desender, A.; Massard-Combe, P.; Vorimore, C.; Guillon, P. Average Total Weight of Surgical Waste and CO_2 Carbon Footprint of Orthopedic Surgery in France, Estimated on the Basis of a Representative Panel. *Orthop. Traumatol. Surg. Res.* **2024**, *110*, 103910. [CrossRef]
54. Klarenbeek, I.C.; Janssen, E.R.C.; Willems, P.C.; Lambers Heerspink, O.F.; van der Eijk, A.C. Waste in Orthopaedic Surgery; an Application of the Healthcare Sustainability Mode and Effect Analysis. *Int. Orthop.* **2025**, *49*, 2393–2401. [CrossRef]
55. Drobetz, N.; Xu, J.; Chang, D.; Hazan, D.; Collins, W.; Drobetz, H. Less Trash, More Treasure. Waste Production and Reduction in Orthopaedic Surgery. *ANZ J. Surg.* **2025**, *95*, 539–543. [CrossRef] [PubMed]
56. Psillaki, M.; Apostolopoulos, N.; Makris, I.; Liargovas, P.; Apostolopoulos, S.; Dimitrakopoulos, P.; Sklias, G. Hospitals' Energy Efficiency in the Perspective of Saving Resources and Providing Quality Services through Technological Options: A Systematic Literature Review. *Energies* **2023**, *16*, 755. [CrossRef]
57. Boston Medical Center Boston Medical Center Recognized as a Top 25 Hospital in the Nation for Environmental Excellence and Practice Greenhealth's Environmental Excellence Awards. Available online: https://www.bmc.org/news/boston-medical-center-recognized-top-25-hospital-nation-environmental-excellence-practice (accessed on 15 November 2025).
58. Yu, D.; Tan, X.; Liu, Z.; Li, D.; Wang, Z.; Yan, P.; Ni, J. Energy Saving and Carbon Reduction Schemes for Hospital with Photovoltaic Power Generation and System Upgrading Technology. *Heliyon* **2023**, *9*, e21447. [CrossRef]
59. Yeoh, C.B. Challenges of Going Green in the Operating Room. *Anaesth. Surg. Open Access J.* **2020**, *2*, 000527. [CrossRef]
60. Carmona-Pomada, B.; Diaz-Co, L.; Azaroual El Bachiri, H.; Nieto-Lorente, N.; Muriel-Serrano, G.; Zarza-Sánchez, L.; Caro-Benito, C.; Monistrol, O. Segregation and Recycling in the Operating Room. An Intervention to Accelerate the Decarbonisation Process in the Health Sector. *J. Clin. Nurs.* **2025**, *34*, 4735–4746. [CrossRef]
61. Bolten, A.; Kringos, D.S.; Spijkerman, I.J.B.; Sperna Weiland, N.H. The Carbon Footprint of the Operating Room Related to Infection Prevention Measures: A Scoping Review. *J. Hosp. Infect.* **2022**, *128*, 64–73. [CrossRef]
62. Lee, S.T.; Liang, C.C.; Chien, T.Y.; Wu, F.J.; Fan, K.C.; Wan, G.H. Effect of Ventilation Rate on Air Cleanliness and Energy Consumption in Operation Rooms at Rest. *Environ. Monit. Assess.* **2018**, *190*, 178. [CrossRef]
63. Cacabelos-Reyes, A.; López-González, J.L.; González-Gil, A.; Febrero-Garrido, L.; Eguía-Oller, P.; Granada-Álvarez, E. Assessing the Energy Demand Reduction in a Surgical Suite by Optimizing the HVAC Operation During Off-Use Periods. *Appl. Sci.* **2020**, *10*, 2233. [CrossRef]
64. Lin, J.; Pai, J.Y.; Chen, C.C. Applied Patent RFID Systems for Building Reacting HEPA Air Ventilation System in Hospital Operation Rooms. *J. Med. Syst.* **2012**, *36*, 3399–3405. [CrossRef] [PubMed]
65. Gumera, A.; Mil, M.; Hains, L.; Fanshaw, S.-R.; Dunne, B. Reusable Surgical Headwear Has a Reduced Carbon Footprint and Matches Disposables Regarding Surgical Site Infection: A Systematic Review and Meta-Analysis. *J. Hosp. Infect.* **2024**, *152*, 164–172. [CrossRef] [PubMed]
66. McCance, E.; Steinbach, I.; Morris, D.S. Comparative Carbon Footprinting Study of Reusable vs. Disposable Instruments in Cataract Surgery. *Eye* **2025**, *39*, 1481–1485. [CrossRef] [PubMed]
67. Heye, T.; Meyer, M.T.; Merkle, E.M.; Vosshenrich, J. Turn It Off! A Simple Method to Save Energy and CO_2 Emissions in a Hospital Setting with Focus on Radiology by Monitoring Nonproductive Energy-Consuming Devices. *Radiology* **2023**, *307*, 230162. [CrossRef] [PubMed]
68. Kodumuri, P.; Jesudason, E.P.; Lees, V. Reducing the Carbon Footprint in Carpal Tunnel Surgery inside the Operating Room with a Lean and Green Model: A Comparative Study. *J. Hand Surg. Eur. Vol.* **2023**, *48*, 1022–1029. [CrossRef] [PubMed]
69. McNally, S.; Phizacklea, E.C.; Gibbs, V.N.; Brown, R.; Wilcocks, K.V.; O'Brien, S.; Burton, H.K.; Evans, S.; Vella-Baldacchino, M.; Khader, A.; et al. Lean Pathways in Orthopaedics: Multiple Wins for Sustainability. *Orthop. Trauma* **2022**, *36*, 265–273. [CrossRef]
70. Van Demark, R.E.; Smith, V.J.S.; Fiegen, A. Lean and Green Hand Surgery. *J. Hand Surg. Am.* **2018**, *43*, 179–181. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

https://doi.org/10.3390/en19030836

PAPER 6

Roletto *et al. European Radiology Experimental* (2026)10:3
https://doi.org/10.1186/s41747-025-00668-w

EUROPEAN SOCIETY OF RADIOLOGY
European Radiology
EXPERIMENTAL

ORIGINAL ARTICLE **Open Access**

Energy performance of MRI systems: on-site validation and comparison with manufacturer declarations

Andrea Roletto[1*], Matteo Verga[2,3], Anna Savio[1], Gian Luca Viganò[2] and Simone Zanoni[4]

Abstract

Objectives This study aims to evaluate the actual energy consumption of two generations of 1.5-T magnetic resonance imaging (MRI) scanners, quantify the benefits in terms of primary energy savings resulting from technological replacement, and compare field estimates of primary energy consumption with those reported in environmental product declarations (EPDs).

Materials and methods Two 1.5-T MRI scanner models, the old model version and its new model replacement, were monitored using a power quality analyzer connected to the electrical cabinet. Electrical power consumption data were collected over 2-week periods, both before and after the scanner replacement. Primary energy consumption was projected over 10 years, and the resulting values were compared with those reported in the EPDs for the two scanners.

Results Over 10 years, cumulative energy consumption is estimated to be 1,010.4 MWh for the new unit *versus* 1,206.7 MWh for the old unit, corresponding to a 16.3% reduction. Considering the range of European primary energy factors (PEFs), energy savings varied from 235.6 to 687.1 MWh. Comparison with EPDs revealed significant discrepancies (± 40%) depending on the national PEF used, demonstrating that EPDs can both overestimate and underestimate actual energy consumption.

Conclusion Replacement of an old MRI model resulted in measurable energy savings, particularly in non-productive phases. However, EPDs do not always reflect clinical operation or the impact of national energy mixes. While energy efficiency is central to sustainable radiology, it should not be the sole driver for equipment replacement, which must remain primarily guided by clinical and diagnostic criteria.

Relevance statement For a radiology department focused on more sustainable practices, it is essential to have accurate data on the environmental performance of medical imaging equipment, which should not be based solely on EPDs, but on real data based on usage patterns and national energy mixes.

Key Points

- Replacing the old MRI scanner reduced energy consumption by 16.3%, mainly due to lower use in non-productive modes.
- Over a 10-year operational period, the primary energy consumption savings varied from 235.6 to 687.1 MWh.
- A discrepancy emerged between EPD-reported and real-world measurements, highlighting the importance of on-site validation for sustainability assessments.

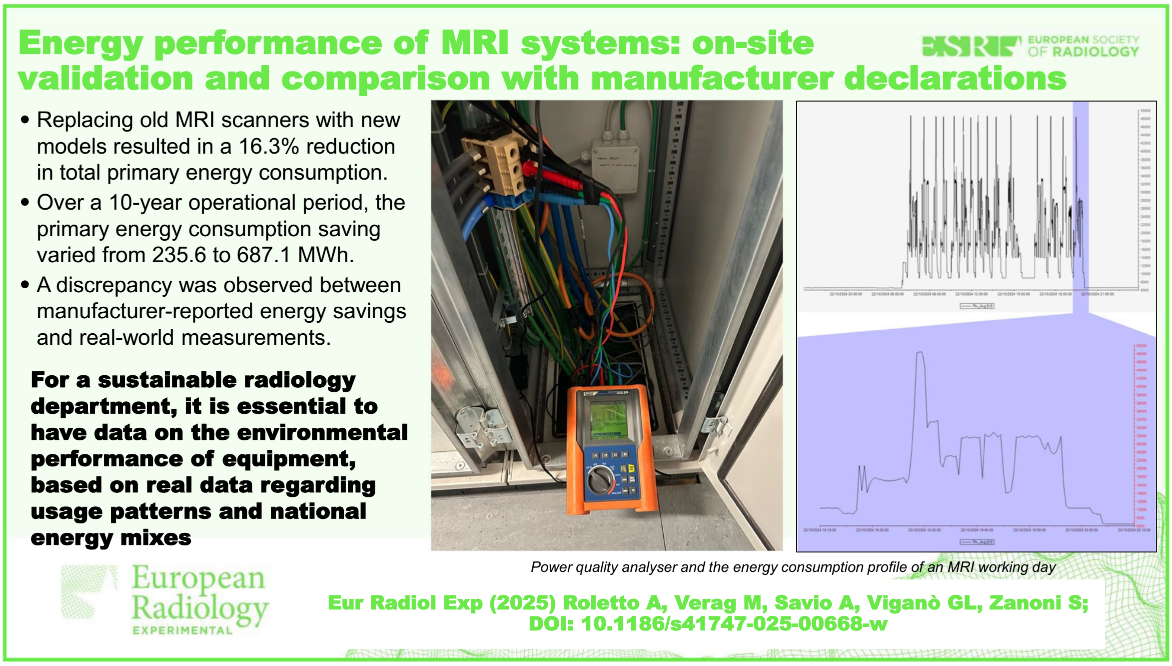
Keywords Carbon footprint, Conservation of natural resources, Electricity, Magnetic resonance imaging, Radiology

*Correspondence:
Andrea Roletto
andrea.roletto@unibs.it
Full list of author information is available at the end of the article

Springer

© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Graphical Abstract



Background

In recent years, the healthcare sector has paid increasing attention to environmental sustainability, especially in high-energy consumption departments such as radiology [1–5]. Magnetic resonance imaging (MRI) scanners, essential for diagnosing a wide range of medical conditions, are known for their substantial energy requirements, intended as the electrical power required by the MRI scanner to perform daily diagnostic activities [6, 7]. Various studies estimate the annual energy consumption of an MRI scanner to exceed 100,000 kWh [8, 9]. In view of this, several studies have examined the possibility of introducing operational strategies aimed at reducing both energy consumption and the carbon footprint of MRI scanners.

Among the most frequently discussed energy-saving strategies in the literature is the management of the MRI's power usage across different operating phases [10–12]. Indeed, it has been estimated that simply switching from "idle" mode to "power save" mode during non-operational hours can reduce energy consumption by 25–33%. This mode adjusts hardware components for reduced power use, enabling substantial energy savings [10]. Recent studies have also investigated energy consumption from different perspectives, such as protocol-level determinants and operational management options [13, 14] or broader strategies integrating ecodesign and sustainable operations for MRI and CT [15].

Leading companies in the medical imaging technology sector are also making significant progress in reducing the energy consumption of MRI scanners, equipping the latest systems with an "eco-power mode" that regulates the helium compressor's operation to limit energy usage [16]. As a result, replacing obsolete MRI systems with more modern counterparts could offer considerable advantages in terms of energy efficiency, both at the hardware and software levels [17]. Initial findings have already been reported by the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry (COCIR), which observed a reduction in the daily energy consumption of MRI scanners over the years. Data show a drop from 226 kWh in 2011 to 165 kWh in 2017, attributing this progress to both more efficient scanner design and smarter operating practices.

This suggests that next-generation MRI technologies not only deliver improved diagnostic performance but also align more closely with environmental sustainability goals [18]. Energy consumption is one of the most important environmental characteristics of medical devices, as it directly influences both operational costs and long-term environmental impact. The concept of

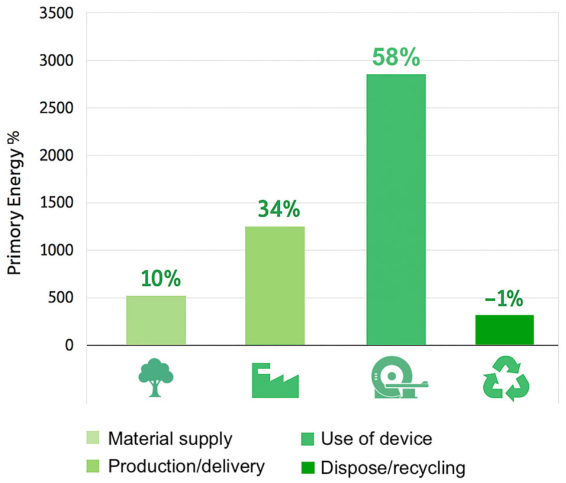


Fig. 1 Distribution of primary energy demand across the life cycle stages of an MRI system. The clinical use represents the largest share of total energy consumption (58%), followed by production and delivery (34%), material supply (10%), and end-of-life disposal/recycling, which provides an energy recovery benefit (-1%). These values highlight the predominant impact of operational energy use on the overall environmental performance of the device (Source: siemens-healthineers.com/sola)

Cumulative Energy Demand (CED) is increasingly used to assess the environmental performance of imaging equipment. CED accounts for the primary energy consumption required to produce, operate, and dispose of a medical device, including all related transportation [19].

Among all these contributing factors, the energy consumed during the clinical use represents the most significant share of the total CED for an MRI scanner throughout its entire life cycle (Fig. 1) [20, 21]. Primary energy consumption includes consumption by the energy sector itself, losses during conversion (*e.g.*, from oil or gas to electricity) and energy distribution, as well as final consumption by end users [22]. To derive primary energy consumption from the direct consumption of a device, a primary energy factor (PEF) must be applied for each energy carrier, which varies between countries and depends on the type of energy supply in the country itself [23, 24].

Most available data on the primary energy consumption performance of a radiological device comes from Environmental Product Declarations (EPDs), which are based on standardized assumptions and technical documentation provided by manufacturers. These documents often report significant improvements in energy efficiency in newer MRI models, but such claims require validation through real-world measurements [25]. Alongside this, broader international initiatives have been launched to harmonize sustainability criteria in the procurement of medical imaging equipment. The Medical Equipment Proactive Alliance (MEPA), for example, has developed 32 basic criteria covering energy efficiency, material use and chemical safety, while promoting refurbishment and life extension programs to maximize the useful life of imaging equipment before disposal [26].

At the European level, sustainability-oriented frameworks are also emerging, such as the Green ID Programme from the European Society of Radiology, which aims to support radiology departments in implementing environmentally responsible practices and benchmarking progress across institutions [27]. Such regulatory frameworks emphasize the importance of supplementing manufacturer-reported data with real-world validation, as pursued in this study. However, to date, no studies have directly compared EPD-reported primary energy consumption with actual field data collected in clinical environments.

This study aims to fill a current gap in the literature by providing a comprehensive, field-based evaluation of the actual energy savings achieved when replacing an MRI system with a more efficient model. Specifically, the objective is to measure real-world energy consumption of two MRI scanners, an old unit and its new replacement, during routine clinical use, and to compare these measurements with the values reported in the manufacturers' EPDs. Based on the verified energy savings, the study also estimates the cumulative primary energy demand over a typical 10-year lifespan of the equipment, converting energy consumption into primary energy equivalents. This allows for an estimation of the potential reduction in environmental impact associated with the replacement.

Materials and methods

In this study, several data sources were combined to enable detailed data analysis. Two time periods within 2024 were chosen, and the corresponding data were retrieved from each source system. The study was set up to investigate the following aspects: (1) the distribution of energy consumption across different scanner activity states; (2) the differences in energy consumption between two MRI scanners of different generations; (3) the estimation of the cumulative primary energy consumption over a typical 10-year system lifespan; (4) the consistency between energy values declared by the manufacturers in the EPDs and those measured during actual clinical operation.

Energy consumption measurement of MRI scanners

Measurements were performed at the Spedali Civili di Brescia, a 1,294-bed public hospital in the city of Brescia, Italy, in July 2024 in the 2 weeks prior to the decommissioning of an old 1.5-T MRI unit and, in October 2024, in the first 2 weeks of full operation of a new 1.5-T MRI unit. The old unit was a Magnetom Aera (Siemens Healthineers),

Fig. 2 Measurement setup for on-site energy monitoring. Power consumption was measured noninvasively with a power quality analyzer (GSC59, HT Instruments) connected to the incoming power line of the MRI electrical cabinet. The analyzer continuously measured voltage, current and power parameters during routine scanner operation, allowing real-time assessment of energy demand without interfering with clinical workflow

equipped with software version VA50A, gradient system of 625 A/2,000 V, and a radiofrequency amplifier peak root mean square power of 26.1 kW. The new unit was a Magnetom Sola (Siemens Healthineers) equipped with software version XA61, gradient system of 625 A/2,000 V, and a radiofrequency amplifier peak root mean square power of 29.2 kW. The normal operating hours of the practices are on average between 8 and 12 h from Monday to Friday, occasionally 8 h on Saturdays and only emergency examinations on Sundays. Over the course of 2 weeks, 153 examinations were performed on the Magnetom Aera (old unit) and 180 on the Magnetom Sola (new unit). As regards the energy consumption associated with the type of examinations, a summary is given in the Supplementary Material (Table S1). Both monitoring periods were fully comparable in terms of scanner utilization, operating hours, and activity, as both systems operated during normal opening hours and according to usual scheduling practices. Although the absolute number of examinations differed, the distribution of clinical activity remained representative of standard workflow. The types of examinations and sequences performed were not reported, as they reflect clinical decision-making and protocol optimization beyond the scope of this study. Furthermore, data collection for the Magnetom Sola began after complete installation and configuration with standard clinical protocols, with staff already trained on the system. Power consumption was measured noninvasively with a power quality analyzer (GSC59, HT Instruments), commonly used in hospital infrastructure energy audits (Fig. 2). Measurements of voltage (V), current (A), effective power (W) and frequency (Hz) were carried out on the main supply lines of the MRI scanner, with time recorded. The measurements were analyzed in a 30-s interval. The measured energy consumption (integral of energy consumption over time (kWh)) includes the operation of the MRI scanner, magnet cooling and the reconstruction server, but not external cooling components and auxiliary devices. Radiology information system (RIS) data containing workflow information describing the start and end of the examination were overlaid on the data collected by the power meter to determine the energy consumption associated with the different states of the scanner activity system. All data were collected by the first and senior authors, in collaboration with the Clinical Engineering and Technical Office of the Civil Hospital of Brescia. No vendor involvement or support was provided during the data collection phase, ensuring the independence and neutrality of the study.

Data analysis

Using the data collected by the power quality analyzer, RIS performance data and preliminary analyses performed by the graphical evaluation software for measurement and network data of power analysis (Topview, HT Instruments), energy consumption signals were segmented according to the activity states of the scanners (Fig. 3):

- active state—the actual scanning period of the scanner during which power consumption deviates from the baseline; the production phase in which images are acquired;
- idle state—the time interval between 'active' time periods within the system's power-on period; this is simply a time interval defined within the system's power-on state and not a production state that can be manually activated.
- stand-by state—the system state in which most components are switched off but can still consume energy due to components that must necessarily remain always switched on (*e.g.*, helium compressor pumps); immediate scanning is not possible, and a power-up sequence of several minutes is required before scanning.

