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GREEN RADIOLOGY: DEVELOPING SUSTAINABLE SYSTEMS TO REDUCE ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACT IN RADIOLOGY

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Abstract

Radiology is one of the most energy-intensive and environmentally impactful sectors within modern healthcare systems, contributing substantially to hospitals' overall ecological footprint. Considering the increasing need to align healthcare services with the United Nations Sustainable Development Goals and national decarbonisation strategies, this doctoral thesis examines the environmental sustainability of diagnostic imaging by integrating evidence from multiple research studies conducted between 2023 and 2025. The main objective was to quantify the energy consumption and environmental impact of diagnostic imaging departments, assess radiology staff perceptions regarding sustainability, and identify concrete mitigation strategies capable of supporting the transition toward more sustainable diagnostic services.

The work covered multiple scientific domains and methods: qualitative and quantitative investigations into radiology staff perceptions and behaviours; analyses of energy consumption in Italian radiology units; on-site measurements of magnetic resonance imaging electricity usage before and after technological replacement; assessments of environmental product declarations published by major vendors; quantification of waste generation and contrast media wastage; and application of life cycle assessment to evaluate the environmental footprint of nuclear medicine diagnostic procedures.

The results consistently demonstrate that diagnostic imaging has a significant and measurable environmental impact. magnetic resonance imaging and computed tomography systems emerge as major contributors due to their high electricity demand and the large share of idle-state consumption. life cycle assessment analyses show that the environmental burden of imaging extends far beyond scanner electricity use: heating, ventilation and air conditioning systems account for a dominant share of overall emissions. Waste analyses indicate that diagnostic activities generate substantial quantities of plastic, paper and glass, as well as significant waste of contrast media. The European survey confirms that radiology staff recognise the importance of environmental sustainability yet show limited knowledge of existing procedures and inconsistent adoption of eco-friendly practices.

The multifactorial nature of radiology's environmental performance is therefore evident. Technological innovation and low-consumption operating modes can lead to significant energy savings, but must be accompanied by organisational strategies, more efficient heating, ventilation and air conditioning management, and improved waste-handling pathways. Furthermore, the progressive decarbonisation of national electricity grids can substantially amplify the impact of local mitigation measures.

Overall, this thesis provides an evidence-based foundation for advancing sustainable radiology. It demonstrates that diagnostic imaging contributes meaningfully to healthcare-related emissions yet offers substantial and actionable opportunities for improvement. By integrating engineering, clinical, organisational, and behavioural perspectives, the work presents a coherent framework to support hospital managers, policymakers and radiology professionals in implementing effective strategies to reduce environmental impact. In conclusion, environmental performance must progressively become a criterion for workflow planning, technology procurement, and professional training, enabling radiology to play a leading role in the transition toward a more sustainable and resilient healthcare system.

Sommario

La radiologia rappresenta uno dei settori più energivori e a maggiore impatto ambientale all'interno dei moderni sistemi sanitari, contribuendo in modo significativo all'impronta ecologica complessiva degli ospedali. Alla luce della crescente necessità di allineare i servizi sanitari agli obiettivi di sviluppo sostenibile delle Nazioni Unite e agli obiettivi nazionali di decarbonizzazione, questa tesi di dottorato analizza la sostenibilità ambientale della diagnostica per immagini integrando le evidenze provenienti da diversi studi condotti tra il 2023 e il 2025. L'obiettivo principale è stato quello di quantificare i consumi energetici e l'impatto ambientale dei reparti di diagnostica per immagini, valutare la percezione dello staff radiologico rispetto ai temi della sostenibilità e identificare strategie concrete di mitigazione in grado di favorire la transizione verso servizi diagnostici più sostenibili. Il lavoro ha compreso ambiti e metodi scientifici molteplici: indagini qualitative e quantitative sulle percezioni e i comportamenti dello staff radiologico; analisi dei consumi energetici in unità operative di radiologia italiane; misurazioni sul campo dei consumi elettrici di sistemi di risonanza magnetica prima e dopo la sostituzione tecnologica; valutazioni delle dichiarazioni ambientali di prodotto pubblicate dai principali produttori; quantificazione della produzione di rifiuti e dello spreco di mezzi di contrasto; applicazione della metodologia "life cycle assessment" per la valutazione dell'impronta ambientale di esami diagnostici di medicina nucleare. I risultati evidenziano in modo coerente come la diagnostica per immagini presenti un impatto ambientale significativo e misurabile. Apparecchiature come risonanza magnetica e tomografia computerizzata emergono come principali contributori, a causa dell'elevata domanda elettrica e dell'ampia quota di consumo in fase di inattività. Le analisi "life cycle assessment" dimostrano che l'impatto ambientale dell'imaging va ben oltre il consumo diretto degli scanner: i sistemi di riscaldamento, ventilazione e condizionamento dell'aria rappresentano una quota predominante delle emissioni complessive. Le analisi sui rifiuti mostrano inoltre che le attività diagnostiche generano notevoli quantità di plastica, carta e vetro, oltre a rilevanti sprechi di mezzo di contrasto. L'indagine europea evidenzia che lo staff radiologico riconosce l'importanza della sostenibilità, ma presenta conoscenze limitate sulle procedure esistenti e un'adozione disomogenea delle pratiche ecologiche. La natura multifattoriale delle prestazioni ambientali della radiologia risulta dunque evidente. L'innovazione tecnologica e le modalità operative a basso consumo possono determinare risparmi significativi, ma devono essere affiancate da strategie organizzative, da una gestione più efficiente dei sistemi di riscaldamento, ventilazione e condizionamento dell'aria e da percorsi ottimizzati di gestione dei rifiuti. Inoltre, la progressiva decarbonizzazione delle reti elettriche può amplificare l'efficacia delle misure di mitigazione implementate a livello locale. Nel complesso, questa tesi offre un punto di partenza basato sulle evidenze per promuovere una radiologia maggiormente sostenibile. Essa dimostra che la diagnostica per immagini contribuisce in modo rilevante alle emissioni del settore sanitario, ma presenta al contempo ampie e concrete opportunità di miglioramento. Integrando prospettive ingegneristiche, cliniche, organizzative e comportamentali, il lavoro delinea un quadro coerente a supporto di dirigenti ospedalieri, decisori politici e professionisti della radiologia nell'implementazione di strategie efficaci per ridurre l'impatto ambientale. In conclusione, le performance ambientali della radiologia devono progressivamente diventare un criterio per la pianificazione dei flussi di lavoro, per la scelta delle tecnologie e per la formazione professionale, affinché il settore possa assumere un ruolo guida nella transizione verso un sistema sanitario più sostenibile.

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Paper IV - Energy Usage Assessment and Energy Savings Estimation in a Radiology Department in Italy

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Nomenclature

AI	Artificial Intelligence
CBCT	Cone beam computed tomography
CECT	Contrast Enhanced Computed Tomography
CED	Cumulative Energy Demand
CO_2 eq	Carbon dioxide equivalent
COCIR	European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry
CT	Computed Tomography
DXA	Dual-energy X-ray absorptiometry
ECR	European Congress of Radiology
EFRS	European Federation of Radiographers Societies
EoL	End-of-Life
EPD	Environmental Product Declaration
[^{18}F]FDG	18F-fluorodeoxyglucose
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
ICM	Iodinated contrast media
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MCXR	Mobile chest X-ray
MEPA	Medical Equipment Proactive Alliance
MG	Mammography
MRI	Magnetic Resonance Imaging
PACS	Picture Archiving and Communication System
Peq	Equivalent mean power demand
PEF	Primary Energy Factor
PET	Positron Emission Tomography
RIS	Radiology Information System
RQ	Research Question
RWS	Reporting workstation
SC	Scientific Contribution
SDG	Sustainable Development Goal
US	Ultrasound
VAS	Visual Analogue Scale
WS	Workstation
XR	X-ray

Chapter 1

Introduction

This chapter includes a brief overview of the study and a description of its objectives, as well as a description of the hypotheses and research questions. In addition, the scope and limitations of the study are described, and an overview of the attached documents and co-authors' statements is provided.