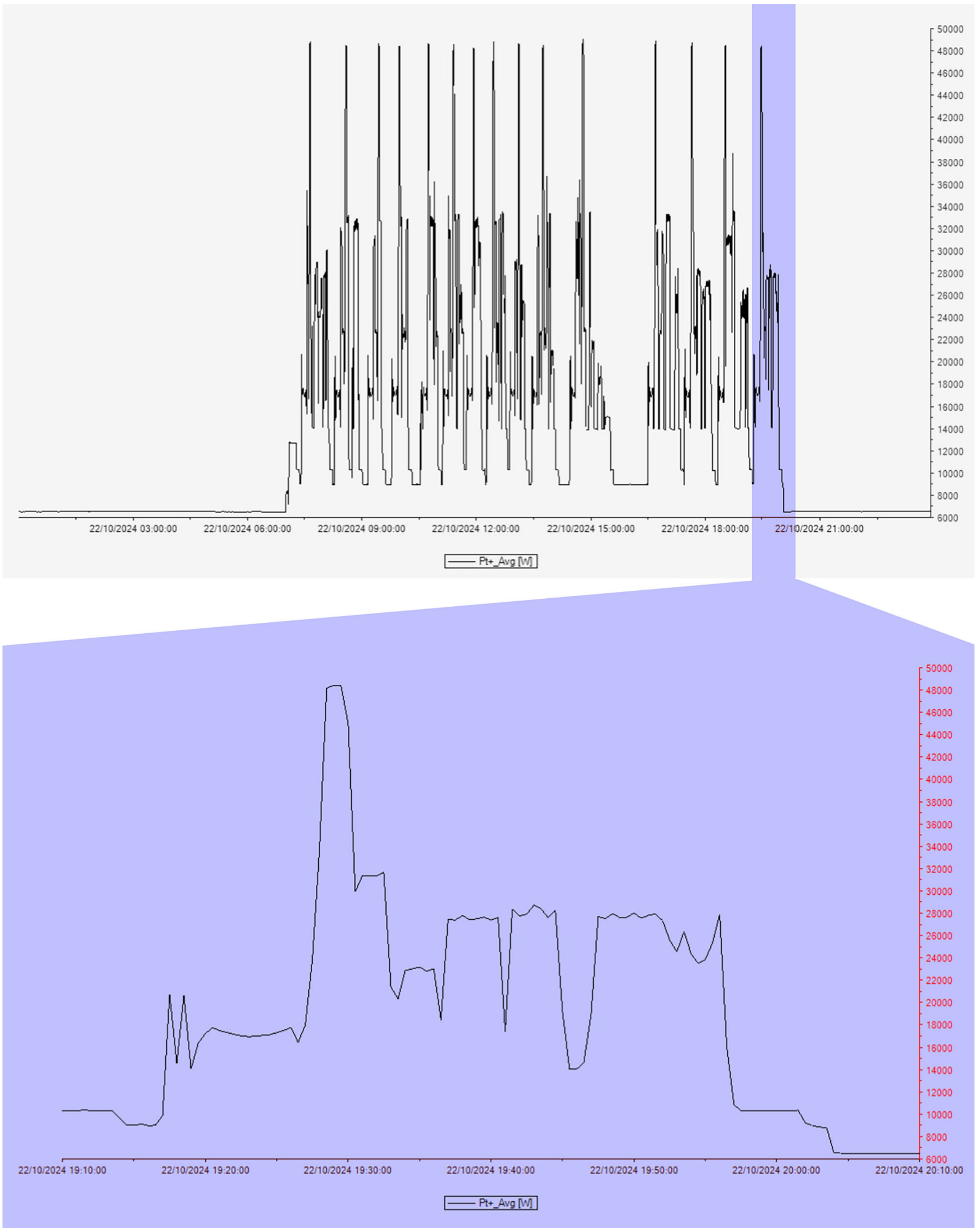


Fig. 3 The graphs show the consumption profile (in W) of an MRI unit working day recorded by the power quality analyzer, in which an MRI scan is zoomed in to show the footprint of energy consumption in the active state

Assessment of environmental product declarations

To better understand how accurately the data provided by manufacturers reflect actual energy requirements, the difference in primary energy consumption measured in the field was compared with that reported in the EPDs for the Magnetom Aera [20] and Magnetom Sola [21] models. These documents, developed according to international standards, provide estimates of primary energy consumption that include all aspects related to the use and maintenance of the equipment, including the energy consumption of heating and cooling systems, based on factory conditions. According to the EPDs, the cumulative primary energy consumption attributable to the use of the devices over 10 years amounts to 3,680 MWh for the Magnetom Aera and 2,874 MWh for the Magnetom Sola, resulting in a difference of -22% between the two generations. For each scanner, energy values were extracted from the respective EPDs, and the difference between the two MRI generations was compared with the difference in primary energy consumption measured in the field during the monitoring period. Unfortunately, EPDs do not indicate which PEF was used to calculate the primary energy consumption of the equipment, so it was not possible to make a direct comparison between the vendors' measurements and field measurements.

Estimation of cumulative primary energy demand

To estimate the primary energy consumption of the two scanners of different generations through on-site measurements, the cumulative primary energy requirement was estimated over a 10-year operating period, in accordance with the EPDs released by the vendors, which represents the average lifespan of an MRI scanner in a clinical setting. The cumulative energy requirement was calculated by multiplying the average weekly energy consumption by the number of weeks in a year (52 weeks) and then by 10 years. To convert this value into primary energy, various PEFs for domestic electricity were considered. The European PEF of 1.9, established in the European Union Directive 2023/807 [28], was used, as well as the PEFs for electricity provided by individual EU members. Reported values range from a minimum of 1.2 to a maximum of 3.5, with an average of 2.3 [29].

Results

Old MRI unit

In the last 2 weeks of its decommissioning, a total of 153 diagnostic examinations were performed with the 1.5-T Magnetom Aera. For 1 day, clinical activity was suspended to perform quality checks by the department of medical physics (not included in the energy calculations). The total energy consumption for a 2-week period of activity was 4,309.6 kWh. The peak power consumption of the scanner, analyzed per aggregated daily maxima, was 48.7 kW ± 13.4 (mean ± standard deviation), ranging 7.3–60.5 kW, while the minimum power measured was 11.8 ± 0.0 kW during idle state and 7.3 ± 0.0 kW during stand-by state. The average daily energy consumption for the scanner was 307.8 kWh. In total, over the 2 weeks of the observation, the scanner consumed 2,284.9 kWh during the active state, 633.5 kWh during the idle state, and 1,391.2 kWh during the stand-by state (Table 1). Stand-by state accounted for 32% of the total energy consumption owing to the continuous operation of the cold head cooling system. MRI idle state energy consumption accounted for 15% of the total energy consumption.

New MRI unit

In the first 2 weeks of its installation, a total of 180 MRI examinations were performed with the 1.5-T Magnetom Sola. The total energy consumption for a 2-week period of activity was 3,886.0 kWh. The peak power consumption of the scanner, analyzed per aggregated daily maxima, was 47.8 kW ± 7.7, ranging 29.6–54.4 kW, while the minimum power measured was 9.5 kW ± 0.8 during idle state and 6.5 kW ± 0 during stand-by state. The average daily energy consumption for the scanner was 277.6 kWh. In total, over the 2 weeks of the observation, the scanner consumed 2,243.1 kWh during the active state, 384.1 kWh during the idle state, and 1,258.8 kWh during the stand-by state (Table 1). Stand-by state accounted for 32% of the total energy consumption owing to the continuous operation of the cold head cooling system. Idle state energy consumption accounted for 10% of the total energy consumption.

Comparison between different activity states of two models

The comparison between the two MRI units is summarized in Table 1. Overall, during different operating states, the reduction is -2% in the active phase, -39% in the idle phase, and -10% in the stand-by phase. Similarly, when looking at average daily consumption, there is a -10% decrease between the two MRI units. Considering power, the average power peak demand decreases by -8% (from 48.7 kW to 45.0 kW) between the old and new models, and the maximum peak power demand is reduced between the old and updated models by -10% (from 60.5 kW to 54.4 kW). The minimum power in waiting mode decreases by -19% and in stand-by mode by -11%.

Regarding the various types of neurological diagnostic examinations performed, Supplementary Table S1 summarizes the comparison between the two scanners. The total number of examinations and their distribution across the different types are similar and comparable. In almost all categories, transitioning from the old model MRI to the upgraded one led to a reduction in average

Table 1 Distribution of MRI energy consumption and power according to the type of activity states of two 1.5-T MRI scanners, with additional technical and operational characteristics

Model	Characteristics	Energy consumption (kWh)							Power (kW)					
		Active state	Idle state	Stand-by state	Total	Daily			Power peak demand				Idle state minimum power	Stand-by state minimum power
						Median	Mean	SD	Maximum	Median	Mean	SD		
Magnetom Aera	Software: VA50A Gradient: 625 A/2,000 V RF amplifier: 26.1 kW Commercial release: 2010 Installed at hospital: 2013	2,284.9	633.5	1,391.2		4,309.6	321.0	307.8	66.1	60.5	52.3	48.7	13.4	11.8
7.3														
Magnetom Sola	Software: XA61 Gradient: 625 A/2,000 V RF amplifier: 29.2 kW Commercial release: 2018 Installed at hospital: 2024	2,243.1	384.1	1,258.8		3,886.0	293.4	277.6	52.1	54.4	49.0	45.0	13.0	9.5
6.5														
Comparison	**-2%**	**-39%**	**-10%**	**-10%**	**-9%**	**-10%**	**-21%**	**-10%**	**-6%**	**-8%**	**-3%**	**-19%**	**-11%**	

Table 2 Comparison of 10-year cumulative primary energy demand (in MWh) for two MRI scanner models (Magnetom Aera and Magnetom Sola) based on on-site measured electricity consumption and converted using different primary energy factors (PEFs)

Model	Source	PEF	10-year primary energy demand (MWh)	Difference from EPD (%)
Magnetom Aera	EPD	–	3,680.0	Reference (100%)
	Field data	1.20 (minimum)	1,448.0	-60.7%
	Field data	1.90 (European)	2,292.7	-37.7%
	Field data	2.30 (average)	2,775.4	-24.6%
	Field data	3.50 (maximum)	4,223.4	+14.8%
Magnetom Sola	EPD	–	2,874.0	Reference (100%)
	Field data	1.20 (minimum)	1,212.4	-57.8%
	Field data	1.90 (European)	1,919.7	-33.2%
	Field data	2.30 (average)	2,323.8	-19.2%
	Field data	3.50 (maximum)	3,536.3	+23.0%

Values are compared with those reported in the respective environmental product declarations (EPDs). The percentage difference indicates the deviation of the field-based estimates from the EPD-reported values

energy consumption, ranging from -3 to -60%. For instance, for noncontrast brain MRI, the average energy consumption decreased from 15.6 kWh with the old MRI unit to 11.8 kWh with the new MRI unit (-32%). As for examination times, the differences between the two models vary according to the type of examination. On average, examinations show a reduction in duration, apart from noncontrast thoracic, lumbosacral and whole-spine, which show an increase.

10-year primary energy demands

Based on the weekly electricity consumption observed during the monitoring period, cumulative energy savings over a 10-year system lifespan were estimated. Assuming 52 weeks of operation per year, this corresponds to a total electricity consumption of 1,206.7 MWh for the old MRI unit and 1,010.4 MWh for the new unit. However, to account for the presence of a routine physical quality check interval during the monitoring of the old MRI unit, the extrapolation was adjusted using an effective 13-day activity window for the old scanner and a 14-day window for the new scanner. To obtain the cumulative primary energy consumption, different PEFs applicable across Europe were considered. By applying a reference PEF of 1.9, the cumulative primary energy demand over 10 years amounts to 2,292.7.0 MWh for the old unit and 1,919.7 MWh for the new unit. When applying the individual national PEFs reported across EU member states, the 10-year primary energy consumption for the old unit ranges from 1,448.0 MWh (minimum) to 4,223.4 MWh (maximum), with an average value of 2,775.4 MWh. For the new model 10-year primary energy consumption ranges from 1,212.4 MWh (minimum) to 3,536.3 MWh (maximum), with an average value of 2,323.8 MWh. This would result in a primary energy savings of 16.3%, ranging from 235.6 MWh (minimum) to 687.1 MWh (maximum), with an average value of 436.8 MWh.

Comparison of primary energy demand with published EPDs

To further contextualize the results, Table 2 compares the 10-year primary energy demand calculated based on on-site measurements using various European PEFs with the values reported in the EPDs. Depending on the national PEF applied, the average difference between EPD values and field-based estimates ranges from -37.7% for the Magnetom Aera to -33.2% for the Magnetom Sola, using the standard EU PEF of 1.9. When applying higher national PEFs, such as 3.5, the calculated demand for the Sola model slightly exceeded the value reported in the EPD (+23.0%), while the Aera model remained broadly in line (+14.8%). These results suggest that EPDs may overestimate primary energy consumption under typical clinical operating conditions.

Discussion

Energy efficiency gains through technological replacement

The results of this study confirm that replacing an older-generation MRI scanner with a newer model can lead to a meaningful reduction in energy consumption, especially during periods when the system is powered on but not actively scanning. Overall, electricity use dropped by around 10%, with the most substantial savings observed during idle and stand-by states. Active scanning showed only a modest improvement, suggesting that gains in efficiency come less from what happens during image acquisition and more from how the system behaves in between scans. This aligns with what has been suggested in previous studies: smarter management of the MRI's operational states, such as through eco-modes and automated power-saving functions, can play a major role in reducing energy use [10, 11]. Interestingly, even with updated hardware, stand-by mode still accounted for about 32% of total energy consumption. That points to the persistent energy demands of helium-based cooling systems, which remain active even when the scanner is not in use [30].

One promising development in this area is the adoption of helium-free MRI systems, which could potentially eliminate the need for continuous cryogenic cooling. These newer systems have the potential to significantly reduce baseline consumption, particularly in facilities where scanners are left powered on 24/7 [31–33]. Moreover, the upgrade of the MRI scanner has led to a reduction of -6.1 kW in the peak power demand. This figure appears highly relevant as this reduction can lead to a decrease in demand on the electrical grid, improving its reliability and contributing to overall cost reductions [34–36]. Moreover, when considering the cumulative primary energy consumption over a 10-year period, the differences in energy demand between the old and new MRI models range from a minimum of 235.6 MWh to a maximum of 687.1 MWh, depending on the PEF applied. This variation highlights how national electricity generation mixes can significantly influence the environmental benefits associated with upgrading medical imaging equipment.

Comparison with environmental product declarations

One of the most relevant contributions of this study is the direct comparison between real-world energy measurements and the figures reported in the manufacturers' EPDs. When applying the standard EU PEF of 1.9, the primary energy demand measured in the field turned out to be significantly lower than the values declared in the EPDs, by 37.7% for the Magnetom Aera and 33.2% for the Magnetom Sola. Interestingly, when applying the highest national PEF currently reported in Europe (3.5), the picture changes: for the Magnetom Sola, the field-based estimate exceeded the value reported in the EPD by 23%. These differences remained substantial even when using different national PEFs, suggesting difficult adaptability to real practice in EPDs, as confirmed by literature in other fields [25, 37, 38]. Although EPDs are built on standardized methodologies and provide a valuable framework for comparing products, they often rely on assumptions that do not always reflect what happens in practice. Usage patterns, climate conditions, and hospital operating schedules vary widely across facilities.

Another limitation is that EPDs do not always specify which PEF was used in their calculations, which makes it harder to reproduce or verify the data. Finally, the PEF itself is not a fixed value; it varies a lot from one country to another, depending on how electricity is produced [29]. In countries with a greener energy mix, the same MRI scanner could have a much lower environmental impact than in countries that rely more heavily on fossil fuels. This means that, in this case, applying country-specific PEFs is essential to understanding the real impact of MRI systems. Only by combining field measurements with localized energy conversion factors can we gain a realistic picture of how much energy is involved in operating this kind of equipment in healthcare. It should also be noted that on-site energy consumption remains the most relevant parameter for hospitals, as it directly reflects operating costs and local sustainability performance. The conversion to primary energy equivalents using the European Commission's PEFs was carried out primarily to enable comparison with the values reported in the EPD, which are expressed in terms of primary energy. As the exact PEFs applied by the supplier are not disclosed and may vary over time with changes in European legislation, these results should not be interpreted as absolute data, but rather as a sensitivity analysis. This uncertainty highlights the importance of greater transparency in EPDs and the need to supplement the data declared by manufacturers with real-world validation.

Implications for sustainable radiology

The results of this study demonstrate that radiology departments aiming to reduce energy consumption should consider the energy performance of MRI scanners as a key decision-making criterion when planning system upgrades. In this context, field energy measurements can be a valuable complement to existing tools, such as EPDs, providing a more accurate picture of actual performance. In recent years, vendors have begun to address sustainability more proactively, as demonstrated by initiatives such as those led by COCIR [18] and the ongoing development of a new Energy Star specification for medical imaging equipment by the U.S. Environmental Protection Agency [39].

By integrating environmental sustainability criteria into competitive procurement processes, radiology departments can move toward more sustainable practices without compromising diagnostic capabilities [40]. In addition to the energy consumption of the equipment, the environmental sustainability of magnetic resonance imaging also depends on auxiliary systems (data storage and "heating, ventilation, and air conditioning" (HVAC) systems) [41, 42], procedure-related waste (*e.g.*, contrast media) [43–45], and the behavior and training of radiology staff [46, 47]. Addressing these aspects jointly can lead to greater benefits in terms of system sustainability. However, it is important to note that energy efficiency alone cannot justify the replacement of medical equipment. Decisions to upgrade or replace imaging systems should be based primarily on clinical and diagnostic performance, including image quality, patient flow, safety, and compatibility with evolving clinical protocols. These parameters were not evaluated in the present study, which focused exclusively on energy consumption and sustainability parameters. Therefore, the results should be interpreted as a contribution to the broader discussion on sustainable radiology and not as a stand-alone argument in favor of system replacement.

Study limitations

This study has limitations that should be considered when interpreting the results.

First, the monitoring period was limited to 2 weeks for each scanner. While this timeframe reflects the department's average workload, it does not account for potential seasonal variations, public holidays, or unusual scheduling patterns that could impact clinical activity and energy consumption. For the old MRI unit, one of the recorded days contains a routine physical quality check interval without clinical examinations (not included in the energy calculations); therefore, the extrapolation to 10 years was calculated using an effective 13-day monitoring window to ensure proportional accuracy. However, comparable studies have demonstrated that shorter monitoring durations can still yield meaningful insights into equipment performance [48, 49]. We acknowledge that MRI workflow may vary over longer periods due to case mix, scheduling patterns, and operational factors. As such, while the chosen observation window is representative of standard practice within our institution, longer or seasonally distributed monitoring periods would provide a more generalizable estimate of MRI energy performance across different settings.

Second, all measurements were conducted at a single hospital, under specific environmental, operational, and organizational conditions. In addition, both scanners were produced by the same vendor, meaning that our findings reflect a single-center, single-vendor experience. This may further limit the generalizability of the results to other settings, particularly in facilities with different usage profiles, technical infrastructures, vendors, or electricity pricing schemes. The monitoring system employed is not certified as a clinical-grade diagnostic device, which may limit the precision of the measurements when compared to certified metrological instruments.

Lastly, given its primarily technical and engineering-oriented focus, the study did not evaluate clinical parameters, such as image quality, diagnostic efficiency, or patient throughput. While these aspects may not directly affect power consumption, they are crucial for understanding the broader efficiency and sustainability of the system in day-to-day practice. Finally, although extrapolating our results over a 10-year system life cycle introduces assumptions, this approach was adopted to provide a realistic benchmark of cumulative performance and is consistent with previous sustainability studies in radiology [50].

In conclusion, this study provides a real-world assessment of the energy performance of two generations of MRI scanners, highlighting the tangible benefits of technological upgrades in terms of energy efficiency. Replacing an outdated 1.5-T MRI scanner with a more recent model led to an overall reduction of approximately 16% in lifetime electricity consumption, with the most significant savings observed during non-productive phases such as idle and stand-by phases.

A key finding of this work is the discrepancy between the primary energy consumption values reported in the EPDs and field measurements. which reached up to ± 40% depending on the applied Primary Energy Factor. This finding suggests that, while EPDs offer useful standardized information, they may not fully reflect real-world performance. On-site validation should therefore be considered an essential step to ensure reliable sustainability assessments and to inform procurement strategies.

Finally, while energy efficiency is a key component of sustainable radiology, it cannot be the sole criterion for equipment replacement. The findings of this study should therefore be interpreted as a contribution to the broader discussion on sustainability in radiology, rather than as a stand-alone argument in favor of scanner replacement.

Abbreviations

CED	Cumulative energy demand
COCIR	Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry
EPDs	Environmental product declarations
MRI	Magnetic resonance imaging
PEF	Primary energy actor
RIS	Radiology information system

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1186/s41747-025-00668-w.

Additional file 1: Table S1. MRI Examination Energy Consumption according to type of MRI examination. The green cells identify the reductions in energy consumption and time achieved by the MRI system upgrade. MRA: Magnetic resonance angiography. Data for the old MRI unit were collected over a 13-day interval, while data for the new MRI unit were collected over a 14-day interval.

Acknowledgements

The authors thank Mirko Pedrinazzi and all the technical team of the Spedali Civili of Brescia, who supported the data collection. No large language models (LLMs) were used in the preparation of this manuscript.

Author contributions

Substantial contributions to the conception or design of the work: AR, GLV and SZ; investigation: AR and MV; methodology: AR and AS; validation: SZ; drafting of the manuscript: AR; critical revision of the manuscript for important intellectual content: MV, AS, GLV, and SZ; and supervision: GLV and SZ. All authors have read and agreed to the published version of the manuscript.

Funding
The authors state that this work has not received any funding.

Data availability
Data are available from the authors upon reasonable request.

Declarations

Ethics approval and consent to participate
Institutional Review Board approval was not required because only fully anonymized observational non-personal data was inspected retrospectively.

Consent for publication
Not applicable.

Competing interests
AR and SZ are members of the Scientific Editorial Board of *European Radiology Experimental* (section: Information technology, social media and environmental sustainability) and, as such, did not participate in the selection or review processes for this article. The remaining authors declare no competing interests.

Author details
[1]Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Brescia, Italy. [2]Clinical Engineering Unit, ASST Spedali Civili di Brescia, Brescia, Italy. [3]Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milano, Italy. [4]Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Brescia, Italy.

Received: 29 July 2025 Accepted: 1 December 2025
Published online: 05 January 2026

References

1. Brown M, Schoen JH, Gross J et al (2023) Climate change and radiology: impetus for change and a toolkit for action. Radiology 307:e230229. https://doi.org/10.1148/radiol.230229
2. Mariampillai J, Rockall A, Manuellian C et al (2023) The green and sustainable radiology department. Radiologie (Heidelb) 63:21–26. https://doi.org/10.1007/s00117-023-01189-6
3. Roletto A, Zanardo M, Bonfitto GR et al (2024) The environmental impact of energy consumption and carbon emissions in radiology departments: a systematic review. Eur Radiol Exp 8:35. https://doi.org/10.1186/s41747-024-00424-6
4. Rockall AG, Allen B, Brown MJ et al (2025) Sustainability in radiology: position paper and call to action from ACR, AOSR, ASR, CAR, CIR, ESR, ESRNM, ISR, IS3R, RANZCR, and RSNA. Eur Radiol 35:5427–5436. https://doi.org/10.1007/s00330-025-11413-7
5. DesRoche C, Castillo F, Sharma S et al (2025) Climate resilient and environmentally sustainable radiology: a framework for implementation. Radiol Adv 2:umaf014. https://doi.org/10.1093/radadv/umaf014
6. Chaban YV, Vosshenrich J, McKee H et al (2024) Environmental sustainability and MRI: challenges, opportunities, and a call for action. J Magn Reson Imaging 59:1149–1167. https://doi.org/10.1002/jmri.28994
7. McKee H, Brown MJ, Kim HHR et al (2024) Planetary health and radiology: why we should care and what we can do. Radiology 311:e240219. https://doi.org/10.1148/radiol.240219
8. Klein H-M (2023) A new approach to the improvement of energy efficiency in radiology practices. Rofo 195:416–425. https://doi.org/10.1055/a-2021-7386
9. Heye T, Knoerl R, Wehrle T et al (2020) The energy consumption of radiology: energy- and cost-saving opportunities for CT and MRI operation. Radiology 295:593–605. https://doi.org/10.1148/radiol.2020192084
10. Woolen SA, Becker AE, Martin AJ et al (2023) Ecodesign and operational strategies to reduce the carbon footprint of MRI for energy cost savings. Radiology 307:e230441. https://doi.org/10.1148/radiol.230441
11. Vosshenrich J, Heye T (2023) Small steps toward a more sustainable and energy-efficient operation of MRI. Radiology 307:e230874. https://doi.org/10.1148/radiol.230874
12. Roletto A, Savio A, Masperi A et al (2025) Energy usage assessment and energy savings estimation in a radiology department in Italy. Energies 18:1936. https://doi.org/10.3390/en18081936
13. Chodorowski M, Ognard J, Rovira À et al (2024) Energy consumption in MRI: determinants and management options. J Neuroradiol 51:182–189. https://doi.org/10.1016/j.neurad.2023.12.001
14. Afat S, Wohlers J, Herrmann J et al (2024) Reducing energy consumption in musculoskeletal MRI using shorter scan protocols, optimized magnet cooling patterns, and deep learning sequences. Eur Radiol 35:1993–2004. https://doi.org/10.1007/s00330-024-11056-0
15. Hernandez AM, Chen AF, Ghatpande O et al (2025) Reducing the energy consumption of magnetic resonance imaging and computed tomography scanners: integrating ecodesign and sustainable operations. J Comput Assist Tomogr 49:191–202. https://doi.org/10.1097/RCT.0000000000001700
16. Siemens Healthineers (2023) Sustainability in MRI: the power of less is more. Available via https://www.siemens-healthineers.com/en-us/magnetic-resonance-imaging/sustainability-in-mri. Accessed 21 Feb 2025
17. Sumner C, Ikuta I, Garg T et al (2023) Approaches to greening radiology. Acad Radiol 30:528–535. https://doi.org/10.1016/j.acra.2022.08.013
18. COCIR (2018) COCIR Self-Regulatory Initiative: for the ecodesign of medical imaging equipment. Available via https://www.cocir.org/fileadmin/6_Initiatives_SRI/SRI_Status_Report/COCIR_SRI_Status_Report_2018_-_June_2019.pdf. Accessed 21 Feb 2025
19. Huijbregts MAJ, Hellweg S, Frischknecht R et al (2010) Cumulative energy demand as predictor for the environmental burden of commodity production. Environ Sci Technol 44:2189–2196. https://doi.org/10.1021/es902870s
20. Siemens Healthcare (2016) MAGNETOM Aera—environmental product declaration. Available via https://marketing.webassets.siemens-healthineers.com/1800000000269019/ff780bc4466b/MRI-MAGNETOM-Aera-EPD_1800000000269019.pdf. Accessed 21 Feb 2025
21. Siemens Healthineers (2018) MAGNETOM Sola—environmental product declaration. Available via https://marketing.webassets.siemens-healthineers.com/1800000005702962/140c018c521f/magnetom-sola_environmental-product-declaration_2018-09_1800000005702962.pdf. Accessed 21 Feb 2025
22. Bel G, Joseph S (2018) Climate change mitigation and the role of technological change: impact on selected headline targets of Europe's 2020 climate and energy package. Renew Sustain Energy Rev 82:3798–3807. https://doi.org/10.1016/j.rser.2017.10.090
23. Wilby MR, Rodríguez González AB, Vinagre Díaz JJ (2014) Empirical and dynamic primary energy factors. Energy 73:771–779. https://doi.org/10.1016/j.energy.2014.06.083
24. Bilardo M, Fabrizio E, Oldini R (2024) Dynamic evaluation of the electrical primary energy factor for building energy performance: insights from 2022 Italian data. E3S Web Conf 523:05005. https://doi.org/10.1051/e3sconf/202452305005
25. Moré FB, Galindro BM, Soares SR (2022) Assessing the completeness and comparability of environmental product declarations. J Clean Prod 375:133999. https://doi.org/10.1016/j.jclepro.2022.133999
26. MEPA (2024) Sustainability criteria for purchasing medical imaging devices. Available via https://www.mepaalliance.org. Accessed 10 Sep 2025
27. European Society of Radiology (2025) Green ID Certificate—Green Imaging Department. Available via https://www.myesr.org/greenid/. Accessed 25 Oct 2025
28. European Union (2022) Commission Delegated Regulation (EU) 2023/807 of 15 December 2022 on revising the primary energy factor for electricity in application of Directive 2012/27/EU of the European Parliament and of the Council. Available via http://data.europa.eu/eli/reg_del/2023/807/oj. Accessed 22 Apr 2025
29. European Commission: Directorate-General for Energy, e7 and Trinomics B.V, (2023) Support to primary energy factors review (PEF) – Final report, Publications Office of the European Union. https://data.europa.eu/doi/10.2833/404077

30. Luo C, Liu G, Deng Y et al (2025) Design and optimization of liquid helium-free cooling systems for magnetic resonance imaging device using multi-physical modeling. Case Stud Therm Eng 66:105761. https://doi.org/10.1016/j.csite.2025.105761
31. Qu H, Wu H, Liu X et al (2023) A 1.5T liquid-helium-free whole-body MRI superconducting magnet: thermal analysis and cool-down time estimation. In: Proceedings of the 2023 IEEE international conference on applied superconductivity and electromagnetic devices (ASEMD). IEEE, Tianjin, pp 1–2
32. Mahesh M, Barker PB (2016) The MRI helium crisis: past and future. J Am Coll Radiol 13:1536–1537. https://doi.org/10.1016/j.jacr.2016.07.038
33. Kravchenko D, Hagar MT, Vecsey-Nagy M et al (2025) Low-field and portable MRI technology: advancements and innovations. Eur Radiol Exp 9:103. https://doi.org/10.1186/s41747-025-00638-2
34. Akhmetov Y, Fedotova E, Frysztacki MM (2025) Flattening the peak demand curve through energy efficient buildings: a holistic approach towards net-zero carbon. Appl Energy 384:125421. https://doi.org/10.1016/j.apenergy.2025.125421
35. Poghosyan A, McCullen N, Natarajan S (2024) Optimising peak energy reduction in networks of buildings. Sci Rep 14:3916. https://doi.org/10.1038/s41598-024-52676-2
36. Schäfer B, Witthaut D, Timme M, Latora V (2018) Dynamically induced cascading failures in power grids. Nat Commun 9:1975. https://doi.org/10.1038/s41467-018-04287-5
37. Olanrewaju OI, Enegbuma WI, Donn M, Oyefusi ON (2025) Assessment of environmental product declaration and databases: towards ensuring data quality assurance practices. Environ Impact Assess Rev 112:107803. https://doi.org/10.1016/j.eiar.2024.107803
38. Moshood TD, Rotimi JOB, Rotimi FE (2024) Combating greenwashing of construction products in New Zealand and Australia: a critical analysis of environmental product declarations. Sustainability 16:9671. https://doi.org/10.3390/su16229671
39. Energy Star (2025) Energy Star medical imaging equipment version 1.0. Available via https://www.energystar.gov/products/spec/medical_imaging_equipment_version_1_0_pd. Accessed 10 Sep 2025
40. Knott JJ, Varangu L, Waddington K et al (2017) Medical imaging equipment study: assessing opportunities to reduce energy consumption in the health care sector. A report to Natural Resources Canada by the Canadian Coalition for Green Health Care. Available via https://greenhealthcare.ca/wp-content/uploads/2016/11/Medical-Imaging-Equipment-Energy-Use-CCGHC-2017.pdf. Accessed 10 Sep 2025
41. Roletto A, Savio A, Marchi B, Zanoni S (2024) Towards a greener radiology: a comprehensive life cycle assessment framework for diagnostic imaging. Environ Climate Technol 28:303–311. https://doi.org/10.2478/rtuect-2024-0024
42. Jia Y, Deng M, Burger R et al (2025) Greenhouse gas emissions due to long-term data storage of CT with reformats and strategies for mitigation. Eur Radiol. https://doi.org/10.1007/s00330-025-12023-z
43. Zanardo M, Ambrogi F, Asmundo L et al (2024) The GREENWATER study: patients' green sensitivity and potential recovery of injected contrast agents. Eur Radiol 35:1205–1214. https://doi.org/10.1007/s00330-024-11150-3
44. Zanardo M, Cozzi A, Cardani R et al (2023) Reducing contrast agent residuals in hospital wastewater: the GREENWATER study protocol. Eur Radiol Exp 7:27. https://doi.org/10.1186/s41747-023-00337-w
45. Dekker HM, Stroomberg GJ, Van der Molen AJ, Prokop M (2024) Review of strategies to reduce the contamination of the water environment by gadolinium-based contrast agents. Insights Imaging 15:62. https://doi.org/10.1186/s13244-024-01626-7
46. Roletto A, Catania D, Rainford L et al (2024) Sustainable radiology departments: a European survey to explore radiographers' perceptions of environmental and energy sustainability issues. Radiography 30:81–90. https://doi.org/10.1016/j.radi.2024.06.022
47. Abuzaid MM, Almuqbil N (2025) Charting a sustainable future in radiology: evaluating radiologists' knowledge, attitudes, and practices toward environmental responsibility. Insights Imaging 16:39. https://doi.org/10.1186/s13244-025-01917-7
48. Chua ALB, Amin R, Zhang J et al (2021) The environmental impact of interventional radiology: an evaluation of greenhouse gas emissions from an academic interventional radiology practice. J Vasc Interv Radiol 32:907–915.e3. https://doi.org/10.1016/j.jvir.2021.03.531
49. Carver DE, Pruthi S, Struk O et al (2025) Measuring the environmental impact of MRI and CT: a life cycle assessment. J Am Coll Radiol. https://doi.org/10.1016/j.jacr.2025.09.030
50. Thiel CL, Vigil-Garcia M, Nande S et al (2024) Environmental life cycle assessment of a U.S. hospital-based radiology practice. Radiology 313:e240398. https://doi.org/10.1148/radiol.240398

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

PAPER 7

2 (2026) 100025

Contents lists available at ScienceDirect

EANM Innovation

journal homepage: www.sciencedirect.com/journal/eanm-innovation

Environmental life cycle assessment of [^{18}F]FDG PET/CT imaging in a hospital-based nuclear medicine department

Andrea Roletto [a,*], Anna Savio [a], Enrico Bertagna [a], Nicolò Sean Chiodini [b], Giuseppe Roberto Bonfitto [b], Arturo Chiti [b,c], Simone Zanoni [d]

[a] Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, Via Branze 38, 25123, Brescia, Italy
[b] Department of Nuclear Medicine, IRCCS Ospedale San Raffaele, Via Olgettina 60, 20132, Milan, Italy
[c] Vita-Salute San Raffaele University, Via Olgettina, 58, 20132, Milan, Italy
[d] Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, Via Branze 43, 25123, Brescia, Italy

ARTICLE INFO

Keywords:
Life cycle assessment
Nuclear medicine
[^{18}F]FDG PET/CT
Sustainability
Environmental impact
HVAC
Radiopharmaceuticals

ABSTRACT

Introduction: The environmental impact of medical imaging is increasingly recognised, yet comprehensive assessments of nuclear medicine, specifically [^{18}F]FDG PET/CT imaging, remain limited. This study aims to perform a detailed Life Cycle Assessment (LCA) of standard [^{18}F]FDG PET/CT vertex-to-mid-thigh examinations to identify significant ecological impacts and suggest mitigation strategies.
Methods: A cradle-to-grave LCA, compliant with ISO 14040 standards, was conducted in an Italian hospital-based nuclear medicine department. A representative [^{18}F]FDG PET/CT protocol was analysed. Energy consumption of imaging equipment was directly measured, while HVAC energy use for each functional space was estimated using official data relating to the trigeneration plant at the hospital. Material-related impacts, including radiopharmaceutical production and single-use supplies, were modelled using SimaPro. Sensitivity analyses assessed the effect of national electricity grid decarbonisation.
Results: The Global Warming Potential (GWP) of a single [^{18}F]FDG PET/CT vertex-to-mid-thigh scan was approximately 7.6 kg CO_2 eq. HVAC systems were the main contributor (47% of GWP), including climate control of the scan room, control room, injection room, and cyclotron facility. Considering the patient care pathway, radiopharmaceutical production accounted for 36% of GWP. Direct scanner electricity use represented only 5.4%, while single-use disposables contributed mainly to toxicity-related impacts and waste generation. Sensitivity analyses indicated that electricity grid decarbonisation could reduce scan-related GWP by up to 50%.
Conclusions: The environmental footprint of [^{18}F]FDG PET/CT is primarily driven by climate control across functional spaces and radiopharmaceutical production. Improving HVAC efficiency, expanding renewable energy use and adopting reusable or lower-impact consumables could substantially reduce the environmental impact of nuclear medicine practices.

1. Introduction

Healthcare systems significantly contribute to environmental impacts, with hospitals representing major consumers of energy and natural resources and generating substantial greenhouse gas emissions and medical waste [1,2]. Among healthcare services, diagnostic imaging stands out for its high energy consumption, largely due to the complexity of the equipment, the need for continuous cooling systems, and the production, transport, and disposal of specialised materials and substances used during examinations [3–5].

Life Cycle Assessment (LCA) is an internationally standardised methodology that evaluates the environmental impacts associated with all stages of a product or service, from raw material extraction to end-of-life disposal or recycling [6]. Applying LCA in healthcare allows for the identification of environmental hotspots and the development of strategies to reduce impacts across the entire life cycle of medical services [7,8]. Several studies have employed LCA to assess the environmental footprint of various healthcare processes, ranging from pharmaceutical production and surgical procedures [9–11] to diagnostic imaging [12,

* Corresponding author.
E-mail addresses: andrea.roletto@unibs.it (A. Roletto), anna.savio@unibs.it (A. Savio), e.bertagna001@unibs.it (E. Bertagna), chiodini.seannicolo@hsr.it (N.S. Chiodini), bonfitto.giuseppe@hsr.it (G.R. Bonfitto), chiti.arturo@hsr.it (A. Chiti), simone.zanoni@unibs.it (S. Zanoni).

https://doi.org/10.1016/j.eanmi.2026.100025
Received 20 October 2025; Received in revised form 18 January 2026; Accepted 21 January 2026
Available online 6 February 2026
3051-2913/© 2026 The Authors. Published by Elsevier B.V. on behalf of European Association of Nuclear Medicine (EANM). This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Abbreviations

CO_2 eq	Carbon dioxide equivalent
EoL	End-of-Life
[18F]FDG	18F-fluorodeoxyglucose
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
PET/CT	Positron Emission Tomography/Computed Tomography
RIS	Radiology Information System
PACS	Picture Archiving and Communication System
VMT	Vertex-to-mid-thigh

13]. Some of these analyses have focused on individual clinical procedures [14], demonstrating that better procedural planning can significantly reduce waste and carbon emissions. Others have examined entire departments, revealing which operational components contribute most to the environmental impact issue [13,15].

Within diagnostic imaging, modalities such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) have received the most attention in environmental sustainability studies [16–18]. However, nuclear medicine remains relatively underexplored from an environmental perspective [19]. Among the procedures performed in nuclear medicine, [18F]FDG PET/CT has been increasingly recognised as a useful tool for evaluating a wide range of malignant tumours, and it now accounts for a substantial proportion of nuclear medicine activity [20,21]. Despite growing interest in environmental sustainability in healthcare, comprehensive LCA studies specifically addressing [18F]FDG PET/CT exams remain limited and underdeveloped.

This study aims to provide an LCA-based estimation of the environmental impact of [18F]FDG PET/CT exams performed in a nuclear medicine department. By quantifying their ecological footprint, it seeks to identify concrete actions that could enhance the sustainability of medical imaging practices.

2. Methods

The analysis was conducted over 1 week (January 10-17, 2025) at San Raffaele Hospital (IRCCS Ospedale San Raffaele) in Milan, within the nuclear medicine department. Only standard [18F]FDG PET/CT vertex-to-mid-thigh (VMT) examinations performed on the same PET/CT system, with a standard scan range from head to pelvis, were included. Full whole-body examinations extending to the feet were excluded, as they are performed only occasionally and require significantly longer acquisition times and room occupancy. The study therefore focused on a consistent diagnostic protocol representative of routine clinical practice.

2.1. LCA goal and Scope

An LCA was performed to estimate the greenhouse gas (GHG) emissions associated with a single [18F]FDG PET/CT VMT scan. A cradle-to-grave approach, compliant with ISO 14040 standards [22], was adopted.

The functional unit was defined as one PET/CT scan performed in an adult patient. The patient pathway was divided into six process steps, as shown in Fig. 1: (1) patient arrival at the hospital, (2) patient reception and registration, (3) intravenous injection of [18F]FDG with a radiopharmaceutical injector, (4) 60-min uptake period, (5) execution of [18F]FDG PET/CT VMT scan, (6) image reconstruction, interpretation,

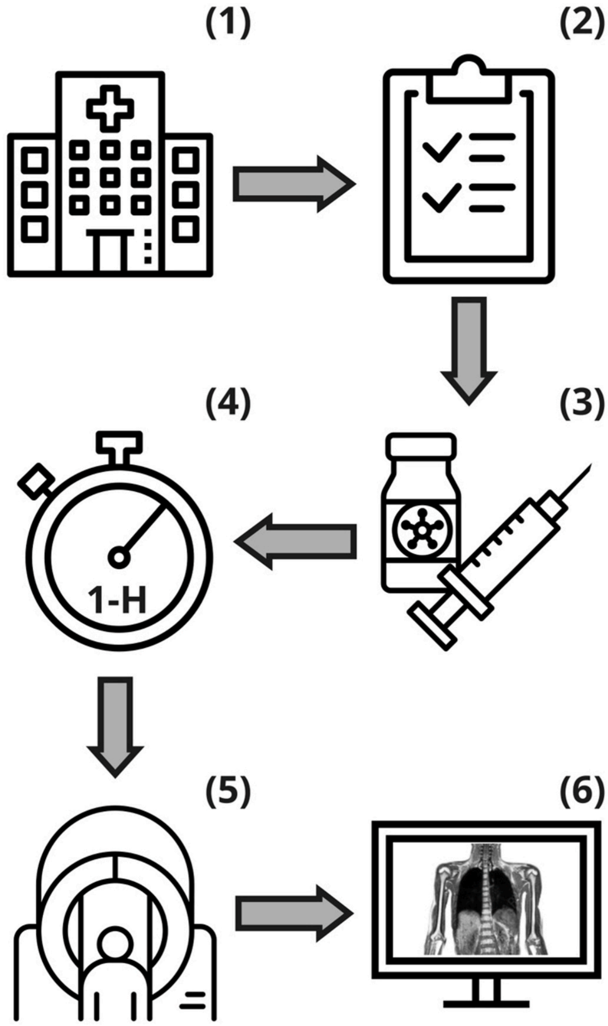


Fig. 1. Patient pathway for a [18F]FDG PET/CT VMT Scan. (1) patient arrival at the hospital, (2) patient reception and registration, (3) intravenous injection of [18F]FDG with a radiopharmaceutical injector, (4) 60-min uptake period, (5) execution of [18F]FDG PET/CT VMT scan, (6) image reconstruction, interpretation, and patient discharge.

and patient discharge. The total average duration of a single session was estimated at approximately 2 h. This pathway served as the basis for the system boundaries considered in the LCA (Fig. 2).

2.2. Life cycle inventory and data collection

The life cycle inventory was modelled using SimaPro software (version 9.6.0.1, Pré Consultants, Amersfoort, The Netherlands) [23] in combination with the Ecoinvent 3.10 database [24]. Further details on data sources and collection methods can be found in the spreadsheet provided in Appendix S1.