In recent years, there has been a growing awareness of the urgent need to promote environmental sustainability across all sectors of society, in line with the United Nations Sustainable Development Goals (SDGs), particularly Goal 3 “Good Health and Well-being”, Goal 7 “Affordable and Clean Energy”, Goal 12 “Responsible Consumption and Production”, and Goal 13 “Climate Action”(United Nations 2015). This includes reducing direct and indirect greenhouse gas emissions, ensuring efficient resource and energy management, minimizing waste, and fostering an environmental culture. As a result, individuals, organizations, and industries are taking proactive measures to reduce their ecological footprint, aiming to achieve not only environmental benefits but also significant economic savings (Zanoni *et al.* 2014).

Climate change is causing a range of effects on communities, including more frequent extreme weather events, air pollution, changing patterns of infectious diseases, impacts on mental health, and others (Watts *et al.* 2021).

Within the healthcare sector, environmental sustainability has emerged as a critical concern (Aunión-Villa *et al.* 2021). Healthcare facilities, including radiology departments, have traditionally been associated with high energy consumption, carbon emissions, waste generation, and the use of potentially harmful substances. However, the growing recognition of the healthcare sector’s significant contribution to environmental degradation has triggered a transformative shift toward more sustainable practices (Zikhathile *et al.* 2022)

In this context, the Greenhouse Gas (GHG) Protocol Corporate Standard (Ranganathan *et al.* 2004) establishes standards and guidelines for organizations to prepare greenhouse gas emission inventories in accordance with the Kyoto Protocol. Its objectives include ensuring an accurate and fair representation of emissions, simplifying inventory compilation, providing data to support strategic emissions management, facilitating participation in GHG programs, and improving consistency and transparency in accounting and reporting across organizations and programs.

Furthermore, considering the categorization of the GHG Protocol Corporate Standard (Ranganathan *et al.* 2004) for company-related carbon emissions, Scope 1 for “direct GHG emissions”, Scope 2 for “indirect GHG emissions from electricity consumption”, and Scope 3 for “other indirect GHG emissions”, healthcare facilities contribute to all three categories. Radiology departments, which play a fundamental role in the diagnosis and treatment of numerous medical conditions, have a particular responsibility to align their practices with environmental sustainability principles. Studies have shown that diagnostic departments account for approximately 9% of the overall carbon footprint of medicine (Picano *et al.* 2022). The healthcare sector as a whole is responsible for about 4–10% of global greenhouse gas emissions (Picano *et al.* 2022). Other studies have demonstrated that computed

tomography (CT) and magnetic resonance imaging (MRI) equipment represent a significant portion of total hospital energy consumption and carbon emissions (Scope 2) (Heye *et al.* 2023). In radiology departments, the main contributor to climate change is the high electricity demand resulting from the use of energy-intensive medical devices such as CT scanners, MRI systems, and workstations (Mariampillai *et al.* 2023) In addition, a significant share of medical equipment remains switched on but idle for nearly one-third of the day (Heye *et al.* 2020) Cooling systems for radiology equipment and the energy consumed by the enterprise Picture Archiving and Communication System (PACS) also contribute substantially to hospitals' total energy use and carbon emissions (Scope 1 and Scope 2), especially when these systems are left running overnight, as is common practice in radiology departments (Schoen *et al.* 2021).

In medium- or large-sized radiology departments, a considerable number of workstations remain continuously powered regardless of their actual use. This practice is particularly widespread in hospital settings, where hundreds of stations contribute to substantial unnecessary energy consumption. As a result, excessive energy use amplifies the environmental footprint associated with radiology (Büttner *et al.* 2021). For these reasons, hospital radiology departments hold significant potential for reducing energy consumption through workflow optimization, the use of control systems, and improved efficiency and utilization of diagnostic equipment.

1.1 Aim and research questions

The aim of this thesis is to quantify the environmental impact and energy consumption of diagnostic imaging departments; to assess how environmental sustainability issues are perceived by professionals working in this field, and to explore potential strategies to mitigate environmental impact and energy use within radiology.

The hypothesis of the thesis is:

- Radiological activities have a non-negligible environmental and energy impact within the national healthcare system, and operational staff, through education and awareness, can contribute to implementing strategies to mitigate these impacts.

The hypothesis is evaluated through the following research questions:

RQ1. What are the attitudes and perceptions of radiological staff on energy and environmental sustainability issues?

RQ2. What is the environmental impact and greenhouse gas emissions of radiology departments?

RQ3. How high is the energy consumption of diagnostic imaging equipment?

RQ4. What strategies can be implemented to mitigate the energy consumption and environmental impact of the radiological area?

Table 1 gives an overview of which research questions are considered in each of appended papers.

Table 1: Overviews showing in which papers the research questions are explored.

Research question	Scientific Contributions						
	1	2	3	4	5	6	7
1		x					
2			x		x		x
3				x		x	x
4				x	x	x	x

The first scientific contribution consisted of a systematic literature review aimed at identifying the research questions of this thesis and defining the main areas of investigation. The analysis of the attitudes and perceptions of staff working in diagnostic imaging regarding environmental and energy sustainability (first research question) was instead developed in the second scientific contribution, which, through a quantitative research approach, explored how healthcare professionals operating in radiology settings perceive the need for environmentally sustainable interventions within their departments and which mitigation actions have already been implemented (see sections 2.3 and 4.1). The second research question focuses on investigating the environmental impact of activities within the diagnostic imaging field, particularly through the quantification of waste generated in specific areas (see sections 3.1 and 4.5) and the assessment of greenhouse gas emissions, using scientific tools such as Life Cycle Assessment (LCA) (see section 4.4). The third research question specifically addressed the energy impact of diagnostic imaging equipment, analysing their total energy consumption both during daily operational activities and during idle periods when the systems were powered on but not productive. The number 4, 6, and 7 scientific contributions examined these aspects through on-site measurements conducted in selected hospitals (see sections 2.2, 4.2, 4.3 and 4.4). Finally, the fourth research question investigated possible strategies to mitigate the energy consumption and environmental impact of the radiology area, exploring both organizational solutions and technological interventions, such as the renewal of imaging equipment and the decarbonization of the energy mix used for electricity generation (see sections 4.2, 4.3 and 4.4).

1.2 Scope and delimitation

The aim of this study is to investigate various aspects of environmental sustainability and energy consumption in diagnostic imaging, with a focus primarily on the national and European contexts. The II scientific contribution explored the broader European landscape, involving healthcare professionals from across the continent. In contrast, the IV, V, VI, and VII scientific contributions focused on different hospitals within the Italian territory, where the electricity supply reflected energy mixes representative of Northern Italy during the 2023–2025 period.

From the perspective of the different specialties within diagnostic imaging, the analysis presented in the 4th scientific contribution considered multiple imaging technologies, including CT, MRI, conventional radiology, mammography, and ultrasound. The 5th contribution focused exclusively on CT, the 6th on MRI, and the 7th addressed nuclear medicine, specifically PET/CT. The results of these analyses are presented in this thesis.

1.3 Overview of the papers used as basis for the thesis and co-author statement

The thesis is based on the following seven papers:

Paper 1

Andrea Roletto, Moreno Zanardo, Giuseppe Roberto Bonfitto, Diego Catania, Francesco Sardanelli, Simone Zanoni

The environmental impact of energy consumption and carbon emissions in radiology departments: a systematic review. European radiology experimental vol. 8,1 35. 29 Feb. 2024

The aim of this systematic review was to identify all strategies to reduce energy use and carbon emissions in radiology. In June 2023, a systematic review (Medline/Embase/Web of Science) was performed to search original articles on environmental sustainability in radiology. The extracted data include environmental sustainability topics (e.g., energy consumption, carbon footprint) and radiological devices involved. Sustainable actions and environmental impact in radiology settings were analysed. Study quality was assessed using the QualSyst tool. From 918 retrieved articles, 16 met the inclusion criteria. Among them, main topics were energy consumption (10/16, 62.5%), life cycle assessment (4/16, 25.0%), and carbon footprint (2/16, 12.5%). Eleven studies reported that 40-91% of the energy consumed by radiological devices can be defined as "nonproductive" (devices "on" but not working). Turning-off devices during idle periods 9/16 (56.2%) and implementing workflow informatic tools (2/16, 12.5%) were the sustainable actions identified. Energy-saving strategies were reported in 8/16 articles (50%), estimating annual savings of thousand kilowatt-hours (14,180-171,000 kWh). Cost-savings were identified in 7/16 (43.7%) articles, ranging from US $9,225 to 14,328 per device. Study quality was over or equal the 80% of high-quality level in 14/16 (87.5%) articles. Energy consumption and environmental sustainability in radiology received attention in literature. Sustainable actions include turning-off radiological devices during idle periods, favouring the most energy-efficient imaging devices, and educating radiological staff on energy-saving practices, without compromising service quality.

Paper 2

Andrea Roletto, Diego Catania, Louise Rainford, Anna Savio, Moreno Zanardo, Giuseppe Roberto Bonfitto, Simone Zanoni

Sustainable radiology departments: A European survey to explore radiographers' perceptions of environmental and energy sustainability issues. Radiography (London, England: 1995) vol. 30 Suppl 1 (2024): 81-90.

This study aims to investigate radiographers' perception and knowledge of environmental sustainability issues. An online survey was created and distributed to European radiographers and therapeutic radiographers. The survey questions (n = 43) include demographic data; questions on their perceptions and actions regarding environmental sustainability in healthcare, energy consumption, emissions from staff travel, waste generation from radiological procedures; the role of radiographers in addressing sustainability issues within their departments. A total of 253 responses were collected from 27 European countries. About their perception on sustainability issues, most participants considered environmental sustainability in healthcare as very important. According to 63.6% (n = 161)

of respondents, the energy consumption of radiological equipment is the major source of environmental footprints from radiology activities. Additionally, 44.7% (n = 113) believe that conducting diagnostic examinations remotely could reduce environmental footprints from staff commuting About their actions at workplace, over 70% (n = 192) reported turning off devices after use. Attention to waste recycling is high, but limited to paper, plastic and glass. Contrast agents recycling procedures are implemented by 13% (n = 33). The absence or unawareness of environmental sustainability procedures in the workplace was reported by 66% (n = 167). Radiographers could play an active role in environmental sustainability programs for 243 (96.1%) participants. This study provides a comprehensive overview of European radiographers' knowledge and perceptions concerning environmental sustainability issues. While radiographers recognize the importance of a green radiology department, significant gaps remain in their understanding of eco-friendly initiatives in radiology units' activities.

Paper 3

Andrea Roletto, Anna Savio, Beatrice Marchi, Simone Zanoni

Towards a Greener Radiology: A Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging. Environmental and Climate Technologies Riga Technical University, 28, no. 1 (2024): 303-311.

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 GHG emissions associated with diagnostic procedures.

Paper 4

Andrea Roletto, Anna Savio, Andrea Masperi, Giuseppe Roberto Bonfitto, Fabio Pala, Carmelo Migliorisi, Simone Zanoni

Energy Usage Assessment and Energy Savings Estimation in a Radiology Department in Italy Energies 18, no. 8: 1936. 2025

This study aims to estimate the energy usage of imaging activities in a radiology department to plan and evaluate different energy waste mitigation strategies. A retrospective analysis of the energy usage of imaging equipment, including CT, MRI, X-ray (XR), and workstations of radiology department in Italy, was carried out. The energy

used was estimated based on equivalent mean power demand values in kWh. From this analysis, mitigation strategies were planned to reduce energy waste. The daily energy usage of the department is 877.5 kWh. The cone beam CT scanner is the imaging device with the lowest daily energy usage (6.6 kWh). Modalities with the highest mean daily energy usage are XR (18.4 kWh), CT (58.3 kWh), and MRI (214.6 kWh). The proposed mitigation strategies led to a reduction in energy waste quantified between 16.6% and 80.4%. The analysis of the energy usage of all imaging devices and workstations makes it possible to assess the energy waste of a radiology department. Understanding these elements is essential to develop strategies to reduce energy waste in radiology.

Paper 5

Andrea Roletto, Luca Bombelli, Giuseppe Roberto Bonfitto, Simone Vito Fasulo, Diego Catania, Simone Zanoni

Analysis of waste generation and environmental impact of a multi-dose iodinated contrast media injection system in an emergency radiology department. Journal of Medical Imaging and Radiation Sciences. Volume 57, Issue 31, May 2026

The aim of this study is to analyse the environmental impact and waste generation of an automatic injector in a radiology emergency department. Iodinated contrast media (ICM) administrations are retrospectively reviewed for all CT examinations performed from May 2023 to April 2024 in a radiology emergency department, through the reports generated by the automatic injector. Administered ICM dose, number of vials, waste generation of contrast media, plastic, glass and paper are recorded. In total, 4418 contrast enhanced CT examinations are performed. 1362 vials of ICM are used for a total of 600.9 L of ICM loaded into the injector. Of these, 456.2 L are injected, with an average dose for examination of 103.3 mL (median “110”, interquartile range “70–127”) and ICM wasted amounted to 144.7 L (32.7 mL per exam), corresponding to 290 vials, 31.7% of the total ICM loaded and the total quantity of iodine wasted correspond to 53.1 kg. 411 daily injector kits and 4801 patient lines are used. This analysis revealed that most of the waste from contrast medium examinations comes from the contrast media remaining in kits that have expired at the end of the day, along with disposable materials that generate glass, plastic and paper waste.

Paper 6

Andrea Roletto, Matteo Verga, Anna Savio, Gian Luca Viganò, Simone Zanoni

Energy performance of MRI systems: on-site validation and comparison with manufacturer declarations. European radiology experimental. vol. 10,1 3. 5 Jan. 2026

This study aims to evaluate the actual energy consumption of two generations of 1.5 T 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). Two 1.5T MRI scanner models, the old MRI model version and its new MRI model replacement, were monitored using a power quality analyser connected to the electrical cabinet. Electrical power consumption data were collected over two-week periods, both before and after the scanner replacement. Primary energy consumption was projected over 10 years and resulting values were compared with those reported in the EPDs for the two scanners. Over 10 years, cumulative energy consumption was 1,206.7 MWh (old MRI model) versus 1010.4 MWh (new MRI model),

corresponding to a 16.3% reduction. Considering the range of European Primary Energy Factors (PEFs), energy savings varied from 132.2 to 385.5 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. Replacement of an old MRI model results 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.

Paper 7

Andrea Roletto, Anna Savio, Enrico Bertagna, Nicolò Sean Chiodini, Giuseppe Roberto Bonfitto, Arturo Chiti, Simone Zanoni

Environmental life cycle assessment of [18F]FDG PET/CT imaging in a hospital-based nuclear medicine department, EANM Innovation, vol. 2, 2026

This study aims to perform a detailed LCA of routine [^{18}F]FDG PET/CT whole-body examinations to identify significant ecological impacts and suggest mitigation strategies. 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 hospital. Material-related impacts, including radiopharmaceutical production and single-use supplies, were modelled using SimaPro. Sensitivity analyses assessed the effect of national electricity grid decarbonization. The Global Warming Potential (GWP) of a single [^{18}F]FDG PET/CT whole-body 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 decarbonization could reduce scan-related GWP by up to 50%. 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.