Energy use of imaging equipment – The energy consumption of the PET/CT scanner, GE Omni Legend (GE Healthcare, Chicago, Illinois, US), was measured non-invasively during the audit period using a GSC59 power quality analyser (HT Instruments). Electrical parameters, including voltage (V), current (A), active power (W), and frequency (Hz), were recorded at 5-s intervals from the main power lines supplying the PET/CT system. The resulting energy consumption data (expressed in kWh) covered the operation of the PET/CT scanner. To calculate the

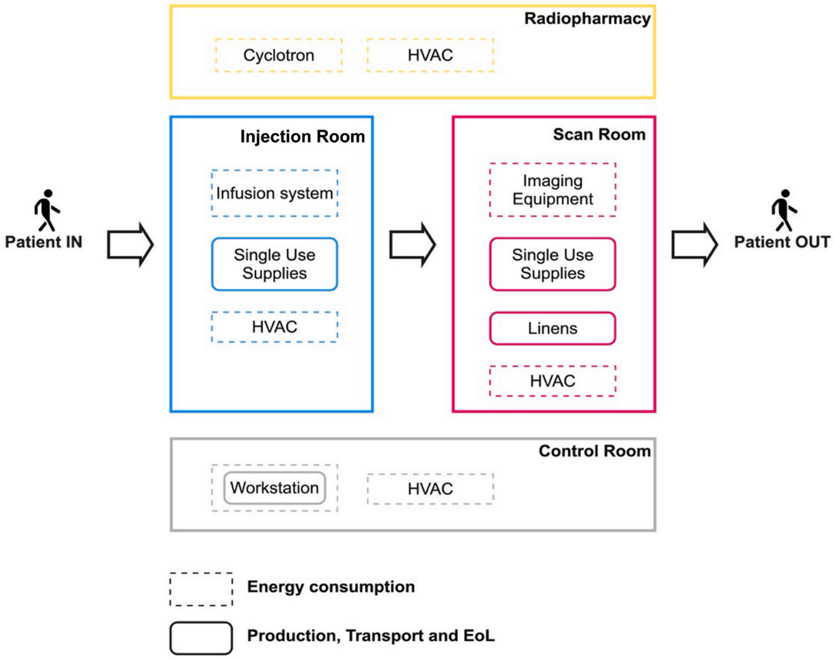


Fig. 2. System Boundaries and Functional Areas for [^{18}F]FDG PET/CT Life Cycle Assessment. Diagram showing the main functional spaces involved in a [^{18}F]FDG PET/CT scan: Radiopharmacy, Injection Room, Scan Room, and Control Room. The elements contributing to the life cycle environmental impacts are grouped into two categories: energy consumption (dashed lines) and material-related processes, including production, transport, and end-of-life (solid lines). HVAC and equipment operation represent energy inputs, while single-use supplies and linens contribute to material impacts. The patient flow from entry to discharge is shown from left to right.

electricity consumption attributable to a single PET/CT scan, the total energy consumed from the beginning to the end of each examination was considered, including all operating states of the equipment (off, idle, ready-to-scan, scan). For the purposes of the LCA study, only the energy consumed during the ready-to-scan and scan phases was considered. The beginning of these two phases was defined as the start of the patient table translation through the scanner ring, while the end of these two phases, and the end of the examination, corresponded to the moment the patient left the examination table. This approach was chosen to reflect real-world energy demands and to provide a conservative estimate of electricity consumption per examination.

Energy use of lighting and other electrical equipment – A visual inventory of lighting and other electrical equipment used during the patient pathway for a [^{18}F]FDG PET/CT VMT scan was collected, including the number and type of computers, monitors, printers and radiopharmaceutical injector Medrad Intego PET Infusion System (Bayer AG, Leverkusen, Germany). Manufacturer data were used to estimate the energy consumption of each device, considering that computers (including the acquisition console), monitors, and printers were assumed to be in energy-saving mode during inactivity. For life cycle purposes, a workstation service life of 4 years and usage of 250 working days per year with 12-h daily operations were considered. Transportation and end-of-life (EoL) phases for these devices were included in the analysis.

Energy use of Heating, Ventilation, and Air Conditioning Systems – The contribution of heating, ventilation, and air conditioning (HVAC) systems was estimated using official data relating to the trigeneration plant at the San Raffaele Hospital in Milan, available through environmental statements [25], energy audits [26] and technical reports on the facility's energy requirements [27]. The plant, located 600 m from the hospital, produces and distributes electricity, hot water, superheated water, and chilled water, which represent different thermal vectors of the centralised energy system rather than distinct clinical end uses, covering the air conditioning needs of a total area of approximately 290,000 m^2. In 2020, total consumption for heating and cooling amounted to 214,125 MWh, corresponding to an average requirement of 738 kWh/m^2 per year, or approximately 2.02 kWh/m^2 per day. In particular, thermal energy in the form of hot water amounted to 71,843 MWh (247.7 kWh/m^2 per year), that in the form of superheated water to 74,225 MWh (255.9 kWh/m^2 per year), while the cooling energy requirement reached 68,057 MWh (234.7 kWh/m^2 per year). These values, obtained from technical documentation, were used as a reference to estimate the environmental impact of the HVAC system in the PET/CT room and its auxiliary spaces. To increase the accuracy of the estimate, HVAC energy consumption was calculated separately for each of the four functional spaces involved in the patient pathway (Radiopharmacy, Injection Room, Scan Room, and Control Room) as illustrated in Fig. 2. The energy consumption of a single PET/CT examination was finally calculated by comparing the allocated HVAC quota to the daily number of services during a typical working week (Monday to Friday, from 8:00 to 20:00). Since [^{18}F]FDG PET/CT VMT examinations account for approximately 50% of all procedures performed, this value was used as the basis for estimating the average consumption per examination. Subsequently, the average consumption per examination was converted into CO_2 equivalent emissions using the specific emission factor of the power plant, equal to 0.259 tCO_2/MWh [25].

Radiopharmaceutical production – The workflow for the radiopharmaceutical production of [^{18}F]FDG included synthesis and quality control steps. The cyclotron facility is located adjacent to the nuclear medicine department. During the study, the critical points of the LCA of the radiopharmaceutical production process were identified as the energy consumption of the cyclotron, IBA Cyclone 18/9 (IBA RadioPharma Solutions) and the energy consumption of the cyclotron room HVAC. Data on the cyclotron's energy consumption were collected by evaluating the technical specifications. Electricity consumption data for the cyclotron were derived from manufacturer technical specifications, assuming a power draw of 60 kW operated over a 2-h cycle. As radiopharmaceutical doses are prepared in a single batch and used for multiple patients, this energy consumption was evenly allocated across the 30 [^{18}F]FDG examinations performed during a typical working day for the entire department, resulting in a per-scan allocation of 4 kWh. The energy demand of the cyclotron room's HVAC system was estimated as described in the previous paragraph.

Semidurable and single-use medical supplies – All medical supplies required for the PET/CT procedure, including disposable and single-use items such as cannulas, Coflex bandages, needles, syringes, and radiotracer vials, were collected directly from the study site. Each item was categorised by material composition using manufacturer data when available or estimated based on scientific literature and specialised databases (see Appendix S1 for a full inventory). For each product, a share of the energy associated with its manufacturing process was accounted for in the LCA. Reusable items were also included and were attributed an energy consumption corresponding to their sterilisation cycle. A standard transport distance of 200 km by a 32-ton truck was assumed for inbound logistics. EoL scenarios distinguish between recyclable materials and potentially infectious waste. Items falling into the latter category were assumed to be incinerated. Waste disposal included an average outbound transport distance of 100 km by a 16-ton truck. The assumed transport distances were selected as conservative and widely adopted default values for medical supply chains in hospital-based LCAs, consistent with transport assumptions commonly adopted in healthcare-related LCA studies assessing pharmaceutical and clinical packaging and healthcare waste management [28,29]. In the absence of item-specific transport data, using standardised representative distances ensures methodological consistency and allows comparability with published LCA models, while preventing underestimation of transport-related impacts.

Workflow Observation and Operational Data – Operational activities related to the PET/CT procedure were directly observed during routine clinical activity in the nuclear medicine department. Time intervals for each phase of the workflow were validated using time-stamped data retrieved from the Radiology Information System (RIS) and Picture Archiving and Communication System (PACS), ensuring accurate quantification of procedure times and room usage. These data were used to inform the life cycle inventory with real-world operational parameters.

Excluded Processes – The construction of the hospital building and its HVAC infrastructure, as well as the manufacturing of major medical equipment (e.g., the PET/CT scanner and radiopharmaceutical injectors), were excluded from the system boundaries. The goal of this study was not to assess the environmental impact of the imaging equipment itself, but rather to evaluate the energy use and material flows directly associated with the provision of a single [^{18}F]FDG PET/CT examination. This boundary definition is consistent with previous LCA studies in radiology, which often focus on the use phase when the functional unit is a single clinical examination. Similarly, the transportation of patients and hospital staff to and from the facility was not considered in this analysis. Energy consumption associated with PACS infrastructure was not considered, as these systems are operated within a separate hospital department and therefore fall outside the boundaries of the examined workflow.

2.3. Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) involves converting the inventory data collected into environmental impact indicators. This process enables a clearer understanding of the potential environmental consequences associated with each stage of the system's life cycle. The ReCiPe 2016 Midpoint methodology has been used to convert the inventory data collected into environmental impact indicators [30] (see Appendix S2 –Table S1 for emissions categories).

2.4. Sensitivity analysis

A sensitivity analysis was conducted to examine the potential influence of differences between national energy grids on overall emissions, modelling electricity supply scenarios with different carbon intensity profiles in energy consumption associated with HVAC systems, recognising variability in operation across different clinical settings. LCA does not lend itself to statistical methods commonly used in medicine.

3. Results

3.1. Life cycle impact assessment per scan

Each [^{18}F]FDG PET/CT VMT scan has a life cycle Global Warming Potential (GWP) of approximately 7.6 kg CO_2 eq (Table 1). This GHG emission per scan falls within the broad range reported for advanced imaging modalities in the literature and underscores the importance of understanding emission sources specific to the PET/CT context. Overall, the findings show that a single PET/CT scan leaves a significant environmental footprint concentrated in a few key processes and inputs.

To facilitate interpretation, results are presented using two complementary perspectives: (i) system component contributions, which aggregate impacts by major input categories, namely HVAC, electricity, single-use disposables, and reusables and (ii) process-level environmental analysis, which reflect the contribution of individual phases along the patient care pathway.

3.2. Component contributions to GWP

A detailed breakdown of the GWP per scan by component, in terms of absolute and relative contributions, is provided in Appendix S2 – Table S1.

As illustrated in Fig. 3, HVAC systems and electricity consumption by other devices were the major relative contributors to GWP, as well as to ozone formation (reported separately in the ReCiPe framework for impacts on human health and on terrestrial ecosystems), terrestrial ecotoxicity, and fossil resource scarcity. In contrast, toxicity-related categories displayed contribution profiles dominated by single-use medical supplies, indicating a greater sensitivity to material production and end-of-life processes. Detailed values can be found in Appendix

Table 1
Life Cycle Impact Assessment Results per [^{18}F]FDG PET/CT Scan. Environmental impact results for a single [^{18}F]FDG PET/CT VMT scan, based on the ReCiPe 2016 Midpoint (H) method. eq: equivalent; kg: kilograms; m^3: cubic meters; CO_2: carbon dioxide; CFC-11: trichlorofluoromethane; Co-60: cobalt-60; $PM_{2.5}$: particulate matter with aerodynamic diameter <2.5 µm; NOx: nitrogen oxides; SO_2: sulphur dioxide; P: phosphorus; N: nitrogen; 1,4-DCB: 1,4-dichlorobenzene; Cu: copper; m^2a crop: square meter-years of crop occupation.

LCIA Impact Category	Unit	Total
Global warming potential	kg CO_2 eq	7.623
Stratospheric ozone depletion	kg CFC11 eq	0.000
Ionizing radiation	kBq Co-60 eq	0.162
Ozone formation, Human health	kg NO_x eq	0.015
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.005
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.017
Terrestrial acidification	kg SO_2 eq	0.011
Freshwater eutrophication	kg P eq	0.001
Marine eutrophication	kg N eq	0.001
Terrestrial ecotoxicity	kg 1.4-DCB	58.412
Freshwater ecotoxicity	kg 1.4-DCB	0.258
Marine ecotoxicity	kg 1.4-DCB	0.397
Human carcinogenic toxicity	kg 1.4-DCB	1.320
Human non-carcinogenic toxicity	kg 1.4-DCB	4.497
Land use	m^2a crop eq	0.153
Mineral resource scarcity	kg Cu eq	0.020
Fossil resource scarcity	kg oil eq	4.946
Water consumption	m^3	0.073

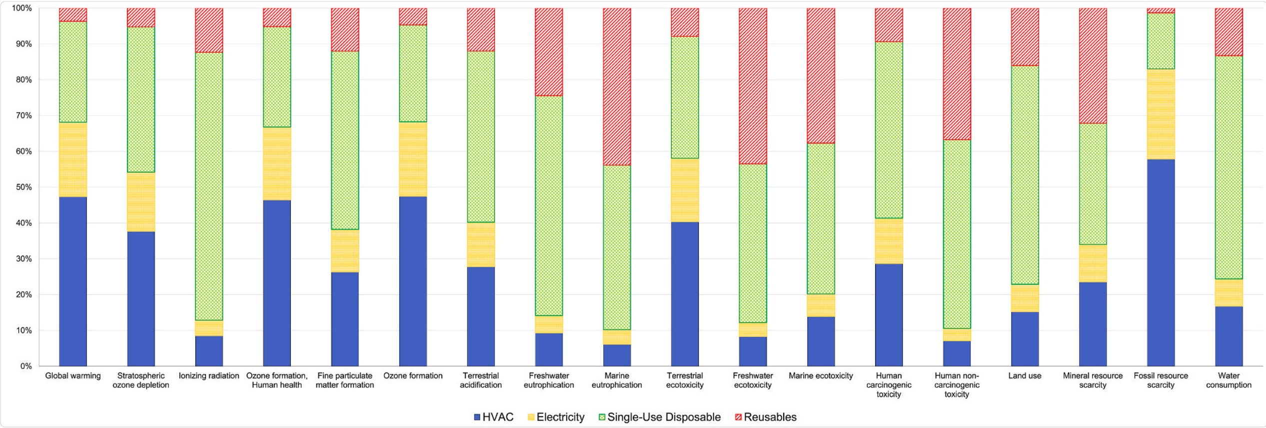


Fig. 3. Life cycle impact category contributions by major component for a single [^{18}F]FDG PET/CT scan. Stacked bar chart showing the percentage contribution of four main components: HVAC (plain blue), Electricity (yellow horizontal lines), Single-Use Disposables (green grid), and Reusables (red diagonal lines), to each impact category assessed using the ReCiPe 2016 Midpoint (H) method.

S2 – Table S2.

For a standard examination, the HVAC system serving the scanner room alone accounted for approximately 16.4% of the total GWP. Additional contributions arose from climate control in adjacent spaces, including the control room (used by medical staff during scanning) and the injection room (housing the MEDRAD® Intego infusion system), which collectively added another 9%. Overall, the facility's HVAC systems, encompassing the scanner, control, injection rooms, and cyclotron facility are responsible for nearly 47% (3.6 kg CO_2 eq.) of the scan's climate-related impacts (Fig. 4, Appendix S2 - Table S2, Appendix S2 – Table S3). The electricity used for [^{18}F]FDG radiopharmaceutical production, via cyclotron operation, represents the third-largest source of emissions, contributing around 13.6% of GWP per scan. When including the energy required to condition the cyclotron facility environment (an additional 22%), the radiopharmaceutical production phase accounts for nearly 36% (2.7 kg CO_2 eq.) of the scan's life cycle GWP (Fig. 5).

By contrast, the direct electricity consumption by imaging equipment during the scan represents a comparatively minor share of total impacts. During the audit period, the total energy consumed by the PET/CT scanner amounted to 964.5 kWh over one week. Daily electricity consumption showed some variability, ranging from 96.3 kWh to 164.6 kWh per day, reflecting differences in daily workload and scanner utilisation (Appendix S2 – Table S4). Of the total weekly consumption, 87.8 kWh were attributable to active scanning phases associated with 56 [^{18}F]FDG PET/CT VMT examinations performed during the study period. This corresponds to an average electricity consumption of 1.6 ± 0.2 kWh per scan, equating to roughly 3.7% (0.6 kg CO_2 eq.) of GWP. The mean scan duration was 12.7 ± 2.5 min per examination. (Appendix S2 – Table S5).

Auxiliary electrical loads, such as the automatic injector and other electronics (monitors, computers, workstation), together contribute about 1%. The production of medical supplies and equipment used for each scan comprises the remainder of the environmental footprint. Single-use disposable items accounted for approximately 28% of GWP (2.1 kg CO_2 eq.), while reusable material, such as laundered linens, had a negligible contribution, amounting to 4% (Fig. 4, Appendix S2 – Table S2, Appendix S2 – Table S3).

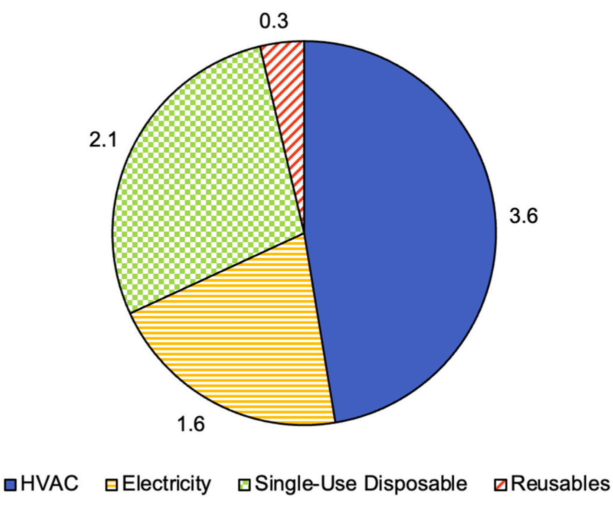


Fig. 4. Breakdown of life cycle GHG emissions, expressed in kg CO_2-equivalent, per [^{18}F]FDG PET/CT scan. The chart shows the relative contributions of major system components: HVAC (plain blue), Electricity (yellow horizontal lines), Single-Use Disposables (green grid), and Reusables (red diagonal lines).

3.3. Process-level environmental hotspots

Evaluating the results by individual process steps along the patient care pathway (Fig. 5) enables the identification of environmental "hotspots" within the PET/CT service delivery.

- Radiopharmaceutical production emerges as the most significant contributor (36%). The synthesis of the [^{18}F]FDG radiotracer at the on-site cyclotron facility is responsible for approximately one-third of total GWP.
- Patient preparation phase, which includes the patient's arrival, intravenous injection of the radiotracer through single-use devices, and the subsequent biodistribution period, represents the second factor contributing to environmental impact.
- Scan execution phase, corresponding to the period when the patient is present in the scanner room and the PET/CT system is operational, accounted for 22% of the total GWP per scan.
- Data management phase, comprising image reconstruction, interpretation, and archiving, contributed minimally to the overall environmental burden. The associated electricity consumption by IT infrastructure (consoles, computers, and monitors) represented less than 10% of the total GWP per scan.

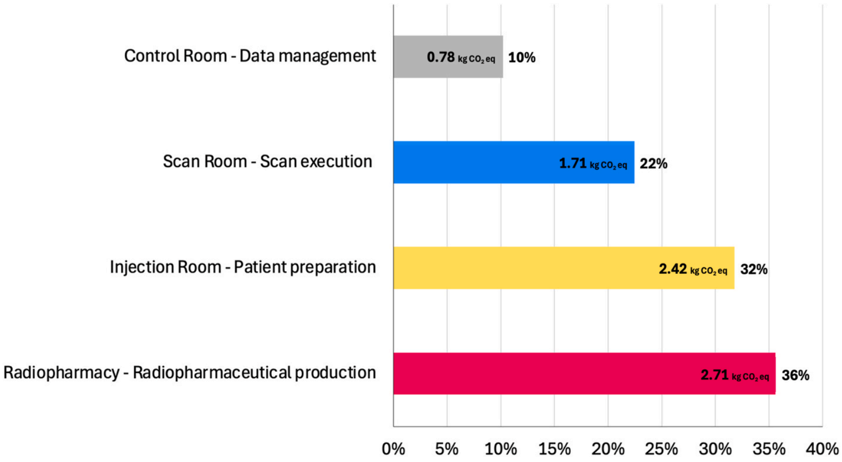


Fig. 5. Process-Level Contribution to Life Cycle GHG Emissions per PET/CT scan. Relative contribution (values and percent contribution) of each functional phase to the total GWP per [^{18}F]FDG PET/CT scan.

3.4. Material input contributions

Although material inputs represent a smaller share of the overall impact, the LCA highlights notable differences between disposable and reusable items across environmental categories (Table S1, Fig. 4). Single-use consumables (e.g., syringes, needles, gloves, tubing, gauze, vials) consistently contribute more than reusables (e.g., washable linens). For GWP, disposables account for approximately 28% of total emissions per scan (2.1 kg CO_2 eq.), while reusables contribute only 4% (0.3 kg CO_2 eq.). This disparity is even greater in categories such as solid waste generation and fossil resource depletion, where disposables dominate due to their plastic content and single-use nature. Certain items, like the blood filter needle, emerge as category-specific hotspots, contributing up to 10% of human carcinogenic toxicity and 4% of freshwater ecotoxicity, driven by stainless steel and plastic manufacturing as well as incineration impacts. An exception occurs in eutrophication categories, where both disposable gauze and reusable linens, largely made from cotton, exhibit elevated impacts due to fertiliser use and wastewater during production and laundering. Single-use cotton gauze is the top contributor to marine eutrophication (29%), while reusable linens, despite their multiple-use advantage, still contribute 13% to this category due to repeated washing cycles.

These results underscore that while energy consumption remains the primary driver of environmental burden, material choices matter, particularly in toxicity, resource use, and eutrophication. Substituting high-impact disposables with lower-impact or reusable alternatives, and minimising unnecessary consumable use, can yield meaningful reductions without compromising clinical safety.