For Paper 1, the original idea and study design were developed by me. I performed the literature search, data extraction, and synthesis, as well as the analysis and interpretation of results. The manuscript was written by me, with valuable comments and revisions provided by Prof. Simone Zanoni and Prof. Francesco Sardanelli. Moreno Zanardo, Giuseppe Roberto Bonfitto and Diego Catania supported the validation of methodological consistency, data interpretation and contextualization of findings within clinical radiology.

For Paper 2, I developed the idea and designed the survey. Moreno Zanardo assisted with survey distribution and preliminary data management. Prof. Simone Zanoni and Prof. Louise Rainford provided essential comments to improve the structure and clarity of the paper. All authors reviewed the final manuscript.

For Paper 3, the research idea was developed jointly by me and Prof. Simone Zanoni. We developed the idea and research design and created the proposed LCA framework. Anna Savio and Beatrice Marchi contributed to data organization and provided constructive feedback during manuscript revision. Prof. Simone Zanoni contributed to the conceptual framework and critically revised the text.

For Paper 4, the idea originated from a specific request by the radiology department of Ospedale Nuovo di Legnano (Legnano Hospital) in Italy, directed by Dr. Carmelo Migliorisi, where Andrea Masperi and Fabio Pala were working. The department sought external expertise to analyse the energy consumption data of their imaging activities and to explore potential energy-saving strategies. I developed the methodological framework, performed the data processing, calculations, and analysis, and drafted the manuscript. Anna Savio supported data management and validation, while Giuseppe Roberto Bonfitto contributed to the interpretation of technical aspects and clinical implications. Prof. Zanoni provided methodological supervision and critically revised the final version of the paper.

For Paper 5, the study concept and design were developed by me. I conducted the data analysis, interpretation, and manuscript drafting. Luca Bombelli supported the collection of injector system data at IRCCS Ospedale San Raffaele, Milan, Italy, (Ospedale San Raffaele), while Giuseppe Roberto Bonfitto, Simone Vito Fasulo and Diego Catania provided clinical and technical insights into workflow optimization. Prof. Simone Zanoni offered methodological supervision and final manuscript revision.

For Paper 6, the research idea originated from my previous work on MRI energy consumption and was further developed in collaboration with Prof. Simone Zanoni. We designed the measurement protocol, conducted the on-site energy assessments, and performed the data analysis and interpretation. Matteo Verga and Gian Luca Viganò contributed to the technical implementation and data collection. Anna Savio assisted in data processing. Prof. Zanoni revised the manuscript and provided critical comments that strengthened the methodological discussion.

For Paper 7, I conceived the study and developed the methodological framework, under the supervision of Prof. Simone Zanoni and Prof. Arturo Chiti. Anna Savio, Enrico Bertagna and I performed the life cycle assessment modelling, data analysis, and interpretation of results. Giuseppe Roberto Bonfitto and Nicolò Sean Chiodini supported data collection and parameter validation. Prof. Zanoni and Prof. Chiti revised the manuscript.

Across all papers, I was responsible for the study conception, data analysis, and manuscript writing. Co-authors contributed within their respective areas of expertise, radiology, sustainability, and systems engineering, through data provision, validation, and critical review. Prof. Simone Zanoni supervised the research throughout all stages, providing methodological guidance and final approval of each manuscript.

1.4 Other publications by the author of the thesis

Anna Savio, Beatrice Marchi, Andrea Roletto, Giuseppe Milano and Simone Zanoni. Sustainable Operating Rooms: A Comprehensive Framework for Environmental Impact Analysis. Environmental and Climate Technologies Riga Technical University, 28, no. 1. 2024

Anna Savio, Andrea Roletto, Beatrice Marchi, Giuseppe Milano, Simone Zanoni. Greening Healthcare: An Approach to Assess the Environmental Impact of Medical Procedures. Proceedings of the Summer School Francesco Turco Conference Paper. 2024

Laura Federico, Andrea Roletto, Diego Catania, Simone Zanoni, Stefano Durante. Leading radiography managers into a greener future: A systematic review of green transformational leadership and sustainable practices. Radiography (London, England: 1995) vol. 31,4. 2

Chapter 2

Background

This chapter outlines the research framework in which the studies included in the scientific contribution were conducted.

2.1 Environmental impact of radiology departments

Healthcare systems are increasingly recognised as significant contributors to global environmental impacts, as they consume large amounts of energy and natural resources, generating GHG emissions and waste (Health Care Without Harm 2019; Watts *et al.* 2021). Within hospitals, radiology departments are one of the most energy-intensive healthcare specialities, as they rely on complex technologies that operate continuously, requiring constant cooling and a power supply to maintain performance (Heye *et al.* 2020). These activities are part of the broader context of the United Nations Sustainable Development Goals, in particular Goal 3 “Good Health and Well-being”, Goal 7 “Affordable and Clean Energy”, Goal 12 ‘Responsible Consumption and Production’ and Goal 13 ‘Climate Action’, which promote the reduction of direct and indirect emissions, energy efficiency and responsible resource management (United Nations 2015).

The main factors contributing to the environmental impact are the electricity consumption of equipment, the generation of waste, and the emissions associated with the life cycle of radiological devices. Radiology departments involve significant direct energy consumption, not only during active operation but also during standby phases and are further impacted by the continuous energy demands of auxiliary systems such as PACS and HVAC (Chua *et al.* 2021; Hainc *et al.* 2020). The composition of the national energy mix strongly influences the environmental impact of the electricity used, as carbon intensity varies between countries depending on the primary sources of production (Bastos *et al.* 2024). For example, a radiological examination performed in a country that is heavily dependent on fossil fuels will have a significantly higher carbon footprint than the same examination performed in a country with a predominantly renewable energy mix (McAlister *et al.* 2022).

In addition to energy consumption, waste production is a critical component of radiology's environmental impact. Diagnostic procedures generate a significant amount of disposable materials such as plastic, syringes, gloves and paper (Voudrias 2018). Particular attention has been given to ICM, which are widely used in CT imaging. It is estimated that more than 100 million contrast-enhanced CT scans are performed annually worldwide, with a total consumption exceeding 10 million litres of ICM (Dekker *et al.* 2022). These substances are only partially metabolized by the human body and are subsequently excreted through urine, entering wastewater and surface water systems (Seitz *et al.* 2006). Furthermore, ICM residues have been detected in rivers and even in drinking water in several countries, as conventional wastewater treatment systems often fail to remove them effectively (Mendoza *et al.* 2016). In addition to the risk of environmental contamination, the production of iodine-based contrast media requires the use of limited natural resources and energy-intensive production processes, making their reuse and recycling a priority (Toia & Ananthakrishnan 2025). New technologies, such as automatic injectors and syringeless

systems, can significantly reduce both the volume of ICM administered and the amount of waste produced (Toia *et al.* 2023). These innovations contribute not only to improving environmental sustainability, but also to optimising operating costs and patient safety (Colombo *et al.* 2013).

Another important aspect concerns the life cycle of radiological equipment. From the extraction of raw materials to the production of components, through to transport, maintenance and final disposal, each stage contributes to generating direct and indirect environmental impacts (Martin *et al.* 2018). Replacing obsolete equipment with more energy-efficient models can improve environmental performance, but it also involves new emissions linked to the production and disposal of the devices (Chaban *et al.* 2024). To understand and quantify these impacts, the LCA methodology is now an essential tool. Defined by the ISO 14040:2006 standard, LCA allows the environmental consequences of a product or service to be assessed throughout its entire life cycle, from production to use, end of life and recycling (Guinée *et al.* 2011). When applied to diagnostic imaging, this methodology allows the identification of the main processes with a high environmental impact and supports the development of targeted strategies to reduce that impact (Thiel *et al.* 2024).

Finally, it is also important to consider sources of indirect impact, such as patient and staff travel to hospitals or for training and conferences. Travel by radiology staff and patients represents a significant component of the carbon footprint associated with radiology (Yakar & Kwee 2020).

Overall, the environmental impact of radiology is multifactorial and involves not only the operation of equipment, but also the organisational and behavioural context in which diagnostic services are provided. Understanding these interconnections is essential for defining effective mitigation strategies and promoting a culture of environmental responsibility within the healthcare professions operating in the radiology field.

2.2 Energy consumption of diagnostic imaging equipment

Energy consumption is one of the most significant aspects of the environmental impact of diagnostic imaging departments, as the equipment used, especially MRI and CT scanners, requires significant amounts of electricity to operate and maintain optimal operating conditions(Heye *et al.* 2020; Woolen *et al.* 2023a). Specifically, it has been calculated that the average energy use for CT and MRI scanners in many developed countries ranges from 1200 to 3079 kWh per 1000 citizens per year, estimating a significant amount of potentially avoidable emissions each year(Furlan *et al.* 2023; Hanneman *et al.* 2024). Several studies have shown that a considerable portion of the electricity consumed by such equipment is attributable to periods of inactivity, during which the systems remain switched on even though they are not performing diagnostic examinations. In the case of MRI equipment, helium compressors and cryogenic systems must remain in operation to ensure the stability of the magnetic field, while in CT systems, consumption derives from the need to keep the equipment ready to scan and the cooling systems operational (Büttner *et al.* 2021; Javadi *et al.* 2023; Vosshenrich & Heye 2023). Typically, the operating phases of diagnostic imaging scanners are divided into four categories (Chaban *et al.* 2024; McKee *et al.* 2024):

- Active state: The actual scanning phase during which power consumption rises above the baseline, corresponding to the image acquisition process.

- Idle state: The interval between active periods while the system remains powered on. This is not a manually selectable production state but a transitional phase within the powered-on condition.
- Stand-by state: The state in which most system components are powered down, though some remain active to maintain essential functions. Immediate scanning is not possible in this mode, and a power-up sequence of several minutes is required before operation.
- Switch-off state: The condition in which the system is completely turned off, with no power supplied to its components. However, this state is generally not applicable to certain modalities such as MRI or PET, which require continuous operation of critical subsystems, such as cooling for MRI and detector for PET, to maintain operational stability.

The overall energy demand of a radiology department depends on multiple factors, including the number and type of examinations performed, daily operating time, and the age and technological efficiency of the equipment. New-generation scanners show significant improvements in energy efficiency thanks to the implementation of dynamic operating modes that allow power modulation based on actual system activity. According to the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry (COCIR), the adoption of new hardware and software solutions has led to a notable reduction in the average daily energy consumption of MRI scanners in recent years, from an estimated 226 kWh in 2011 to 165 kWh in 2017, an improvement largely attributed to the introduction of "eco-power" operating modes and more energy-efficient system designs (COCIR 2018). In addition to the main imaging equipment, the digital infrastructures associated with diagnostic imaging also contribute significantly to overall energy consumption. Although the power demand of each individual workstation is lower than that of an imaging device, their large number and continuous operation have a considerable impact on the overall energy balance of radiology departments (Doo *et al.* 2024). The concept of 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 (Huijbregts *et al.* 2010). Among all these contributing factors, the energy consumed during the clinical use represents the most significant share of the total CED for a radiological scanner throughout its entire life cycle. 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 (Bel & Joseph 2018). 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 (Bilardo *et al.* 2024; Wilby *et al.* 2014). Most available data on primary energy consumption performance of a radiological device come from EPDs, which are based on standardized assumptions and technical documentation provided by manufacturers. These documents often report significant improvements in energy efficiency in newer diagnostic scanner models, but such claims require validation through real-world measurements (Moré *et al.* 2022). In summary, the energy consumption of diagnostic imaging equipment results from a combination of technological, organizational, and infrastructural factors. The availability of real consumption data, integrated with primary energy indicators and information on the local energy mix, represents a

key element for accurately assessing the efficiency of radiology departments and for planning future improvement actions aligned with the environmental sustainability principles of the healthcare sector.

2.3 Perceptions of radiology staff on energy and environmental sustainability issues

The growing focus on environmental sustainability in the healthcare sector has highlighted how staff involvement and awareness are key elements in the success of any strategy to reduce environmental impact. In radiology, in particular, the daily activities of technical and medical staff have a direct impact on energy consumption and waste production, making training and awareness-raising on these issues central to lasting cultural and operational change (Mariampillai *et al.* 2023; McKee *et al.* 2024). Numerous recent studies have emphasised that the transition to "green radiology" cannot be achieved through technological innovations or infrastructure interventions alone but must also include the adoption of sustainable behaviours by operators. Radiologists, Radiographers and other healthcare professionals working in the field of diagnostic imaging play a key role in reducing energy consumption, limiting the use of disposable materials and promoting more conscious waste management (Sarchosoglou *et al.* 2024; Woolen *et al.* 2023b; Zigmund *et al.* 2023).

Despite growing media and institutional attention to the issue, the literature shows that healthcare workers' knowledge and perception of environmental issues remain uneven. Several authors point out that most professionals are aware of the environmental impact of their sector but still lack concrete tools to quantify and reduce it systematically (Gendy *et al.* 2022; Soares *et al.* 2023). Surveys conducted among radiologists and radiographers in European and international contexts reveal a general willingness to adopt sustainable practices, but also the presence of cultural and organisational barriers. Among these, the lack of specific guidelines, limited training on the subject and the perception that green practices may reduce clinical efficiency represent the main obstacles (Abuzaid & Almuqbil 2025; Peters *et al.* 2021). Furthermore, the workload pressure and the priority given to clinical productivity often reduce the time and resources available for adopting more sustainable practices. Another important element that emerged from the studies concerns the role of professional training. The integration of modules dedicated to environmental sustainability into university and postgraduate training programmes is recognised as an essential condition for promoting greater awareness among future healthcare professionals. In some pilot projects, specific training courses have helped to improve understanding of the relationship between clinical activity and environmental impact, encouraging a more critical and responsible approach (Hampshire *et al.* 2021; McKee *et al.* 2024). In summary, the literature highlights how radiology staff are showing increasing sensitivity to sustainability issues, but that this awareness needs to be accompanied by continuous training, clear guidelines and strong institutional support. Only through an integrated approach that combines technical expertise and environmental responsibility will it be possible to build a truly shared culture of sustainability in diagnostic imaging departments.

2.4 Mitigation strategies for energy consumption and environmental impact of the radiology area

Mitigating the environmental impact in the radiological area requires an integrated approach that combines technological innovation, management optimisation and improvement of energy infrastructure (Rockall *et al.* 2025).