3.5. Sensitivity analysis

The environmental impact associated with electricity consumption varies considerably depending on the energy mix. In this study, the carbon emission of HVAC system during a single PET/CT scan performed was estimated at 3.6 kg CO_2 eq. emissions, representing about 47% of the total Global Warming Potential. This makes it one of the main contributors to the overall carbon footprint of the procedure. The calculation was based on an average emission factor of 0.259 tCO_2/MWh, sourced from the specific emission factor of the trigeneration power plant of San Raffaele Hospital. While this local value was adopted to ensure site-specific accuracy, it should be noted that it is relatively high and does not fully reflect recent decarbonisation trends in the national energy mix. For comparison, the average grid electricity emission factor reported at the European level is 0.207 tCO_2/MWh in 2023 [31]. In 2024, the share of electricity generated from renewable sources in Italy has increased from 31% to 41.2% [32]. This transition towards renewables is leading to the progressive decarbonisation of the electricity mix and, consequently, to a reduction in CO_2 eq. emissions per unit of electricity consumed. To assess the sensitivity of the results to this evolving scenario, a hypothetical reduction in the emission factor was modelled. A 25% decrease in CO_2 eq. emissions per kWh would result in a reduction of approximately 0.9 kg CO_2 eq. per scan, while a 50% decrease would lead to a reduction exceeding 1.8 kg CO_2 eq. These findings highlight the significant impact that energy mix decarbonisation can have on the environmental footprint of medical imaging procedures. As the share of renewable energy continues to increase, a substantial decrease in the carbon intensity of PET/CT scans can be expected, thereby improving the environmental sustainability of these diagnostic practices.

4. Discussion

This study provides a comprehensive LCA of [^{18}F]FDG PET/CT VMT imaging performed in a hospital-based nuclear medicine department, identifying key environmental impacts and opportunities for mitigation. The analysis shows that a single PET/CT scan has an ecological footprint of 7.6 kg CO_2 eq, mainly determined by energy-intensive processes related to room HVAC systems (47%). This result is consistent with other previous studies analysing the environmental impact of healthcare activities, which also highlight climate control as an important environmental critical point [14,15]. In particular, Chua et al. [15], who calculated the volume of GHG associated with interventional radiology procedures, identify the climate control system as responsible for 49% of the emissions. Although HVAC systems installed inside a building can account for approximately 50-60% of the building's total energy consumption [33], several studies applying an LCA framework to assess the environmental impact of radiological practices have excluded these systems from their boundaries [12,13]. Given the differences in methodological approach among the various studies and the scarcity of published data in the specific setting of nuclear medicine, a direct comparison of the result is challenging. Adopting a uniform and standardised framework for Life Cycle Assessments in medical imaging would enhance the comparability of results across different studies [7]. It is important to emphasise that the performance of HVAC systems depends mainly on external seasonal conditions, where hot summer or cold winter conditions significantly alter the environmental impact [34]. Improving the efficiency of HVAC systems, which are subject to strict temperature and humidity requirements for healthcare areas, through the adoption of advanced air conditioning technologies could significantly reduce the environmental impact associated with PET/CT [35, 36].

Single-use medical materials account for the second largest contribution to the GWP of a single PET/CT scan (28%, 2.1 kg CO_2 eq. per scan), also contributing significantly in terms of toxicity, fossil resource depletion and waste generation. These results confirm what has been reported in the literature regarding the need to move towards reusable medical devices or more sustainable alternatives in healthcare settings [37]. In our assessment, all waste associated with single-use devices was disposed of in incinerators, partly due to their potential radioactive contamination, as is typical in nuclear medicine departments [38]. Nevertheless, better waste sorting would reduce the environmental impact associated with the use of single-use materials in radiology [39].

At present, environmental criteria are not systematically included in supplier selection at the departmental level, as procurement is largely centralised. However, sustainable procurement represents a relevant opportunity to reduce the environmental footprint of nuclear medicine services.

Direct electricity consumption is the third-largest contributor to the GWP (21%, 1.6 kg CO_2 eq. per scan), encompassing all equipment and systems requiring electrical power, including the PET/CT scanner, computers, monitors, printer, automatic radiopharmaceutical injector, cyclotron electricity use, room lighting, and laundry services. It is interesting to note that the direct electricity consumption of the PET/CT scanner contributed minimally (5.4%) to the overall GWP. This result contrasts with the common belief that diagnostic imaging equipment is among the main consumers of energy [16,40]. However, it highlights the importance of adopting operational strategies aimed at reducing scanner downtime and optimising patient flows [4].

Considering the patient care pathway, the production of radiopharmaceuticals has a big contribution to GWP per examination (36%), mainly due to the electricity consumption associated with the cyclotron and the related environmental conditioning. This significance is also confirmed in the study by Godard et al. [19], where, however, the production of radiopharmaceuticals is associated with the environmental impact of transport from the external production facility and the nuclear medicine department. In our case, this amount of emissions is not present because the radiopharmacy is itself part of the nuclear medicine department.

Sensitivity analysis has shown that variations in energy sources significantly influence the environmental profile of PET/CT examinations. In particular, the environmental impact associated with electricity consumption was found to be highly dependent on the carbon intensity of the national energy mix. By modelling a hypothetical decarbonisation of the grid, we found that a 25% reduction in the emission factor would result in a reduction of approximately 0.9 kg CO_2 eq. per single examination, while a 50% reduction would lead to savings of 1,8 kg CO_2 eq. Similar results were highlighted in the sensitivity analysis by Thiel et al. [13], which estimated that decarbonisation of the grid would result in a 57% reduction in CO_2 eq. emissions from diagnostic imaging activities. These results highlight the enormous potential of national energy policies in reducing the environmental impact of diagnostic imaging.

One aspect excluded from the LCA boundaries of this study was patient transport and staff commuting. This methodological choice was made because it would have involved several variables in terms of transport types, distances, and, above all, personal information that needed to be collected, leading to considerable complications from an ethical point of view. However, it is important to emphasise that this component also has a high environmental impact in activities associated with clinical practice. Godard et al. [19] identify it as the primary factor in the carbon footprint of nuclear medicine departments, and other studies in the literature have also highlighted the environmental impact of transportation in various radiological contexts [41,42].

The rigorous methodological approach of LCA adopted in this study, based on direct observational data and on-site measurements, reinforces the accuracy and practical applicability of the results. However, some limitations must be acknowledged. First, the study includes data from only one week of observation and from only one PET/CT scanner. Although a longer audit may be preferable, the volume of data collected and analysed in this study is comparable to that of previously published LCAs conducted in the healthcare setting. Furthermore, the exclusion of impacts related to infrastructure construction, patient and staff transportation, and variability in scanner use outside standard clinical hours may result in an underestimation of the overall life cycle impacts. While LCA represents a robust and standardised methodology for quantifying environmental impacts, its application in medical settings is associated with several inherent limitations. Healthcare processes are highly context-dependent, and LCA results rely on modelling assumptions, allocation choices, and secondary datasets that may not fully capture clinical variability, organisational differences, or patient-specific factors. Moreover, limited availability of primary environmental data for medical technologies and supplies often necessitates the use of generic databases, introducing uncertainty in impact estimates. A key strength of this study lies in its detailed, measurement-based approach and its focus on a complete PET/CT patient pathway, providing one of the first comprehensive environmental assessments of [^{18}F]FDG PET/CT imaging. By identifying specific and actionable hotspots, this work offers leverage points where targeted interventions could lead to reductions in environmental impact. Even modest improvements in these areas, when scaled across high-volume PET/CT examinations, could translate into substantial cumulative environmental benefits. Future studies including these factors, together with comparisons between different types of nuclear medicine examinations and equipment models, could provide further insights into the environmental impact of nuclear medicine departments.

5. Conclusions

This study presents one of the first detailed LCAs of [^{18}F]FDG PET/CT imaging, showing that a single vertex-to-mid-thigh scan generates about 7.6 kg CO_2 eq., mainly from HVAC operation and radiopharmaceutical production. In contrast, the PET/CT scanner's direct electricity use is minimal, highlighting the need to focus sustainability efforts beyond equipment efficiency alone. The results indicate that optimising climate control systems, improving radiopharmaceutical production processes, and reducing high-impact single-use consumables could substantially lower environmental impacts. Sensitivity analysis further shows that grid decarbonisation and seasonally adapted HVAC operation represent major opportunities for emission reduction. This study provides robust, measurement-based evidence to inform sustainability strategies in nuclear medicine, supporting the integration of energy efficiency, sustainable procurement, and climate-adapted operations into PET/CT practice.

CRediT authorship contribution statement

Andrea Roletto: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Anna Savio:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Enrico Bertagna:** Writing – original draft, Software, Methodology, Formal analysis. **Nicolò Sean Chiodini:** Visualization, Investigation. **Giuseppe Roberto Bonfitto:** Writing – review & editing, Visualization, Investigation. **Arturo Chiti:** Writing – review & editing, Validation, Supervision. **Simone Zanoni:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Arturo Chiti is Associate Editor of EANM Innovation—he was not involved in any way in the evaluation, revision, or decision process of this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eanmi.2026.100025.

Data availability

Data will be made available on request.

References

[1] Health Care Without Harm. Health care's climate footprint – how the health sector contributes to the global climate crisis and opportunities for action. Available from: https://global.noharm.org/resources/health-care-climate-footprint-report. [Accessed 14 March 2025].

[2] Romanello M, Walawender M, Hsu S-C, Moskeland A, Palmeiro-Silva Y, Scamman D, et al. The 2025 report of the Lancet countdown on health and climate change: climate change action offers a lifeline. Lancet 2025;406:2804–57.

[3] Schoen J, McGinty GB, Quirk C. Radiology in our changing climate: a call to action. J Am Coll Radiol 2021;18:1041–3.

[4] Woolen SA, Kim CJ, Hernandez AM, Becker A, Martin AJ, Kuoy E, et al. Radiology environmental impact: what is known and how can we improve? Acad Radiol 2023;30:625–30.

[5] Roletto A, Zanardo M, Bonfitto GR, Catania D, Sardanelli F, Zanoni S. The environmental impact of energy consumption and carbon emissions in radiology departments: a systematic review. Eur Radiol Exp 2024;8:35.

[6] Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al. Life cycle assessment: past, present, and future. Environ Sci Technol 2011;45:90–6.

[7] Roletto A, Savio A, Marchi B, Zanoni S. Towards a greener radiology: a comprehensive life cycle assessment framework for diagnostic imaging. Environ Clim Technol 2024;28:303–11.

[8] Drew J, Christie SD, Tyedmers P, Smith-Forrester J, Rainham D. Operating in a climate crisis: a state-of-the-science review of life cycle assessment within surgical and anesthetic care. Environ Health Perspect 2021;129.

[9] Chen Z, Lian JZ, Zhu H, Zhang J, Zhang Y, Xiang X, et al. Application of life cycle assessment in the pharmaceutical industry: a critical review. J Clean Prod 2024; 459:142550.

[10] Thiel CL, Eckelman M, Guido R, Huddleston M, Landis AE, Sherman J, et al. Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the United States. Environ Sci Technol 2015;49:1779–86.

[11] Savio A, Marchi B, Roletto A, Milano G, Zanoni S. Sustainable operating rooms: a comprehensive framework for environmental impact analysis. Environ Clim Technol 2024;28:1.

[12] McAlister S, McGain F, Petersen M, Story D, Charlesworth K, Ison G, et al. The carbon footprint of hospital diagnostic imaging in Australia. Lancet Reg Health West Pac 2022;24:100459.

[13] Thiel CL, Vigil-Garcia M, Nande S, Meijer C, Gehrels J, Struk O, et al. Environmental life cycle assessment of a U.S. hospital-based radiology practice. Radiology 2024;313:e240398.

[14] Leapman MS, Thiel CL, Gordon IO, Nolte AC, Perecman A, Loeb S, et al. Environmental impact of prostate magnetic resonance imaging and transrectal ultrasound-guided prostate biopsy. Eur Urol 2023;83:463–71.

[15] Chua ALB, Amin R, Zhang J, Thiel CL, Gross JS. The environmental impact of interventional radiology: an evaluation of greenhouse gas emissions from an academic practice. J Vasc Interv Radiol 2021;32. 907–15.e3.

[16] Heye T, Knoerl R, Wehrle T, Mangold D, Cerminara A, Loser M, et al. The energy consumption of radiology: energy- and cost-saving opportunities for CT and MRI operation. Radiology 2020;295:593–605.

[17] Chaban YV, Vosshenrich J, McKee H, Gunasekaran S, Brown MJ, Atalay MK, et al. Environmental sustainability and MRI: challenges, opportunities, and a call for action. J Magn Reson Imaging 2024;59:1149–67.

[18] Roletto A, Verga M, Savio A, Viganò GL, Zanoni S. Energy performance of MRI systems: on-site validation and comparison with manufacturer declarations. Eur Radiol Exp 2026;10:3.

[19] Godard F, Oosthoek J, Alexis A, Léo P, Fontaine E, Dahmani M, et al. Estimation of carbon footprint in nuclear medicine: illustration of a French department. Eur J Nucl Med Mol Imaging 2025;52:3455–64.

[20] Reinert CP, Sekler J, la Fougère C, Pfannenberg C, Gatidis S. Impact of PET/CT on clinical management in patients with cancer of unknown primary—a registry study. Eur Radiol 2020;30:1325–33.

[21] Huasong H, Shurui S, Shi G, Bin J. Performance of 18F-FDG-PET/CT in head and neck squamous cell carcinoma of unknown primary: systematic review and meta-analysis. Clin Transl Imaging 2021;9:361–71.

[22] International Organization for Standardization. ISO 14040:2006 – life cycle assessment: principles and framework. Available from: https://www.iso.org/standard/37456.html. [Accessed 14 March 2025].

[23] PRé sustainability. SimaPro [computer program]. Available from: https://simapro.com. Accessed 14 March 2025.

[24] Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, et al. The ecoinvent database: overview and methodological framework. Int J Life Cycle Assess 2005;10:3–9.

[25] IRCCS Ospedale San Raffaele. Dichiarazione ambientale EMAS 2021 – centrale di cogenerazione e teleriscaldamento. 2020. Milano, [Accessed 19 August 2025].

[26] Esco GKSD. Diagnosi energetiche ambito sanitario – Ospedale San Raffaele. 2023. Milano, [Accessed 19 August 2025].

[27] Marzocchi L, Piemonte C. Energia e teleriscaldamento: l'esperienza dell'Istituto San Raffaele. 2017. Milano, [Accessed 19 August 2025].

[28] Baehr J, Göllner-Völker L, Baehr M, Muthukumar H, Lapa N, Schebek L. Life cycle assessment of pharmaceutical and clinical packaging for medication administration. Int J Life Cycle Assess 2024;29:416–32.

[29] Bassani F, Rodrigues C, Marques P, Freire F. Life cycle assessment of pharmaceutical packaging. Int J Life Cycle Assess 2022;27:978–92.

[30] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: harmonised life cycle impact assessment at midpoint and endpoint. Int J Life Cycle Assess 2017;22:138–47.

[31] European Environment Agency. Greenhouse gas emission intensity of electricity generation in Europe. 2025. [Accessed 26 July 2025].

[32] Terna – Rete Elettrica Nazionale. Consumi elettrici 2024 in aumento del 2,2%. 2025. [Accessed 6 June 2025].

[33] Chua KJ, Chou SK, Yang WM, Yan J. Achieving better energy-efficient air conditioning: a review. Appl Energy 2013;104:87–104.

[34] Pachano JE, Peppas A, Bandera CF. Seasonal adaptation of VRF HVAC model calibration in a Mediterranean climate. Energy Build 2022;261:111941.

[35] Gholamzadehmir M, Del Pero C, Buffa S, Fedrizzi R, Aste N. Adaptive-predictive control strategy for HVAC systems in smart buildings. Sustain Cities Soc 2020;63: 102480.

[36] Aparicio-Ruiz P, Ragel-Bonilla JC, Barbadilla-Martín E, Guadix J. Integration of the adaptive approach in HVAC system operation: a case study. Appl Sci 2025;15: 1243.

[37] Rizan C, Mortimer F, Stancliffe R, Bhutta MF. Plastics in healthcare: time for a re-evaluation. J R Soc Med 2020;113:49–53.

[38] Woolridge AC, Phillips PS, Denman AR. Systematic analysis of radioactive healthcare waste generation in an acute hospital. Resour Conserv Recycl 2008;52: 1198–208.

[39] Roletto A, Catania D, Rainford L, Savio A, Zanardo M, Bonfitto GR, et al. Sustainable radiology departments: a European survey of radiographers' perceptions. Radiography 2024;30:81–90.

[40] Martin M, Mohnke A, Lewis GM, Dunnick NR, Keoleian G, Maturen KE. Environmental impacts of abdominal imaging: a pilot investigation. J Am Coll Radiol 2018;15:1385–93.

[41] Yakar D, Kwee TC. Carbon footprint of air travel to international radiology conferences: FOMO? Eur Radiol 2020;30:6293–4.

[42] Yakar D, Kwee TC. Carbon footprint of the RSNA annual meeting. Eur J Radiol 2020;125:108869.

PAPER 8

healthcare

MDPI

Article

Integrating Energy Efficiency into Healthcare Operations: A Discrete-Event Simulation Approach for Surgical Pathways

Francesco Sferrazzo [1], Beatrice Marchi [1], Anna Savio [1], Andrea Roletto [1] and Simone Zanoni [2,*]

[1] Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, 25123 Brescia, Italy; f.sferrazzo@studenti.unibs.it (F.S.); beatrice.marchi@unibs.it (B.M.); anna.savio@unibs.it (A.S.); andrea.roletto@unibs.it (A.R.)

[2] Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia, 25123 Brescia, Italy

* Correspondence: simone.zanoni@unibs.it

Abstract

Background/Objectives: Healthcare facilities are among the most energy-intensive public buildings, yet hospital decision-support models rarely integrate energy-related performance indicators alongside operational metrics. This study aims to address this gap by developing a discrete-event simulation framework capable of jointly evaluating clinical efficiency and energy consumption in elective orthopedic surgical pathways. **Methods:** A comprehensive discrete-event simulation model was developed to represent the diagnostic imaging and orthopedic surgical process. The model was parameterized using a hybrid data-collection approach that combined clinical activity data, scientific literature, and expert judgment. Energy consumption was modeled by differentiating fixed loads, such as heating, ventilation, and air-conditioning systems and lighting, from activity-dependent loads associated with diagnostic and surgical equipment. Baseline performance was assessed and compared with alternative scenarios for organizational and technological improvements. **Results:** The analysis showed that fixed infrastructural loads, particularly HVAC systems, were the main drivers of per-patient energy consumption, with inefficient space utilization and prolonged idle times. Scenario analysis demonstrated that organizational interventions, such as increasing operating room throughput and optimizing MRI scheduling, can substantially reduce energy intensity by diluting fixed loads and decreasing idle consumption. Technological interventions, such as replacing conventional surgical lamps with LED systems, produced smaller but still beneficial reductions. The combined implementation of organizational and technological strategies yielded the greatest overall improvement. **Conclusions:** Integrating energy metrics into discrete-event simulation provides effective support for hospital decision-making by revealing the interaction between workflow design, resource utilization, and environmental performance. The findings indicate that organizational redesign, particularly when combined with technological upgrades, can significantly improve both operational efficiency and sustainability in hospital settings. This study highlights discrete-event simulation as a promising tool for energy-aware healthcare planning.

Keywords: healthcare; energy efficiency; discrete-event simulation; operating rooms; sustainability; hospital management; FlexSim Healthcare

Check for updates

Academic Editor: Hsin-Chieh Wu

Received: 11 February 2026
Revised: 9 April 2026
Accepted: 20 April 2026
Published: 23 April 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Environmental sustainability has established itself as a priority in global policy debates, driven by the escalating demand for energy and the persistent reliance on fossil fuel-based systems, which remain the primary drivers of climate change [1]. While international decarbonization efforts are underway, the transition comes with significant economic implications; achieving a net-zero economy requires a fundamental transformation of the global energy mix to mitigate costs and unlock potential growth opportunities [2].

Within this broader framework, the healthcare industry exhibits a structural paradox: while essential for societal well-being, the sector significantly contributes to environmental degradation [3]. Recent global assessments indicate that healthcare is responsible for approximately 4.4% of total net emissions, a footprint comparable to that of the fifth-largest emitting country in the world [4]. Furthermore, pollution resulting from healthcare services inadvertently exacerbates public health challenges, creating a feedback loop that increases healthcare demand [5].

Energy consumption in healthcare facilities is characterized by high intensity and poor integration into operational decision-making [6]. This issue is particularly acute in the Operating Room (OR). Although ORs typically occupy a small fraction of a hospital's total footprint, they are responsible for a disproportionately high share of energy consumption-often three to six times more than other hospital wards [7]. This intensity is largely driven by stringent HVAC (Heating, Ventilation, and Air Conditioning) requirements for infection control, which necessitate continuous operation even during non-productive hours [8]. Consequently, operating theatres represent a critical area for implementing energy reduction strategies without compromising patient safety [9].

To address these complexities, Discrete-Event Simulation (DES) has been widely acknowledged as a robust scientific approach for analyzing healthcare systems with stochastic behavior and resource constraints [10]. DES allows managers to evaluate scenarios and optimize patient flows without disrupting real-world operations [11]. However, a systematic review of the literature reveals a significant methodological gap: existing simulation studies focus predominantly on operational KPIs, such as waiting times and throughput, with limited explicit integration of dynamic energy consumption metrics [12]. This lack of integration restricts the ability of decision-makers to evaluate trade-offs between operational efficiency and environmental performance [13].

Building on these findings, this project aims to develop an integrated discrete-event simulation model within FlexSim Healthcare. The research focuses on orthopedic surgery, a discipline identified as having one of the highest carbon footprints due to the intensive use of power tools, consumables, and sterilization processes [14]. The proposed model maps the complete surgical pathway, assigning energy profiles to medical equipment and infrastructural systems based on verified clinical duty cycles.