Several studies have shown that a significant portion of diagnostic activity consumption is due to periods of inactivity, during which equipment remains on even though it is not performing tests. The introduction of targeted operational strategies, such as automatic deactivation of systems in "power save" mode, intelligent power-up planning and dynamic workload management, can reduce energy consumption by up to 25–33% without affecting the clinical availability of the machines (Büttner et al. 2021; Woolen et al. 2023). At the same time, reducing scan times is an effective measure for limiting direct consumption. The adoption of abbreviated protocols, which maintain diagnostic quality but reduce the duration of the examination, allows for energy savings proportional to the time of use. Studies in the field of MRI have documented reductions in acquisition times of between 30% and 50% (Ahmadinejad *et al.* 2023; Ibrahim *et al.* 2024). The application of accelerated acquisition techniques based on deep learning has enabled reductions of up to 70% in both examination time and energy consumption, demonstrating a positive impact on the overall productivity of radiology departments(Afat *et al.* 2024; Ayde *et al.* 2022). On the technological front, medical equipment manufacturers have introduced eco-design systems and low-consumption operating modes, which automatically regulate the operation of the helium compressor based on actual loads, significantly reducing power consumption (Siemens healthineers 2023). Replacing obsolete equipment with new-generation models is therefore one of the most effective strategies for reducing energy consumption and related emissions, thanks to simultaneous improvements in both hardware and software (Sumner *et al.* 2023). In addition to direct electricity consumption, HVAC systems make a significant contribution to the energy balance of diagnostic departments, as they are essential for ensuring thermal stability and equipment reliability. It has been estimated that these systems can account for up to 40–50% of the total electricity consumption of a radiology area(Chua *et al.* 2013). The application of adaptive and predictive control strategies, supported by sensors and dynamic regulation algorithms, allows for optimised efficiency and reduced energy waste (Aparicio-Ruiz *et al.* 2025; Gholamzadehmir *et al.* 2020). From a systemic perspective, the decarbonisation of energy sources represents a long-term measure to reduce overall environmental impact. According to the European Environment Agency (European Environment Agency 2025), the average emission intensity of electricity production in Europe is steadily decreasing thanks to the growing share of renewable energy in the energy mix, although significant differences remain between countries. The PEF for electricity varies from around 1.2 in systems heavily based on renewable sources to over 2.5 in those still dependent on fossil fuels (Bastos *et al.* 2024). Hospital energy planning, which includes the integration of trigeneration systems and supply from renewable sources, therefore plays a strategic role in healthcare sustainability policies. Finally, the assessment of environmental impact through LCA makes it possible to identify the main contributors to emissions throughout the entire life cycle of imaging equipment and diagnostic services, providing a quantitative basis for management and procurement decisions (Guinée *et al.* 2011; Thiel *et al.* 2024). The integration of minimum environmental criteria and initiatives such as the Medical Equipment Proactive Alliance (MEPA) contributes to spreading a model of radiology that is increasingly efficient, responsible and consistent with the sustainability objectives outlined by European and international policies (MEPA 2024)

Chapter 3

Methodology

This chapter outlines the methodological approaches adopted across the scientific contributions included in this doctoral research.

As mentioned in Section 1.1, each of the individual scientific contributions was designed to address specific research questions derived from the results of the initial systematic literature review. Since these research questions explored different dimensions of environmental sustainability within radiology, different scientific methods were applied during the three years of the doctoral programme, each tailored to the objectives and scope of the respective contribution. The methodological diversity reflects the multifaceted nature of sustainability in diagnostic imaging, encompassing topics such as energy efficiency, environmental impact assessment, life cycle modelling, and behavioural or organisational aspects that influence sustainable practices among radiology professionals. Consequently, both quantitative and qualitative approaches were employed, ranging from direct energy monitoring and environmental modelling to perception surveys and analyses. The geographical context of the research also varied during the doctoral study, in response to the evolving needs of the research group and the opportunity to capture a more comprehensive and heterogeneous perspective. Data collection and case studies were therefore conducted in different institutional and geographical contexts, including several Italian hospitals and European collaborations, to compare not only technical and infrastructural characteristics, but also cultural and attitudinal variability in the approach to environmental sustainability in radiology. This methodological pluralism was designed with the aim of ensuring that the thesis work is both scientifically robust and practically relevant. Each study is therefore methodologically independent but conceptually aligned with the overall objective of the doctoral project.

3.1 System approach

Applying a systemic approach allows us to analyse the environmental sustainability of radiology as an interconnected network of factors. Each scientific contribution addressed a specific subsystem within this broader framework: from the energy consumption of imaging equipment to staff perceptions and behavioural aspects, from waste management to the life cycle impact. Identifying the boundaries of the system, the time frame and the correlations between these subsystems allows for a broader understanding of the environmental performance of diagnostic imaging services.

The six scientific contributions analyse different dimensions of environmental sustainability in radiology in a complementary manner. As summarised in Table 2, each study focuses on a specific subsystem within the broader context of diagnostic imaging. The research covers different system boundaries and methodological approaches. Paper II investigates the perceptions and attitudes of radiographers regarding environmental and energy sustainability in different European countries, while Paper III defines an LCA model applied to diagnostic imaging, aimed at assessing environmental impacts in a standardised and reproducible manner.

At the departmental level, Paper IV quantifies the energy consumption of the main imaging modalities through direct measurements, while Paper V compares the actual energy performance between two MRI systems belonging to different technological generations. Paper VI analyses the waste production associated with the use of ICMs in CT procedures, addressing both environmental and resource management aspects. Finally, Paper VII applies the LCA methodology to quantify the overall environmental footprint of PET/CT procedures with [^{18}F]FDG, integrating energy, material and emission parameters.

Table 2: An overview of methods and approaches applied in the papers.

Paper ID	Aim	Radiological Setting	Geographical Setting	Observation Period	Research Method	Environmental Impact Focus
Paper II	Explore radiographers' perceptions of environmental and energy sustainability.	/	Multi-country (Europe)	2023-2024	Survey study	Awareness, attitudes, perceived sustainability practices
Paper III	Define an LCA framework for diagnostic imaging.	/	/	2024	Systematic Review	Life Cycle Assessment impact (GWP, energy, waste)
Paper IV	Estimate the energy consumption of a radiology department.	Radiology Department ASST Ovest Milanese	Legnano, Italy	2023-2024	Experimental / waste quantification	Operational energy use
Paper V	Compare energy performance of old and new MRI systems.	Magnetic Resonance Imaging Unit ASST Spedali Civili	Brescia, Italy	2024-2025	Field measurement, manufacturer data comparison	Energy efficiency, CO_2 savings
Paper VI	Analyse waste generation from iodinated contrast media in CT exams.	CT Unit (Emergency Radiology Department) IRCCS Ospedale San Raffaele	Milan, Italy	2025	Life Cycle Assessment	Material waste and resource use
Paper VII	Assess the life cycle impact of [^{18}F]FDG PET/CT examinations.	Nuclear Medicine Department IRCCS Ospedale San Raffaele	Milan, Italy	2025	Life Cycle Assessment	Life Cycle Assessment impact (GWP, energy, waste)

3.2 Methodologies used to perform studies in the appended papers

Different methodologies were adopted across the studies included in this doctoral thesis. Paper II involved a cross-sectional survey aimed at exploring radiographers' perceptions of environmental and energy sustainability across Europe. Paper III employed a systematic review to define a Life Cycle Assessment (LCA) framework applicable to diagnostic imaging. In Papers IV, V, and partly VII, direct energy measurements were collected to estimate the overall energy consumption of different medical imaging modalities. Paper VI focused on the quantification of waste generated from the use of ICM in CT examinations. Finally, Paper VII applied a cradle-to-grave LCA methodology.

3.2.1. Methodology adopted in Paper II

For the Paper II, the questionnaire was initially designed using information on the main topics of environmental sustainability of the healthcare system, energy consumption of radiology departments, emissions from radiology staff travel and waste generation from radiology activities from previous literature analysis. The survey was design

using Survey Monkey (https://www.surveymonkey.com) to enable widespread distribution and ease of data collection.

The questionnaire comprised of closed questions or using a visual analog scale (VAS) (Crichton N 2001) (n = 43) and were divided into five sections. The first section, concerning demographic questions, included questions on age, country of origin, professional experience, educational and professional qualifications, place of work and clinical speciality practised. Subsequent sections asked questions about their perceptions and their actions at work regarding the topic of environmental sustainability in the healthcare system and more specifically on issues of energy consumption, GHG emissions from staff travel, waste generation from radiological procedures and finally their idea on the role that radiographers and therapeutic radiographers could play regarding sustainability issues in their departments. The survey was made available in 5 different languages: English, French, German, Italian and Spanish.

To verify the appropriateness, clarity and reliability of the survey developed, a pilot study was carried out by distributing it to six external research-active radiographers, with experience in survey design, who were asked for feedback on the validity of the questions, the functionality of the online tool and the time needed to complete it. The experts provided minor recommendations regarding the mode, content, and grammar of the question text, which were then integrated into the survey. Five radiographers from each country whose mother tongue was included in the survey translations were involved in the revision of the text in their respective languages, checking its accuracy and providing minor corrections.

Distribution was initially through personal and professional contacts of radiographers and therapeutic radiographers across all Europe, via a “snowballing” technique, via emails with virtual link (and subsequent reminders) and social media posts (Facebook, LinkedIn), and was also distributed using a virtual link at the European Federation of Radiographers Societies (EFRS) Research Hub during the European Congress of Radiology 2024 (February 28 – March 3, 2024, Vienna) (Rainford 2022). EFRS Research Hub at the European Congress of Radiology 2024 promoted a series of online questions to its member organisations and wider. The survey was intended to be completed in approximately 15 min. No incentive was offered for survey participation. All responses were collected anonymously. Participants confirmed their voluntary participation and identified themselves as radiographers, therapeutic radiographers, radiography students, or retired radiographers based in Europe.

Descriptive statistics were used to summarise participant demographics, current situation in Europe regarding environmental footprint of radiological activities, perceptions of European radiographers and therapeutic radiographers on environmental sustainability issues in radiology and to analyse future challenges. Frequencies were reported together with their respective percentages. Data were visually assessed for normality and analysed using the Shapiro-Wilk test. P-values less than 0.05 from the Shapiro-Wilk test indicated non-normal distribution. For normally distributed data, the mean and standard deviation were reported, while the median and interquartile range were used for non-normally distributed data.

3.2.2. Methodology adopted in Paper III

For the Paper III, 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. 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. A study was excluded if it was 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. A study was included in the final analysis if it was 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.

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.

3.2.3. Methodology adopted in Paper IV

In accordance with the energy audits of processes standard UNI CEI EN 16247-3:2022 (UNI Ente italiano di normazione 2022) and the cycle Plan-Do-Check-Act of ISO 50001 (The International Organization for Standardization 2018), a retrospective analysis of the energy usage of all imaging equipment and reporting and RIS/PACS workstations for diagnostic activities was carried out. Through this, the areas of highest energy usage were determined, and possible energy waste mitigation strategies were planned. Figure 1 presents a graphical representation of the study's methodological flowchart.

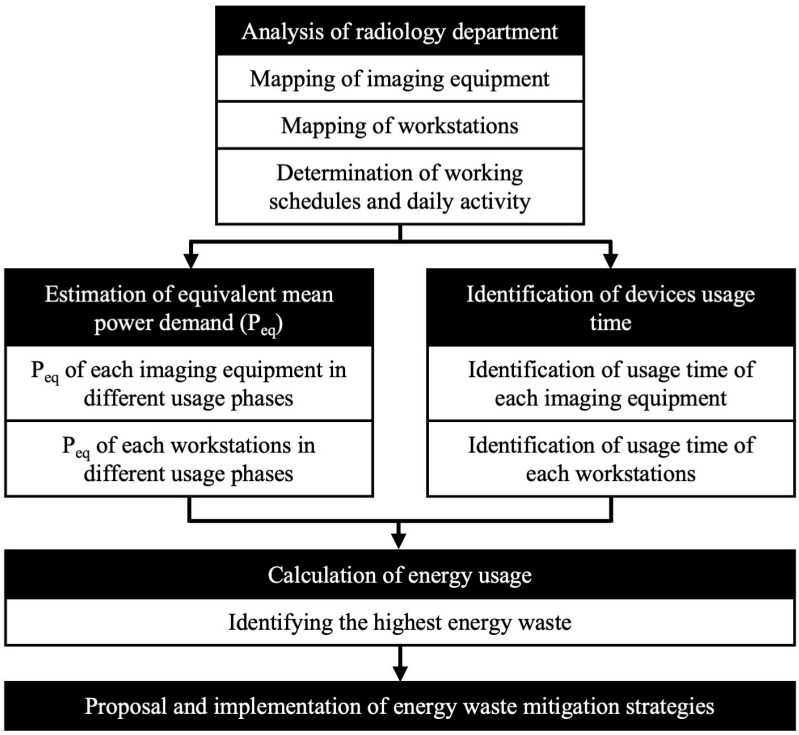


Figure 1: Paper IV flowchart.

The energy usage of all imaging devices, cone beam computed tomography (CBCT) (n = 1), CT (n = 1), dual-energy X-ray absorptiometry (DXA), (n = 1), mammography (MG) (n = 2), MRI (n = 2), mobile chest X-ray (MCXR) (n = 2), ultrasound (US) (n = 5), X-ray (XR) (n = 5), and all reporting (n = 10) and RIS/PACS (n = 27) workstations of the operational unit of Radiology at Ospedale Nuovo di Legnano (Legnano Hospital), a 555-bed public hospital in the metropolitan city of Milan, Italy, was evaluated. The floor plan of the department is shown in Figure 2.

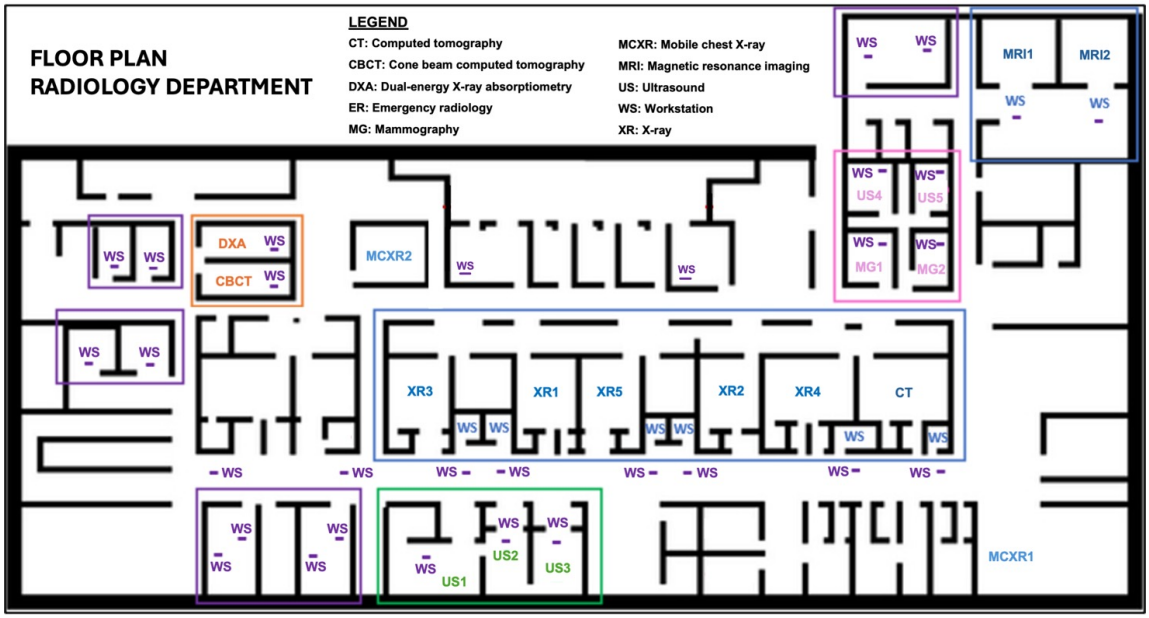


Figure 2: Floor plan of the radiology department of Ospedale Nuovo di Legnano.

The working hours considered for the estimation of energy usage were from 8:10 a.m. to 3:30 p.m. (7.3 hours) for all XR, DXA, MRI1, MG2, US3, US4, US5 scanners; from 8:10 a.m. to 12:00 p.m. (4 hours) for the CBCT scanner;

from 8:10 a.m. to 4:30 p.m. (8.3 hours) for the CT scanner; from 8:10 a.m. to 5:30 p.m. (9.3 hours) for the US1 and US2 scanners; from 8:10 a.m. to 7:30 p.m. (11.3 hours) for the MG1 scanner; from 8:10 a.m. to 11:30 p.m. (23.3 hours) for the MRI2 scanner; and 24 hours of operation for the MCXR devices of the Radiology operational unit.