The core novelty of this study lies in a paradigm shift: repurposing Discrete-Event Simulation (DES), traditionally a tool for operational throughput, into a dedicated engine for environmental sustainability. While previous research focuses on reducing waiting times or increasing patient flow, this framework treats energy consumption not as a static building overhead, but as a dynamic clinical variable. By mapping specific equipment duty cycles directly onto the stochastic flow of surgical activities, the model provides a bottom-up quantification of the energy footprint per patient, a metric largely absent in current healthcare modeling.

The remaining sections of this work are organized as follows. Section 2 examines the relevant literature on energy usage in healthcare facilities and the use of discrete-event simulation for hospital operations, emphasizing extant research gaps. Section 3 describes the suggested methodology, including the creation of the discrete-event simulation model,

https://doi.org/10.3390/healthcare14091134

data sources, and the incorporation of energy-related variables. Section 4 presents the outcomes of the simulation studies, which include a baseline analysis and an evaluation of several organizational and technology energy efficiency measures. Section 5 reviews the findings and provides managerial perspectives, focusing on the implications for hospital decision-makers and sustainability-oriented planning. Finally, Section 6 summarizes the article and suggests areas for future investigation.

2. Literature Review

This section presents the current state of the art in the use of modeling and simulation approaches to promote energy efficiency and sustainability in healthcare facilities. The literature review has two goals: first, to examine how simulation-based methods have been used in healthcare settings and whether energy-related aspects are explicitly considered; and second, to identify methodological limitations and research gaps that motivate the current study.

2.1. Review Procedure

To carefully explore existing studies, a structured literature search was conducted utilizing the Scopus database. The review was led by three research questions. It should be noted that this review follows a structured rather than fully systematic approach; the broad search scope is intentional, as appropriate for an exploratory scoping study aimed at mapping an emerging research area.

1. Which modeling and simulation approaches are most commonly used to depict and enhance energy efficiency in healthcare facilities, and in what operational or structural contexts are they implemented?
2. How are energy characteristics, temporal dynamics, and performance indicators represented and incorporated into healthcare simulation models to evaluate sustainability?
3. To what extent do simulation models integrate energy-related objectives with operational and infrastructure constraints to aid decision-making that considers efficiency, sustainability, and quality of care?

The original search addressed the intersection of simulation and healthcare systems, yielding 19,345 documents. An organized combination of keywords was employed, divided into three theme areas: healthcare systems, decision-making and optimization, and simulation methodologies (Table 1).

Table 1. Overview of keywords used in the literature search.

	Research Area	**Keywords**	
	Healthcare system	"Healthcare system"	
AND	Decision & Optimization	"Decision making"	
		OR	"Optimization"
		OR	"Decision support system"
		OR	"Efficiency"
AND	Simulation approach	"Simulation"	
		OR	"Queueing theory"

To correlate the results with the study's aims, a multi-step filtering technique was used (Figure 1). First, the search was limited to articles that directly mentioned healthcare systems, resulting in 2547 documents. Second, papers designated as solely medical or clinical subject areas were eliminated, removing biological studies unrelated to system-level

https://doi.org/10.3390/healthcare14091134

modeling and lowering the dataset to 1006 entries. Further refining based on keywords relating to decision-making, efficiency, optimization, and simulation models, combined with a filter for peer-reviewed journal articles and reviews only, yielded 139 results. An abstract screening was then conducted to identify research that specifically addressed energy efficiency or sustainability at the system level. During this phase, 87 papers were discarded because they dealt with misaligned themes such as infectious illness modeling, patient monitoring technology, or logistics studies that addressed operational efficiency without taking energy into account. The remaining 52 articles underwent full-text analysis to establish thematic relevance and remove duplicates, yielding a final sample of 23 documents for the qualitative synthesis.

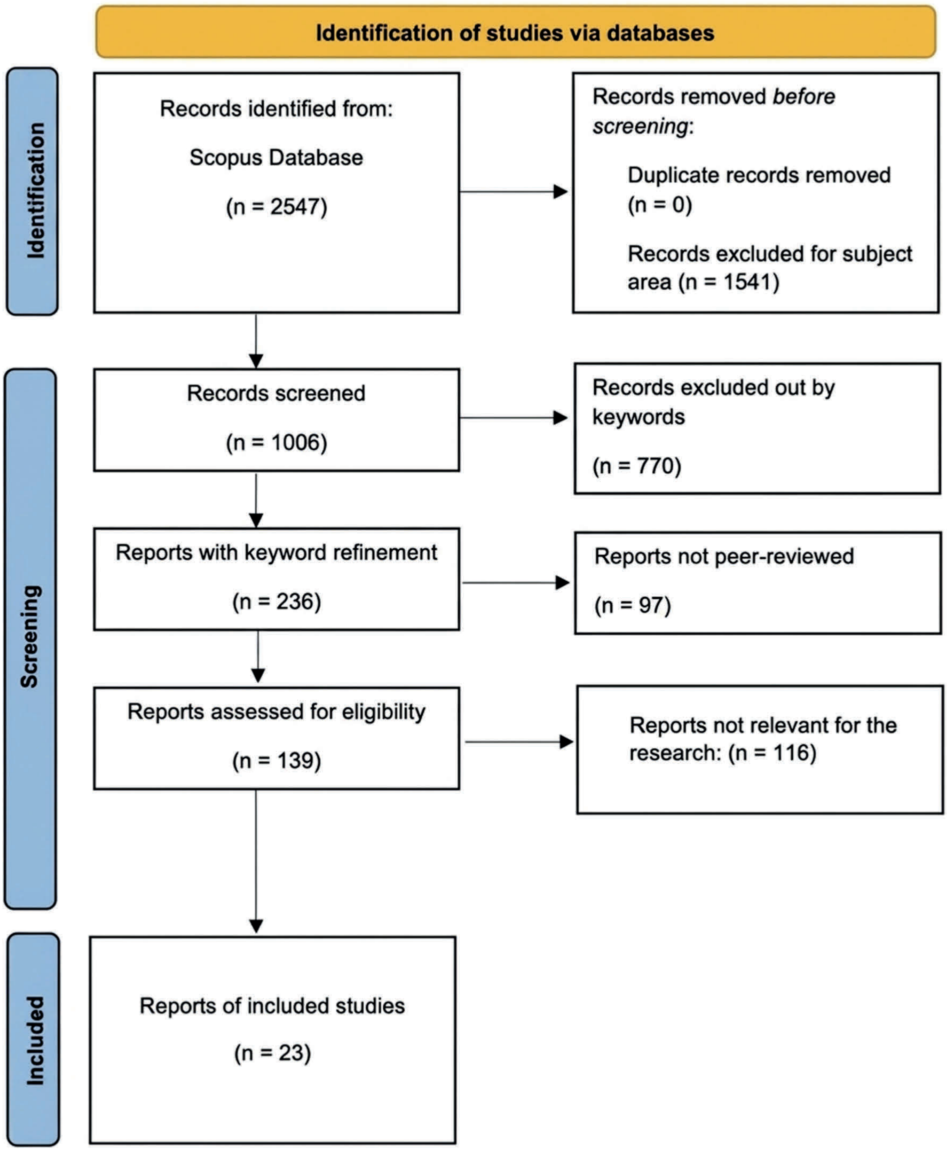


Figure 1. Structured search and selection flowchart.

To guide the analysis and maintain consistency across investigations, an interpretive analytical framework was created (Table 2). The framework is organized into three dimensions: (i) modeling and simulation methodologies, (ii) energy representation, and (iii) objectives, restrictions, and energy indicators. The first component, Modeling and Simulation Techniques, looked at the most used paradigms (such as DES or agent-based modeling), their application contexts (e.g., emergency rooms, logistics), and whether these models were coupled with optimization techniques. The second dimension, Energy Representation, examined how healthcare facilities' energy performance is represented in the models. It especially evaluated whether energy-related factors (for example, electricity use) were included, if temporal dynamics associated with energy use were modeled, and what performance criteria were used. Finally, the third analytical component addressed Objectives, Constraints, and Energy Indicators. It investigated whether simulation systems include objective functions associated with energy-related goals, if environmental or infrastructure constraints are considered, and whether energy KPIs are used to evaluate performance. This viewpoint evaluates whether simulation provides concrete support for sustainability-focused decision-making.

Table 2. Analytical framework for the literature review.

Analytical Framework		
Modeling and Simulation Techniques	**Energy Representation**	**Objectives, Constraints and Energy Indicators**
• Types of simulation models • Application domains • Integration with optimization algorithms	• Inclusion of energy parameters • Modelling of temporal energy dynamics • Use of energy performance metrics	• Definition of sustainable objective functions • Environmental and infrastructure constraints • Use of energy-related KPI for performance evaluation

2.2. Results of the Literature Analysis

The analysis of the selected papers synthesizes the current state of simulation modeling in healthcare, reflecting the operational and environmental trends discussed in previous sections. The review confirms that while simulation is a mature instrument for operational efficiency, its application to environmental sustainability is still emerging and unevenly distributed.

Discrete-event simulation (DES) clearly remains the primary standard for optimizing clinical workflows. Several studies, such as [15,16], utilize this approach to resolve bottlenecks in Emergency Departments, while others, including [17,18], focus specifically on improving scheduling and team dynamics in Operating Rooms. Beyond single-unit optimization, the literature highlights a trend toward broader, strategic applications: for instance [19,20] propose hybrid and metamodeling approaches to manage complex system interactions, whereas [21–23] develop frameworks to support long-term resource allocation and value-based healthcare planning.

Regarding sustainability, the examination of energy relevance reveals a clear dichotomy between digital and physical domains. The integration of energy variables is predominantly found in studies focusing on ICT infrastructures. A significant cluster of research applies simulation-optimization to minimize energy consumption in digital ecosystems: for instance [24,25] optimize IoT and Cloud resource provisioning, while a broader group including [26–30] focuses on energy-aware architectures for edge computing, WBANs, and IoHT systems.

In contrast, models addressing the energy footprint of the hospital building itself are significantly fewer. Benchmarks and consumption analyses are provided by [6,31], while specific technological or structural interventions, such as HVAC automation and

https://doi.org/10.3390/healthcare14091134

isolation room airflow, are examined in [32–34]. Broader environmental metrics remain niche, with [35,36] being the sole examples addressing sustainable water management and Life Cycle Assessment (LCA), respectively.

The fragmentation of sustainability integration is especially apparent when studying the essential components of simulation and simulation-optimization models:

1. Objective functions. The primary goals remain operationally driven, with most studies aiming to minimize waiting times or maximize throughput [15–17]. Purely energy-oriented objectives are standard in the digital domain [24,25] but are only emerging in broader hospital management frameworks.
2. Constraints. The feasibility of solutions is largely dictated by structural and operational limits [21,22]. While technological constraints are common in IT-focused studies [26], environmental constraints such as thermal comfort are less frequently applied [33,34].
3. Energy performance indicators. The transition to environmental KPIs is in its early stages. While digital studies explicitly measure energy metrics like network lifetime [28,29], indicators for physical sustainability remain rare, appearing only in specialized contributions [31,36].

In conclusion, the literature analysis confirms that while the methodological foundation for healthcare simulation is solid, a significant gap exists in applying these tools to the physical energy performance of hospital facilities.

2.3. Research Gaps

The literature review identifies numerous significant gaps, which motivate the current investigation. The principal novelty of this work resides in its integration of clinical stochasticity with physical energy consumption, a relationship that remained unexplored in all 23 studies identified in our structured literature search. Although prior DES-based studies have demonstrated strong performance in evaluating operational metrics, they have not modeled device-specific energy states as a direct function of clinical workflow dynamics.

First, despite the methodological maturity of simulation and optimization techniques in healthcare, most models continue to prioritize short-term operational efficiency, addressing localized constraints without explicitly tying them to environmental performance or sustainability goals. A key shortcoming is the insufficient incorporation of the physical and environmental components of healthcare facilities into simulation frameworks. This limitation is especially important because hospitals are among the most energy-intensive public buildings [6], with surgical rooms accounting for roughly 20–40% of overall hospital energy usage [37].

Nonetheless, simulation studies in surgical contexts mostly focus on throughput, scheduling, and delay reduction, with energy measurements rarely incorporated into the modeling logic. Even recent studies that show operational gains from advanced scheduling algorithms [34] typically include detailed energy KPIs.

Furthermore, the examined research indicates a poor relationship between energy factors and the spatial, organizational, and functional structure of hospital environments. Most contributions use a micro-level approach (e.g., single operating rooms or departments), while system-wide or pathway-oriented approaches are limited. When energy is included, it is frequently represented by aggregated building-level indicators or IT-related measures, rather than specifically modeling energy flows, temporal dynamics, or sustainability goals associated with healthcare procedures.

These shortcomings highlight the need for integrated simulation models that can capture clinical workflows, operational restrictions, and energy usage trends simultaneously. Embedding energy-related objectives, constraints, and performance indicators within

https://doi.org/10.3390/healthcare14091134

discrete-event simulation frameworks is a promising approach to decision-making that improves both operational performance and environmental sustainability, one that this study aims to advance. To synthesize the main shortcomings identified in the literature and clearly position the contribution of this study, Table 3 presents a structured gap mapping that contrasts existing research practices with the expected advancements and specific contributions of the current study across key analytical dimensions.

Table 3. Summary mapping of the research gaps identified in the literature review.

Gap Mapping			
Dimension	**Literature Provides**	**Expected**	**Contribution of the Study**
Modelling Focus	Operational performance, patient flow, waiting time reduction	Integration of energy efficiency in core clinical models	Shift from purely operational DES to Sustainability-Driven DES, linking clinical stochasticity with physical energy flows.
Constraints and KPIs	Staff availability, resource use, patient throughput	Standardized environmental constraints and energy-related KPIs for decision-making	Identification and implementation of energy-aware constraints and indicators in OR management
Scope and Level	Focus on micro-level operations, but limited to clinical or logistic aspects	Multidimensional models addressing both operational and environmental targets at the micro level	Integrated evaluation of clinical performance and environmental sustainability in surgical scheduling
Energy Representation	Sparse and often limited to IT infrastructure or general building-level metrics	Explicit modelling of energy flows, temporal dynamics, and sustainability targets in healthcare processes	Inclusion of energy parameters and metrics directly related to OR usage and scheduling decisions

3. Methodology

The research methodology employs a systematic and sequential strategy to integrate operational and energy viewpoints within a single simulation environment. The methodology is divided into four major phases: (i) problem identification and system boundaries, (ii) data collection and parameterization, (iii) simulation model creation, and (iv) results evaluation.

The first phase concentrated on discovering energy inefficiencies in healthcare facilities, with a special emphasis on operating rooms, which have high energy intensity and complicated organizational dynamics. This phase was aided by a comprehensive literature study aiming at identifying methodological shortcomings in the incorporation of energy measurements into healthcare simulation models.

The second phase included data collection and the creation of a comprehensive input database. The database contains process descriptions, resource limitations, activity durations, patient flows, and energy consumption profiles. Data were collected using a hybrid strategy that included scientific literature, clinical information, and expert-based estimates, assuring both realism and consistency with real-world operations.

The third phase involved creating a simulation model and outlining the cause-and-effect links between clinical activities, resource use, and energy consumption. The Discrete-Event Simulation approach was chosen because it is well-suited for modeling complex systems with stochastic behavior, limited resources, and time-dependent patient flows. DES allows healthcare processes to be represented as discrete events unfolding across time, reflecting both variability and operational restrictions. Examples include patient arrivals, diagnostic imaging examinations, and surgical operations.

https://doi.org/10.3390/healthcare14091134

The final phase centered on model execution and results evaluation. The simulation outputs were assessed to evaluate operational performance and energy usage patterns, as well as to identify potential organizational and technological improvements.

3.1. System Boundaries

The system boundaries were determined at the micro level, with an emphasis on orthopedic surgery rooms, which were chosen for their high energy demand and administrative relevance. Orthopedic surgery was selected for its high energy intensity, driven by the extensive use of power devices, imaging equipment, and sterilization processes, making it a particularly relevant context for an energy-conscious analysis. The focus on elective procedures further supports this choice, as scheduled interventions allow for a more tractable modeling approach with predictable patient flows and resource allocation. The configuration of two operating rooms and one diagnostic imaging unit reflects a realistic and representative micro-level layout, sufficiently complex to capture the interactions between clinical workflows and energy consumption while remaining manageable for simulation purposes. Importantly, different layout configurations, varying in the number of rooms or diagnostic units, would naturally entail different patient volumes and arrival patterns; however, since demand and service capacity are intrinsically linked, the structural relationships modeled here retain their validity across configurations, making this case study representative of a broader class of hospital micro-systems. To represent the interdependence of clinical efficiency and energy usage, the simulation scope was divided into two logically connected functional units: the Diagnostic Imaging Unit and the Orthopedic Surgery Unit. The Diagnostic Imaging Unit is responsible for all preoperative diagnostic imaging activities, including patient registration, specialist consultations, and diagnostic imaging studies, in particular X-ray and Magnetic Resonance Imaging (MRI). The modeled pathway encompasses the complete process, from patient arrival to diagnostic imaging procedure completion, and includes both human resources and high-energy-consuming medical equipment. The Orthopedic Surgical Unit includes the entire perioperative pathway (see Appendix A). The process is divided into three phases: preoperative (admission, bed assignment, and surgical eligibility checks), intraoperative (patient transfer to the operating room, anesthesia, and surgical execution), and postoperative (patient monitoring in the PACU until transfer to the ward).

Within these parameters, logistical support operations such as operating room sanitization and equipment cleaning were precisely modeled. These transition times are crucial from an energy standpoint, as infrastructure-based loads (such as HVAC and lighting systems) continue to operate despite the absence of clinical activity. Processes outside of the operating block, such as long-term inpatient stays, were omitted from thorough modeling, yet logical interfaces were preserved to accommodate downstream capacity restrictions.

3.2. Input Data

The simulation model was parameterized with a hybrid data collection technique that combined secondary data (i.e., literature-based values, clinical databases) and primary data based on expert interviews. This method allows the specification of activity durations, resource availability, patient route probabilities, and energy consumption characteristics. A dedicated dataset was created for 57 elective orthopedic surgeries, which were categorized by anatomical district and difficulty degree. To preserve the stochastic nature of real clinical workflows and represent case-mix variation, activity durations were not modeled deterministically. Instead, empirical mean values and standard deviations (see Appendix B) were converted into probability distributions (triangular and log-normal) based on the characteristics of each process phase, such as patient preparation, surgery, and recuperation. The

https://doi.org/10.3390/healthcare14091134

selection of each distribution type was guided by the statistical properties of the underlying activity. Log-normal distributions were adopted for surgical durations, which typically exhibit right-skewed variability consistent with occasional prolonged procedures. Triangular distributions were applied to preparation and recovery phases, for which expert interviews provided reliable estimates of minimum, most likely, and maximum durations, making this distribution the most appropriate choice given the available data. Routing probabilities were defined on an empirical basis, combining structured interviews with clinical experts and a review of the surgical case mix for the selected elective orthopedic procedures. The 80/20 split between X-ray and MRI reflects the observed prevalence of X-ray in routine pre- and postoperative diagnostic checks, with MRI reserved for cases requiring more detailed soft tissue assessment. Energy consumption was determined by multiplying simulated operation periods by each resource's nominal power rating (see Appendix C). The model distinguishes between two types of energy consumption: infrastructure-based loads (e.g., HVAC systems and lighting) and activity-dependent variable loads (e.g., medical equipment like MRI scanners, C-arms, and arthroscopy towers) that vary based on usage and duty cycles.

Medical equipment was modeled in three operational states (idle, base load, and peak), allowing the simulation to capture intermittent power requirements and realistic load profiles (Figure 2).

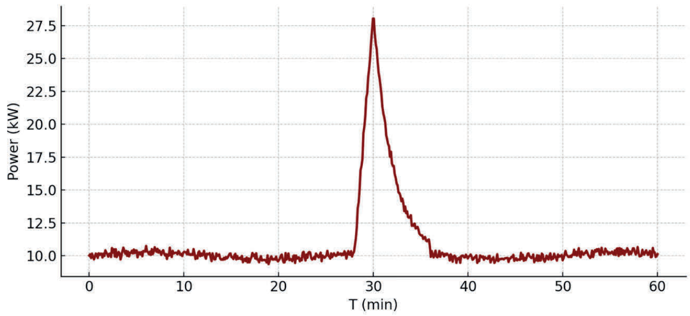


Figure 2. Example of a peak in a load profile.

3.3. Simulation Model

To enable model development and validation, the simulation model was constructed in FlexSim Healthcare (Version 25.2.0, FlexSim Software Products Inc., Orem, UT, USA), which has a dedicated healthcare object library and three-dimensional visualization capabilities. The DES paradigm brings together the Diagnostic Imaging Unit and the Orthopedic Surgical Unit into a single framework.

The simulation was set up to simulate a typical operational day, from 8:00 a.m. to 8:00 p.m., with a 45-min non-operational break. The outputs of each replication were averaged to derive mean performance indicators. The standard deviation across replications was computed to assess the stability of results, ensuring that reported values reflect the expected system behavior rather than the outcome of a single simulation run. To establish statistical robustness and account for the stochastic variability inherent in the model, fifty independent replications of the daily operational schedule were carried out. For each replication, the simulation generated a complete set of performance indicators, including resource utilization rates, patient wait times, and throughput. Mean values were then computed across all replications and used as the primary basis for result reporting. Standard deviations were calculated to assess output stability and are reported alongside mean values for the key operational indicators. Energy consumption figures were subsequently derived deterministically by applying the power profiles of each device to the mean simulated

https://doi.org/10.3390/healthcare14091134

activity durations. Because of this deterministic derivation, the energy and emission values reported in Table 4 do not carry confidence intervals and should be interpreted as indicative central estimates, consistent with an exploratory modeling approach.

Table 4. Estimated CO_2 emissions per patient and per day in baseline and alternative scenarios.

Scenario	Energy (kWh/Patient)	CO_2 (kg/Patient)	Patients/Day	CO_2 (kg/Day)
Surgery baseline	21.1	5.4	6	32.4
Surgery HVAC	16.6	4.2	8	33.6
Surgery LED	19.8	5.1	6	30.6
Surgery HVAC + LED	15.3	3.9	8	31.2
Diagnostic Imaging baseline	10.1	2.6	30	78
Diagnostic Imaging scenario	8.5	2.2	30	66

3.3.1. Diagnostic Imaging Unit

The Diagnostic Imaging Unit paradigm encompasses the entire preoperative imaging route. The physical layout consists of a reception area, waiting room, examination rooms, and two dedicated diagnostic suites: one MRI room and one X-ray room (Figure 3).

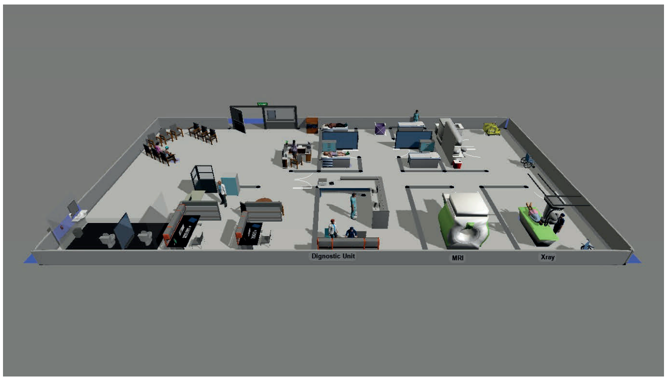


Figure 3. Representation of the diagnostic unit in the FlexSim environment.

- Technological resources. Energy-intensive diagnostic equipment (MRI and X-ray) was explicitly modeled. Patient routing to imaging modalities is probabilistic and is determined by the surgical procedure type.
- Staff. The unit consists of a receptionist, two nurses, two radiologists, and two radiographers who perform diagnostic imaging examinations.

3.3.2. Orthopedic Surgical Unit

The Orthopedic Surgical Unit replicates the perioperative process for elective procedures (Figure 4). The modeled layout includes a reception area, an eight-bed ward, two preoperative preparation stations, two operating rooms, and two post-operative recovery stations.

- Technological resources. Operating rooms are outfitted with procedure-specific medical instruments. The probability of use for each intervention, as well as the simulated surgical case mix, determines device activation. Multiparameter monitors, infusion pumps, and motorized beds are examples of additional equipment used throughout the pre- and postoperative stages.

https://doi.org/10.3390/healthcare14091134

- Staff. Administrative staff, ward nurses, PACU nurses, preoperative physicians, and dedicated OR teams (surgeons, anesthetists, scrub nurses) make up the workforce. Two operators are allocated to the sanitization and sterilization chores, which are critical for OR turnover.

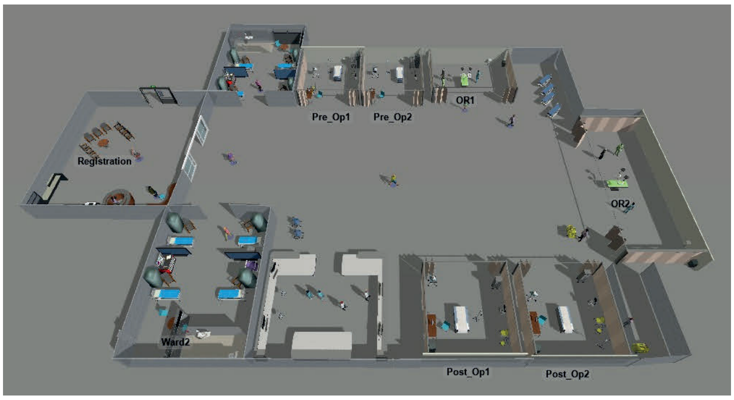


Figure 4. Representation of the orthopedic surgical unit in the FlexSim environment.

3.3.3. Energy Consumption Model

The total daily energy consumption of the operating block (E^{Day}_{System}) is calculated as the sum of the energy consumed by the diagnostic and the orthopedic surgical units.

$$E^{Day}_{System} = E^{Day}_{Diagn} + E^{Day}_{OR} \quad (1)$$

The daily energy consumption of unit $x(E^{Day}_x$, in kWh) is computed by aggregating the consumption of each device d across its discrete operational states $j \in J$ and all simulated patients N:

$$E^{Day}_{Unit} = \sum_d \sum_{j \in J} P_{j,d} \cdot \left(\sum_{i=1}^{N} \frac{T_{i,j,d}}{60} \right) \quad (2)$$

where:

- d is the index running over all devices considered in the unit.
- J is the set of discrete operational states of device d, defined as J = {Idle, Base Load, Peak}.
- $P_{j,d}$ is the average power drawn by device d in state j (in kW).
- N is the total number of simulated surgical interventions or patients per day.
- $T_{i,j,d}$ is the duration in minutes that device d is in state j during intervention i.

The energy modeling framework establishes that the duration of stay in each operational state $(T_{i,j,d})$ is determined by the specific simulation logic of the functional unit. To ensure physical consistency and accurate energy accounting, the model applies a time decomposition logic: the total operational duration allocated for the device $\left(T^{Op}_{i,d}\right)$ is strictly portioned in the Total Active Time $\left(T^{act}_{i,d}\right)$, representing the effective usage, and the Idle Time $\left(T^{idle}_{i,d}\right)$, representing the standby period. This principle ensures that no operational time remains unaccounted for and is applied consistently across units, even if using two different calculation methods:

1. Surgical Unit Logic: since intra-operative usage is intermittent, operational durations are derived probabilistically based on the procedure duration T_i and the probability of usage $p(s_i\ ,\ d)$ of device d for the specific surgery type s_i.

The implementation utilizes the Average Duty Cycle δd to apply the partition constraint

- Active Time $\left(T_{i,d}^{act}\right)$: calculated as the portion of the procedure where the device is effectively running.

$$T_{i,d}^{act} = T_i \cdot p(s_i\ ,\ d) \cdot \delta d \tag{3}$$

- Idle Time $\left(T_{i,d}^{idle}\right)$: calculated as the remaining time where the device is present but in standby.

$$T_{i,d}^{idle} = T_i \cdot p(s_i\ ,\ d) \cdot (1 - \delta d) \tag{4}$$

2. Diagnostic imaging Unit Logic: The durations $\left(T_{i,d}^{Op}\right)$ are determined by the probabilistic patient routing and the fixed duration of maintenance activities between patients, ensuring that actual utilization and idle times reflect the operational constraints of the diagnostic imaging suite.
The calculation is further refined by partitioning active time into base and peak components, a necessity for accurate energy measurement, using the partition factor (β_d):

$$T_{i,d}^{base} = T_{i,d}^{act} \cdot \beta_d \text{ and } T_{i,d}^{peak} = T_{i,d}^{act} \cdot (1 - \beta d) \tag{5}$$

4. Results

In this section, the results of the discrete-event simulation are presented in detail, starting from the baseline "AS-IS" scenario and subsequently evaluating the effects of targeted organizational and technological interventions designed to improve both operational performance and energy efficiency.

4.1. AS-IS Results

The examination of the discrete-event simulation models for the Diagnostic imaging and Orthopedic Surgical Units under the "AS-IS" scenario establishes a solid foundation for future improvement evaluations. The results show a strong relationship between workflow efficiency and energy intensity per patient, with space limits highlighted as the key system bottlenecks.

- Diagnostic imaging unit. In the baseline situation, with 30 patients per day and routing set to 80% for X-ray and 20% for MRI, energy consumption and equipment use showed large asymmetries.
  - X-ray: Each examination consumes about 1.1 kWh per patient (26.3 kWh/day), which increases to 2.1 kWh per patient when the assigned HVAC share is considered. Despite frequent use, the X-ray machine is idle for 55.6% ± 4.1% of the time, with a base load of 33.6% ± 3.2% and a peak load of only 1.04% ± 0.10%.
  - MRI: MRI energy use is significantly greater, at 33.1 kWh per patient each test (41.1 kWh with allocated HVAC). The MRI is idle for 69.6% ± 10.3% of its operating period, which reflects the need for continual magnet cooling, with a base load of 20.6% ± 7.6% and a peak of 6.9% ± 2.5%.
- The Diagnostic Imaging Unit's weighted average energy consumption is 10.1 kWh per patient. The analysis of patient waiting dynamics shows that the majority of delays are caused by a lack of diagnostic imaging room availability ("Wait for Location" state), demonstrating that throughput is mostly limited by structural capacity.
- Orthopedic Surgery Unit. The simulation of six elective operations over two operating rooms emphasizes the importance of space restrictions in workflow and energy intensity. Patient wait times are dominated by location unavailability ("Wait for Location" state), with an average of 56.52 min, compared to 26.51 min for personnel availability ("Wait for Staff" state). Operating rooms are used 36.91% ± 5.8% of the time, with

https://doi.org/10.3390/healthcare14091134

sanitization and preparation (Maintenance) taking up an additional 20.97% ± 1.4%. The remaining 41.78% ± 5.9% represents idle time. The total energy requirement for each surgery patient, including fixed and activity-dependent loads, is 21.1 kWh. The breakdown by component reveals the dominance of HVAC fixed loads (18 kWh per patient), making energy intensity extremely sensitive to room downtime. Surgical lighting contributes to 1.514 kWh per patient, while intraoperative devices account for 0.70 kWh, with the C-arm responsible for 75.5% of device consumption. The pre- and postoperative phases contribute 0.35 and 0.545 kWh, respectively (Figure 5).

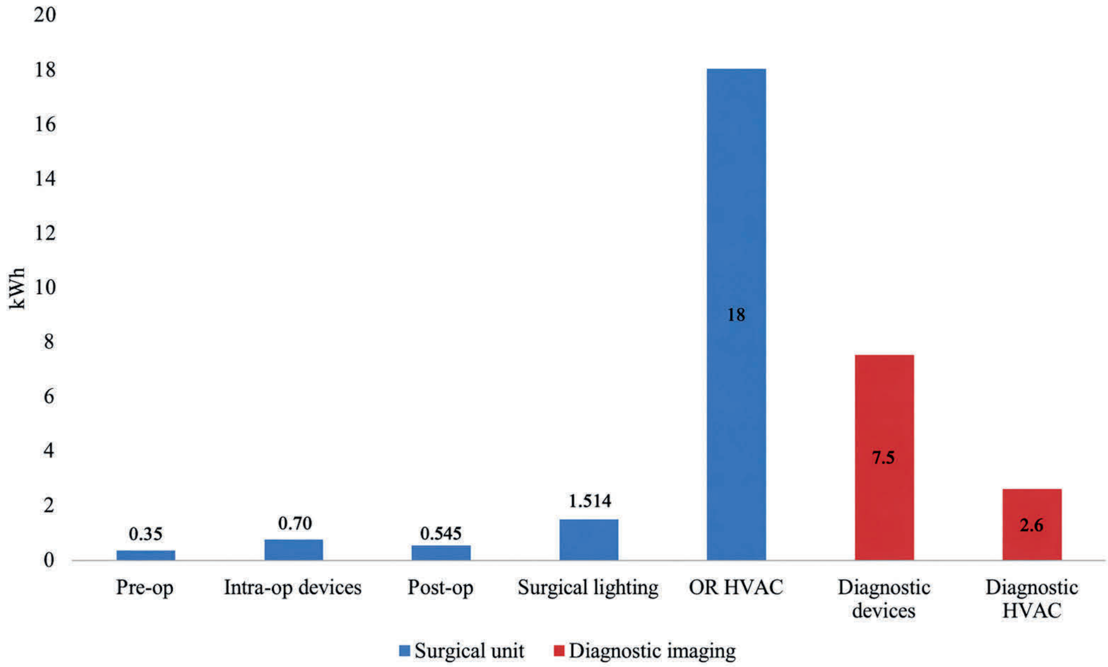


Figure 5. Breakdown of the energy consumption per patient in the different phases of the simulation.

The validation and comparison of results confirm the consistency of the simulation model with theoretical estimates, as the values obtained for the surgical unit are in line with the expected order of magnitude of 18 kWh per patient, derived from the analytical assessment of the cumulative energy demand of HVAC systems, lighting, and biomedical devices. The intraoperative phase is confirmed as the dominant energy component in both analytical approaches.

The AS-IS scenario indicates that operational inefficiencies, particularly long rotation times, increase energy costs per patient due to fixed infrastructural loads, laying the groundwork for developing targeted improvement scenarios.

4.2. Improvements Proposal

The AS-IS analysis highlighted two key causes of high energy intensity: fixed infrastructural loads dominated by HVAC and operational inefficiencies due to space turnover. Three improvement scenarios were developed and simulated, combining organizational strategies to increase operating room throughput and reduce idle consumption in diagnostic imaging, together with technological interventions aimed at lowering nominal energy demand.

The first intervention focused on organizational optimization within the Operating Room to leverage HVAC dilution. Given that HVAC is the most energy-intensive component (18 kWh per patient), boosting operating throughput effectively reduces its per-patient impact. The simulated intervention raised daily procedures from six to eight (four in each OR) within the same 12-h shift by incorporating short, compatible elective surgeries. As a result, the HVAC contribution per patient dropped from 18 to around 13.5 kWh, and total intraoperative energy usage decreased from 21.1 kWh to 16.6 kWh per patient, demonstrating that boosting operating room use is a successful technique for reducing fixed-load energy consumption. It should be noted that per-patient energy intensity improvements do not necessarily translate into reductions in absolute daily emissions when throughput increases simultaneously. In this scenario, the daily CO_2 rises from 32.4 to 33.6 kg/day because more patients are treated, even though each patient's individual footprint decreases.

In parallel, a technological intervention was evaluated regarding the lighting systems. This scenario assessed the impact of replacing standard surgical lamps (1.0 kW) with LED lighting systems. The modification lowered lighting consumption from 1.5 kWh to around 0.2 kWh per patient, resulting in a direct savings of 1.3 kWh per procedure. Additionally, the reduced heat dissipation from LEDs lowers the internal heat gain, further reducing the need for HVAC cooling.

Furthermore, a combined scenario integrating both scheduling optimization and LED upgrade was analyzed to evaluate potential synergies. The results show that this combination yields the most significant reduction, lowering energy intensity to 15.3 kWh per patient.

Finally, the optimization analysis was extended to the Diagnostic Imaging Unit to address MRI idle time. In this unit, energy consumption is mostly driven by extended idle time for magnet cooling [18,38]. The recommended strategy rearranged MRI scheduling, concentrating sessions on two active days per week and turning off the scanner on the remaining days. Consequently, the weekly MRI use decreased from 1125 kWh to 454 kWh, resulting in a 60% savings, and the average energy usage per patient in the unit was reduced from 10.1 to 8.5 kWh. The weekly baseline (1125 kWh) was obtained by scaling the daily model output across five operational days; under the bundled scenario, full active consumption applies to two days while the remaining three days incur stand-by-only loads, yielding the 454 kWh weekly estimate. The per-patient figure (10.1 to 8.5 kWh) reflects a separate calculation based on the average energy per examination on active days.

Table 4 summarizes the detailed results regarding energy consumption and estimated CO_2 emissions for all simulated scenarios. CO_2 emissions were estimated by applying the Italian national grid emission factor of 0.256 kg CO_2/kWh to the simulated energy consumption values.

5. Discussion and Managerial Insight

The analysis conducted in this study indicates that energy efficiency and environmental sustainability in healthcare facilities are closely linked to workflow organization and operational decision-making. Rather than being determined primarily by the volume of clinical activity, energy consumption appears to be substantially shaped by the continuous availability of infrastructure and equipment. This finding confirms a well-established paradox of high-technology settings: energy demand is largely driven by fixed and quasi-static loads that persist independently of actual utilization levels.

As highlighted in the results section, the most effective way to reduce energy usage and CO_2 emissions is through a combination of organizational and technological interventions. The combined scenario demonstrates that addressing fixed infrastructural loads through organizational measures (HVAC dilution) and nominal loads through technical upgrades (LED) provides a multiplier effect that outperforms the effects of individual actions.

https://doi.org/10.3390/healthcare14091134

When multiple strategies' effectiveness is compared, a distinct hierarchy emerges. Organizational solutions consistently outperform solely technological ones in both surgical and diagnostic imaging settings. Increasing throughput and optimizing HVAC consumption in surgical units generates a significantly higher carbon saving compared to lighting upgrades alone. This effect is explained by the structural characteristics of operating rooms, which are typically 3 to 6 times more energy-intensive than the rest of the hospital due to strict air quality, temperature, and sterility standards [39]. Under these conditions, the marginal energy cost of an extra procedure is negligible, while increased usage dramatically reduces energy intensity per patient.

The impact of organizational strategies is considerably more noticeable in the diagnostic imaging domain. The MRI bundling scenario resulted in a drastic reduction in energy consumption. This finding emphasizes that, for energy-intensive systems with significant idle consumption, work organization and scheduling strategies are the most effective sustainability lever. This aligns with recent literature illustrating that reducing idle activity provides greater benefits than marginal efficiency gains in device performance.

Replacing conventional surgical lighting with LED lights results in a minor reduction in emissions (about 0.3 kg CO_2 per patient). While this intervention is technically solid and helps to reduce nominal loads, it does not address underlying process inefficiencies and thus cannot compensate for long idle times or unused spaces.

Although this analysis focuses on Scope 2 emissions from electricity usage, the effects go beyond that. Improved operating room use can also help to lower Scope 1 emissions by avoiding the unwanted dispersion of volatile anesthetic gases caused by extended theater activation [7]. Similarly, Scope 3 emissions can be indirectly decreased by reducing cancellations, improving schedule dependability, and minimizing the waste of sterile materials and consumables [40].

From an economic standpoint the energy efficiency is not simply an environmental goal, but also a financial resilience plan. Hospitals can increase financial stability while confirming their sustainability pledges by reducing their reliance on volatile energy prices.

The results provide three crucial insights for managers:

1. Integrating operational and energy management. Clinical operations and facility management must be addressed together rather than as distinct domains. Decisions about scheduling, case mix planning, and resource allocation frequently have a higher impact on energy use than engineering interventions alone. Integrating energy data into operational planning processes is so critical.
2. Adoption of dynamic, process-oriented key performance indicators. Energy- and emission-based metrics, like kWh per patient or $kgCO_2$ per procedure, should be used alongside traditional static indicators. Making the environmental cost of therapeutic activities apparent promotes more informed decision-making and the adoption of sustainable practices.
3. Priority is given to organizational intelligence. Before investing in capital-intensive technological retrofits, healthcare facilities may benefit from focusing on optimizing current resources through organizational redesign and schedule changes. These initiatives may offer faster returns on investment and potentially facilitate the effective adoption of future technology advancements. These insights are grounded in an exploratory single-site model and require validation against empirical operational data before generalization.

Overall, the discussion emphasizes that healthcare sustainability is essentially a managerial and organizational concern, necessitating the development of tools and models capable of addressing clinical performance, resource use, and environmental impact simultaneously.

https://doi.org/10.3390/healthcare14091134

A critical practical challenge in realizing these organizational gains lies in the structural fragmentation of hospital decision-making. Scheduling, clinical operations, and facility management typically function as separate domains, with limited data exchange and misaligned incentive structures. As a result, decisions that could jointly optimize patient throughput and energy consumption, such as concentrating MRI sessions or filling OR slots with compatible short procedures, are rarely coordinated across these functions.

To overcome this barrier, hospitals can pursue a few targeted actions. First, establishing a cross-functional governance structure, bringing together OR coordinators, anesthesiologists, radiologists, and facility managers, creates the institutional accountability needed to align scheduling decisions with energy performance goals. Within this structure, clearly defining which roles are responsible for monitoring energy KPIs and who holds authority over scheduling adjustments is essential to avoid the diffusion of responsibility that typically stalls sustainability initiatives. Second, embedding energy intensity metrics, such as kWh per patient or $kgCO_2$ per procedure, into the same reporting dashboards used for operational performance makes energy visible within existing clinical governance frameworks, rather than relegating it to a separate sustainability report. Third, simulation tools such as the one developed in this study can play a concrete role in these settings: by quantifying the energy impact of scheduling alternatives, they provide a shared, evidence-based reference that supports negotiation across departments with different priorities.

6. Conclusions

The primary goal of this study was to close the gap between the operational management of healthcare procedures and the growing need for energy efficiency and environmental sustainability in hospital facilities. This study demonstrates how clinical workflows can be approximated within a simulation environment while also quantifying the energy consumption associated with healthcare operations through the development and implementation of an integrated discrete-event simulator. In doing so, the proposed framework broadens standard healthcare simulation beyond operational success indicators to include energy-related issues, which are becoming increasingly important for sustainable hospital management.

The findings demonstrate the effectiveness of simulation as a decision-support tool in complex healthcare settings. The model is designed to capture the unpredictable and resource-constrained nature of hospital procedures, allowing for the explicit measurement of energy use across diagnostic imaging and surgical pathways. A preliminary consistency check of the simulation architecture suggests that the model's energy consumption estimates are broadly aligned with theoretical assumptions and order-of-magnitude values reported in the literature. While this does not constitute a formal validation against field-measured data, it supports the internal plausibility of the proposed approach and provides a reasonable basis for exploratory scenario analysis. As a result, the model offers hospital decision-makers a structured framework for exploring organizational and technical improvement scenarios while maintaining quality of care and operational continuity.

The principal limitation of this study lies in the nature of the input data. Owing to the absence of extensive metering infrastructures, several energy-related parameters were estimated on the basis of scientific literature and expert judgment rather than direct field measurements. Although this approach is suitable for exploratory modeling, it necessarily entails a degree of approximation. In addition, the scope of application was intentionally restricted to elective orthopedic surgery. While this delimitation enabled a more focused and in-depth analysis, it also required simplifying assumptions regarding interactions with other hospital departments and shared resources, which are inherently interdependent in real-world hospital operations.

https://doi.org/10.3390/healthcare14091134

Notwithstanding these limitations, the findings of this study provide a foundation for several future lines of research aimed at overcoming the current constraints. First, the integration of the simulation framework with real-world energy data, acquired through sensors, smart meters, or hospital energy management systems, represents a necessary step toward enhancing both model accuracy and empirical validity. Second, future developments should incorporate multi-objective optimization approaches capable of balancing clinical performance, energy consumption, and environmental impact through the application of advanced algorithms and sensitivity analyses. Third, extending the proposed framework to additional hospital departments and clinical pathways will be essential for evaluating its scalability and for supporting the development of a hospital-wide, energy-aware decision-support system.

Author Contributions: Conceptualization, B.M.; Methodology, B.M.; Software, F.S.; Formal analysis, B.M.; Data curation, F.S.; Writing—original draft, F.S.; Writing—review & editing, B.M., A.S., A.R. and S.Z.; Supervision, B.M. and S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request, since the data used as input for the simulation includes data that combines clinical activity data, scientific literature, and expert judgment contributions: The full data and settings of the input for the Flexsim Healthcare simulation will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MRI	Magnetic Resonance Imaging
LED	Light Emitting Diode
OR	Operating Room
HVAC	Heating, Ventilation and Air Conditioning
DES	Discrete Event Simulation
KPI	Key Performance Indicator
IoT	Internet of Things
IT	Information Technology
PACU	Post-Anesthesia Care Unit
WBAN	Wireless Body Area Network
LCA	Life Cycle Assessment

https://doi.org/10.3390/healthcare14091134

Appendix A

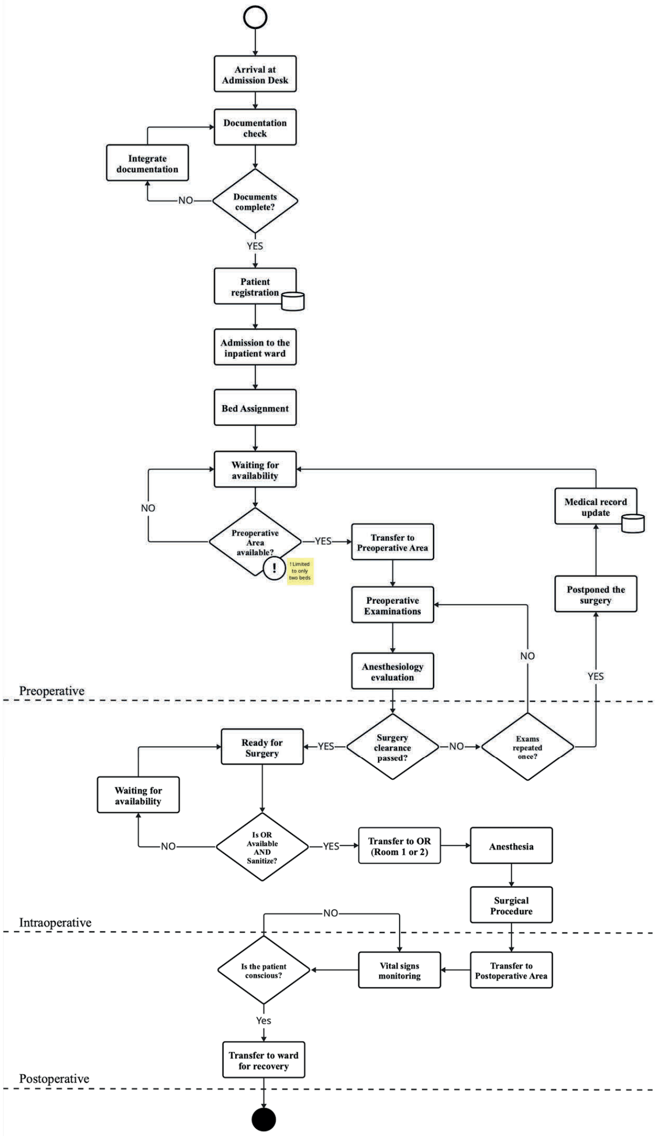


Figure A1. Orthopedic surgical process flow divided into preoperative, intraoperative and postoperative phases.

Appendix B

This appendix provides a detailed temporal analysis of the procedures. The data regarding intervention durations is aggregated by anatomical district and complexity. Additionally, the tables outline the specific operating times for the devices and the duration of each distinct process phase. The values reported represent simulation input parameters derived from a hybrid data collection approach combining scientific literature, structured interviews with clinical experts. Average durations and standard deviations are used as input parameters to define the probability distribution adopted in the simulation model.

https://doi.org/10.3390/healthcare14091134

Table A1. Elective orthopedic surgeries aggregated by anatomical district and complexity level, based on duration.

Anatomical District	Surgical Complexity Level	Type of Surgeries	Average Duration (min)	Average Standard Deviation (min)	Average Buffer Time (min)
Hip	Medium	1	90	22.5	45
	High	1	150	45	90
Lower Limb	Medium	1	120	33.6	70
Upper Limb	Low	1	55	9.4	20
Pelvis	Medium	1	100	30	60
Ankle	Low	1	50	16.5	35
	Medium	4	85	20.3	43.8
Spine	Low	1	50	14	30
	Medium	5	87	16.8	51
	High	3	143.3	29.4	88.3
Fingers	low	1	40	11.2	25
Femurs	Medium	1	90	25.2	55
Knee	Low	1	35	8.8	20
	Medium	4	88.8	21	43.8
	High	1	130	36.4	75
Elbow	High	1	140	38.8	65
Hand	Low	4	30	14.7	18.8
	Medium	3	75	15.1	36.7
Foot	Low	4	38.8	10.8	25
	Medium	7	72.9	19.5	40
Wrist	Medium	3	106.7	29.9	63.3
Shoulder	Medium	3	108.3	27.1	55
	High	1	135	28.2	60
Tibia	Medium	1	85	23.8	50
Miscellaneous	Low	1	30	9.9	20
	Medium	1	60	16.8	35
	High	1	130	28.6	60

Table A2. Macro-activities durations in the orthopedic surgical pathway.

Phase	Activity	Average Duration (min)	Average Standard Deviation (min)	Variability Factors
Diagnostic and preparatory tests	X-ray imaging	10	3	Minor variability due to exam execution
	CT imaging	15	5	Moderate variability
	MRI imaging	30	10	Higher variability, longer exam
	Laboratory tests (blood, urine)	12	4	Variability from sampling procedures
	Specialist consultations	25	10	Depends on patient complexity

https://doi.org/10.3390/healthcare14091134

Table A2. *Cont.*

Phase	Activity	Average Duration (min)	Average Standard Deviation (min)	Variability Factors
Admission and registration	Arrival at hospital	15	5	Variability due to patient flow
	Documentation check and integration	15	5	Delays if incomplete
	Patient registration and bed assignment	25	10	Dependent on ward capacity
Preoperative preparation	Transfer to pre-operative area	10	3	Possible bottlenecks
	Anaesthesiology evaluation	20	5	Longer in case of comorbidities
	Surgery clearance check	5	1	Final eligibility verification
Intraoperative	OR preparation and patient transfer	30	6	Dependent on turnover and logistical efficiency
	Anaesthesia induction	20	8	Technique-dependent
Postoperative recovery	Vital signs monitoring	120	40	Standard ~2h, prolonged if complications
	Transfer to ward	30	10	Dependent on bed availability
Ward stay	Ward monitoring	1440 (24 h)	720	Typically 1–3 days
Follow-up	Control imaging	20	7	Outcome verification
	Post-op laboratory tests	10	4	Routine postoperative blood analysis
	Clinical control visit	15	5	Routine evaluation
Turnover & sterilisation	Instrument reprocessing	50	15	Depends on sterilisation workload and turnover

Appendix C

This appendix presents detailed tables outlining the technical specifications of the devices employed. Specifically, the data includes the power ratings and the respective duty cycle for each component and phase. Note that the parameters listed document the full clinical pathway context; the simulation model itself was scoped to MRI and X-ray only. Parameters for CT and other modalities are provided for completeness and to support potential future extensions of the model.

Table A3. Estimated power demand of infrastructural systems that remain constantly active.

Resource	Operating Mode	Power Range (W)	Duty Cycle (%)	Notes
HVAC (OR)	Active	3000–6000	100	Depends on air changes per hour (ACH) and thermal set-points
Surgical lighting	Active	500–1500	100	Target lux maintained throughout OR use
Anaesthesia workstation	Standby	100–200	100	Continuous readiness and monitoring
Multiparameter monitoring	Active	50–100	100	Small but constant load

https://doi.org/10.3390/healthcare14091134

Table A4. Estimated power demand of clinical devices active only during specific phases.

Resource	Operating Mode	Power Range (W)	Duty Cycle (%)	Notes
Electrosurgical unit (ESU)	Active	300–800	5–20	Pulsed activation, low average duty
Arthroscopy tower	Active	500–900	30–80	Includes light source, pump, and camera
C-arm fluoroscopy	Active	2000–5000	1–10	Short pulses; high instantaneous draw
Suction	Active	100–300	20–60	Varies with surgical technique and field conditions
Infusion pump	Active	50–100	40–100	Low draw potentially continuous
Orthopaedic drill	Active	80–200	5–30	Intermittent use during drilling
Oscillating bone saw	Active	100–300	5–20	Short bursts during bone cutting
Surgical microscope	Active/Standby	200–500	20–100	Includes lighting and electronics
Irrigation pump	Active	50–200	20–80	For arthroscopy or wound irrigation
Powered screwdriver	Active	50–150	10–50	Short cycles during screw/pin insertion

Table A5. Estimated power demand of diagnostic imaging and recovery equipment.

Phase	Resource	Power Range (W)	Duty Cycle (%)	Notes
Diagnostic and preparatory tests	X-ray generator	20,000–50,000	1	Very short exposure high instantaneous draw
	CT scanner	30,000–60,000	5	High draw only during acquisition
	MRI	15,000–30,000	10–40	Active load during image acquisition
	Ultrasound	100–500	10–60	Regional anaesthesia, vascular access, focused checks
	Diagnostic devices	50–200	5–20	ECG, spirometer, blood analysers
Postoperative recovery and follow-up	Multiparameter monitor	50–100	100	Bedside monitoring throughout recovery
	Infusion pump	50–100	40–100	Potentially continuous
	Motorized bed	200–400	10	Short activations for positioning
	Oxygen therapy system	100–500	60–100	Flow generators, humidifiers
	Post-operative X-ray	20,000–50,000	1	Control imaging if clinically required
	Ultrasound (checks)	100–500	10–60	Focused post-op assessments

https://doi.org/10.3390/healthcare14091134

References

1. United Nations Regional Information Centre (UNRIC). *Causes of Climate Change*; UNRIC: Brussels, Belgium, 2019. Available online: https://unric.org/it/cause-del-cambiamento-climatico/ (accessed on 8 October 2025).
2. McKinsey & Company. The Net-Zero Transition: What It Would Cost, What It Could Bring. McKinsey Sustainability Insights. 2022. Available online: https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition-what-it-would-cost-what-it-could-bring (accessed on 8 October 2025).
3. Pichler, P.P.; Jaccard, I.S.; Weisz, U.; Weisz, H. International comparison of health care carbon footprints. *Environ. Res. Lett.* **2019**, *14*, 064004. [CrossRef]
4. Lenzen, M.; Malik, A.; Li, M.; Fry, J.; Weisz, H.; Pichler, P.-P.; Chaves, L.S.M.; Capon, A.; Pencheon, D. The environmental footprint of health care: A global assessment. *Lancet Planet. Health* **2020**, *4*, e271–e279. [CrossRef]
5. Eckelman, M.J.; Sherman, J. Environmental Impacts of the U.S. Health Care System and Effects on Public Health. *PLoS ONE* **2016**, *11*, e0157014. [CrossRef] [PubMed]
6. Bawaneh, K.; Nezami, F.G.; Rasheduzzaman, M.; Deken, B. Energy Consumption Analysis and Characterization of Healthcare Facilities in the United States. *Energies* **2019**, *12*, 3775. [CrossRef]
7. MacNeill, A.J.; Lillywhite, R.; Brown, C.J. The impact of surgery on global climate: A carbon footprint assessment of operating theatres in three health systems. *Lancet Planet. Health* **2017**, *1*, e381–e388. [CrossRef] [PubMed]
8. Smith, J.T.; Boakye, L.A.; Ferrone, M.L.; Furie, G.L. Environmental Sustainability in the Orthopaedic Operating Room. *J. Am. Acad. Orthop. Surg.* **2022**, *30*, 1039–1045. [CrossRef]
9. Rizan, C.; Bhutta, M.F.; Reed, M.; Lillywhite, R. The Carbon Footprint of Waste Streams in a UK Hospital. *J. Clean. Prod.* **2021**, *286*, 125446. [CrossRef]
10. Karnon, J.; Stahl, J.; Brennan, A.; Caro, J.J.; Mar, J.; Möller, J. Modeling using discrete event simulation: A report of the ISPOR-SMDM Modeling Good Research Practices Task Force-4. *Value Health* **2012**, *15*, 821–827. [CrossRef]
11. Günal, M.M.; Pidd, M. Discrete event simulation for performance modelling in health care: A review of the literature. *J. Simul.* **2010**, *4*, 42–51. [CrossRef]
12. Vázquez-Serrano, J.I.; Peimbert-García, R.E.; Cárdenas-Barrón, L.E. Discrete-Event Simulation Modeling in Healthcare: A Comprehensive Review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 12262. [CrossRef]
13. Mansouri, S.A.; Aktas, E.; Besikci, U. Green Scheduling of a two-machine flowshop: Trade-Off between makespan and energy consumption. *Eur. J. Oper. Res.* **2016**, *248*, 772–788. [CrossRef]
14. Saleh, J.; Mitchell, A.; Kha, S.; Outterson, R.; Choi, A.; Allen, L.; Chang, T.; Ladd, A.; Goodman, S.; Fox, P.; et al. The Environmental impact of orthopaedic surgery. *J. Bone Jt. Surg.* **2023**, *105*, 74–82. [CrossRef]
15. Allihaibi, W.G.; Masoud, M.; Elhenawy, M.; Liu, S.Q.; Burke, J.; Karim, A. Solving the emergency care patient pathway by a new integrated simulation–optimisation approach. *IEEE Access* **2021**, *9*, 100895–100910. [CrossRef]
16. Duma, D.; Aringhieri, R. Real-time resource allocation in the Emergency Department: A case study. *Omega* **2023**, *117*, 102844. [CrossRef]
17. Ala, A. A simulation-based optimization evaluation of operating room in healthcare under limitation capacity: A multi-objective approach. *Spectr. Eng. Manag. Sci.* **2024**, *2*, 85–99. [CrossRef]
18. Roletto, A.; Zanardo, M.; Bonfitto, G.R.; Catania, D.; Sardanelli, F.; Zanoni, S. The environmental impact of energy consumption and carbon emissions in radiology departments: A systematic review. *Eur. Radiol. Exp.* **2024**, *8*, 35. [CrossRef]
19. Kar, E. Hybrid simulation in healthcare: A systematic exploration of models, applications and emerging trends. *J. Simul.* **2025**, *19*, 231–249. [CrossRef]
20. Sahlaoui, F.Z.; Aboueljinane, L.; Lebbar, M. A review on simulation-based metamodeling in emergency healthcare: Methodology, applications, and future challenges. *Simulation* **2023**, *99*, 989–1009. [CrossRef]
21. Ordu, M.; Demir, E.; Tofallis, C.; Gunal, M. A novel healthcare resource allocation decision support tool: A forecasting-simulation-optimization approach. *J. Oper. Res. Soc.* **2020**, *72*, 1700186. [CrossRef]
22. Fanti, M.P.; Mangini, A.M.; Dotoli, M.; Ukovich, W. A three-level strategy for the design and performance evaluation of hospital departments. *IEEE Trans. Syst. Man Cybern. Syst.* **2013**, *43*, 742–753. [CrossRef]
23. Traoré, M.K.; Zacharewicz, G.; Duboz, R.; Zeigler, B. Modeling and simulation framework for value-based healthcare systems. *Simul. Trans. Soc. Model. Simul. Int.* **2018**, *95*, 481–497. [CrossRef]
24. Rajagopal, S.M.; Supriya, M.; Buyya, R. Resource provisioning using meta-heuristic methods for IoT microservices with mobility management. *IEEE Access* **2023**, *11*, 60915–60938. [CrossRef]
25. Sahoo, S.; Sahoo, B.; Turuk, A.K. A learning automata-based scheduling for deadline sensitive task in the cloud. *IEEE Trans. Serv. Comput.* **2021**, *14*, 1589–1601. [CrossRef]
26. Yu, K.; Chakraborty, C.; Xu, D.; Zhang, T.; Zhu, H.; Alfarraj, O. Hybrid quantum–classical optimization for low-carbon sustainable edge architecture in RIS-assisted AIoT healthcare systems. *IEEE Internet Things J.* **2024**, *11*, 38987–38998. [CrossRef]

https://doi.org/10.3390/healthcare14091134

27. Hossam, H.S.; Abdel-Galil, H.; Belal, M. An energy-aware module placement strategy in fog-based healthcare monitoring systems. *Clust. Comput.* **2024**, *27*, 7351–7372. [CrossRef]
28. Alimorad, A.; Maadani, M.; Mahdavi, M. REO: A reliable and energy efficient optimization algorithm for beacon-enabled IEEE 802.15.4-based WBANs. *IEEE Sens. J.* **2021**, *21*, 15891–15901. [CrossRef]
29. Alatoun, K.; Matrouk, K.; Mohammed, M.A.; Nedoma, J.; Martinek, R.; Zmij, P. A novel low-latency and energy-efficient task scheduling framework for Internet of Medical Things in an edge fog cloud system. *Sensors* **2022**, *22*, 5327. [CrossRef] [PubMed]
30. Arivazhagan, N.; Somasundaram, K.; Babu, D.V.; Nayagam, M.G.; Bommi, R.M.; Mohammad, G.B.; Kumar, P.R.; Natarajan, Y.; Arulkarthick, V.J.; Shanmuganathan, V.K.; et al. Cloud-Internet of Health Things (IOHT) Task Scheduling Using Hybrid Moth Flame Optimization with Deep Neural Network Algorithm for E Healthcare Systems. *Sci. Program.* **2022**, *2022*, 4100352. [CrossRef]
31. Kahwash, F.; Hammad, A.W.A.; Abu-Hamd, M.; Salman, A. Energy consumption in hospitals: Benchmarking and strategies for reduction. *Energy Rep.* **2021**, *7*, 5732–5746. [CrossRef]
32. Psillaki, M.; Apostolopoulos, N.; Makris, I.; Liargovas, P.; Apostolopoulos, S.; Dimitrakopoulos, P.; Sklias, G. Hospitals' energy efficiency in the perspective of saving resources and providing quality services through technological options: A systematic literature review. *Energies* **2023**, *16*, 755. [CrossRef]
33. Almhafdy, A.; Korany, H.Z.; Cao, S.-J.; Yang, B. Airflow distribution in hospital isolation rooms with different ventilation and exhaust vent configurations. *Indoor Built Environ.* **2024**, *33*, 41–56. [CrossRef]
34. Vladu, A.; Ghitea, T.C.; Daina, L.G.; Țîrț, D.P.; Daina, M.D. Enhancing operating room efficiency: The impact of computational algorithms on surgical scheduling and team dynamics. *Healthcare* **2024**, *12*, 1906. [CrossRef]
35. Faezipour, M.; Ferreira, S. A system dynamics approach for sustainable water management in hospitals. *IEEE Syst. J.* **2018**, *12*, 1278–1285. [CrossRef]
36. Savio, A.; Roletto, A.; Marchi, B.; Zanoni, S. Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging. *Environ. Clim. Technol.* **2024**, *28*, 303–311. [CrossRef]
37. Rovira-Simón, J.; Sales-i-Coll, M.; Pozo-Rosich, P.; Hueto-Madrid, J.A.; Cánovas Paradell, R.; Ochoa de Echagüen Aguilar, A.; Carbonell-Cobo, M.; de Castro, R.; Shaw, G. The Green Surgical Block 4.0: Automation of the operating theatre's climate conditions through a real-time patient-flow solution. *Future Healthc. J.* **2023**, *10*, 46–49. [CrossRef]
38. Roletto, A.; Verga, M.; Savio, A.; Viganò, G.L.; Zanoni, S. Energy performance of MRI systems: On-site validation and comparison with manufacturer declarations. *Eur. Radiol. Exp.* **2026**, *10*, 3. [CrossRef]
39. Rizan, C.; Steinbach, I.; Nicholson, R.; Lillywhite, R.; Reed, M.; Bhutta, M.F. The Carbon Footprint of Surgical Operations: A Systematic Review. *Ann. Surg.* **2020**, *272*, 986–995. [CrossRef] [PubMed]
40. GlobalSurg Collaborative; NIHR Global Health Research Unit on Global Surgery. Reducing the environmental impact of surgery on a global scale: Systematic review and co-prioritization with healthcare workers. *Br. J. Surg.* **2023**, *110*, 804–817. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

https://doi.org/10.3390/healthcare14091134