The study was divided into two parts. The first part estimated the daily energy usage of each diagnostic modality and all reporting and RIS/PACS workstations in relation to the daily diagnostic activities performed, excluding when they are switched off at the end of the working day. The second part hypothesized and tested three different energy usage mitigation strategies: 1) optimizing the energy usage of reporting and RIS/PACS workstations, 2) reorganizing diagnostic activities to reduce energy waste, and 3) selecting for lower-energy imaging examinations without compromising clinical appropriateness.

To estimate the energy usage for each diagnostic imaging device and equipment (reporting and RIS/PACS workstations), initially the usage time (expressed in hours, hrs) per day were collected, considering the radiology department's activities performed between 1 January 2023 and 28 February 2023.

Regarding all imaging scanners, usage periods were divided into two states:

- active period: the productive time which includes patient or scanner positioning and image acquisition.
- idle period: the non-productive waiting time interval between “active” time periods, when devices are “on” but not working.

As only the clinical operating hours of the imaging equipment were considered for this estimation, any energy consumption during the stand-by phase, i.e. when the scanner is switched off or not used after the working hours, was not estimated. The time (T, expressed in hours) for the active period and the idle period was assessed by considering the total number of working hours per day, the total number of diagnostic examinations performed and the allocated time duration of a planned examination (Table 3).

Table 3: Working schedules, number of examinations performed, time spent during activity and waiting periods for each imaging modality.

	Start	End	Opening (hrs)	Exams per month	Exams per Day	Exam time (min)	Time (T)	
							Active period (hrs)	**Idle period (hrs)**
XR 1	8:10	15:30	7.3	600	30	10	5.0	2.3
XR 2	8:10	15:30	7.3	800	40	10	6.7	0.6
XR 3	8:10	15:30	7.3	200	10	10	1.7	5.6
XR 4	8:10	15:30	7.3	800	40	10	6.7	0.6
XR 5	8:10	15:30	7.3	80	4	10	0.6	6.7
DXA	8:10	15:30	7.3	88	11	10	1.8	5.5
CBCT	8:00	12:00	4.0	40	10	10	1.6	2.4
CT	8:10	16:30	8.3	350	36	10	6.2	3.1
MRI 1	8:10	15:30	7.3	248	10	35	5.8	1.5
MRI 2	8:10	23:30	15.3	500	22	35	12.8	2.5
MG 1	8:10	19:30	11.3	660	30	10	5	6.3
MG 2	8:10	15:30	7.3	40	2	10	0.3	7
US 1	8:10	17:30	9.3	500	25	20	8.3	1
US 2	8:10	17:30	9.3	500	25	20	8.3	1
US 3	8:10	15:30	7.3	200	10	20	3.3	4
US 4	8:10	15:30	7.3	300	15	20	5	2.3
US 5	8:10	15:30	7.3	200	10	20	3.3	4
MCXR 1	0:00	24:00	24.0		10	10	1.7	22.3
MCXR 2	0:00	24:00	24.0		25	10	4.2	19.8

RIS/PACS workstations usage periods were associated with three different states:

- Active period: the production time during which workstations are actively used by department staff;
- Idle period: the non-productive waiting time interval between “active” time periods, when workstations are “on” but not working
- Stand-by period: the non-productive time the equipment was switched on but there was no related imaging activity. During stand-by period workstations are able to consume less power, while being able to resume its normal functions quickly.

The hours associated with these different periods can be found in Table 4.

Table 4: Number of hours for active. stand-by and inactive period for workstations (WS), reporting workstations (RWS).

Different energy consumption period of Reporting workstation in the Unit of Radiology			
	Active period (hrs)	Stand-by period (hrs)	Idle period (hrs)
RWS 1 - 2	6.5	2.1	15.4
RWS 3 - 4	5.8	2.0	16.1
RWS 5 - 10	9.1	2.3	12.6
Mean	7.2	2.1	14.7
Different energy consumption period of RIS/PACS workstation in the Unit of Radiology			
	Active period (hrs)	Stand-by period (hrs)	Idle period (hrs)
WS (n = 27) Mean	6.8	10.2	8.0

3. Methodology

Radiological equipment typically exhibits energy profiles characterized by short bursts of high-power demand followed by extended low-power intervals during the active phase (Figure 3) (Heye *et al.* 2020). To simplify comparisons between these varying consumption patterns, the equivalent mean power demand, representing the total power supplied over the duration of a specific phase, was considered for both activity and waiting periods. This approach provides a single, easily interpretable parameter that consolidates the variable consumption profile and facilitates straightforward comparison of different power requirements. On the other hand, for MRI and ultrasound scanners, the equivalent mean power demand during the active phase and the idle phase coincides, as the scan, although having some peaks during acquisition, has a rather constant active consumption, with the scanner constantly ready to scan (Chaban *et al.* 2024; Heye *et al.* 2020).

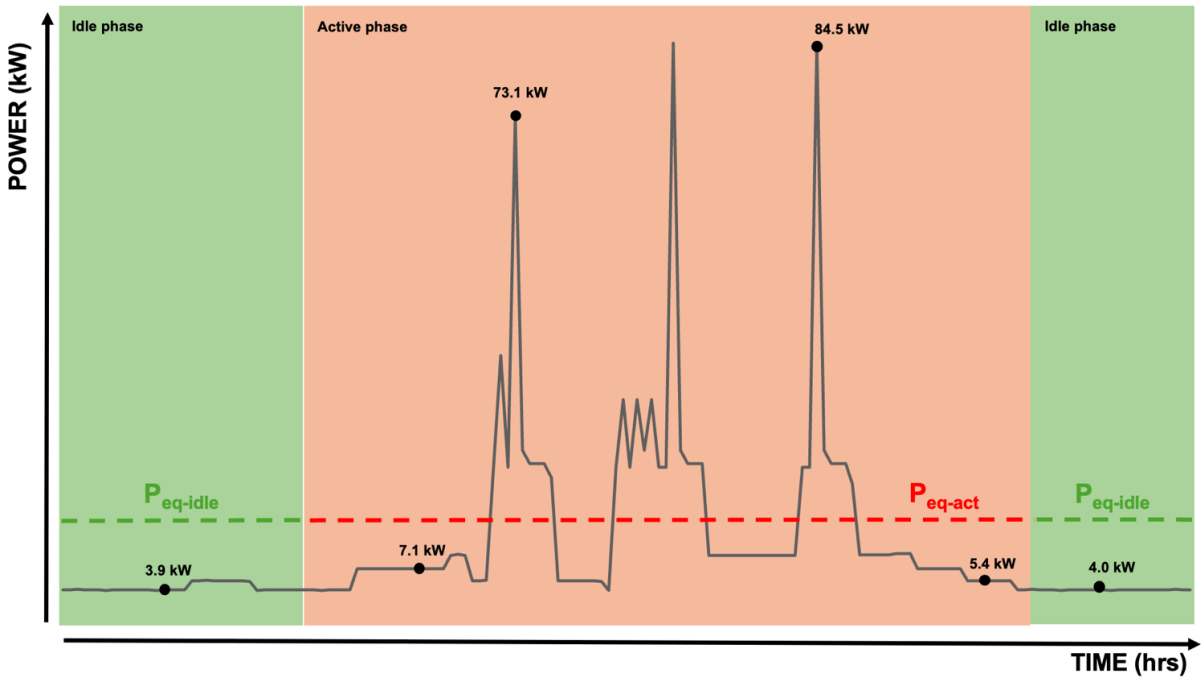


Figure 3: Diagram showing the representation of a CT scan is segmented (orange area) according to scan time. The equivalent mean power demand represents the average power required by the scanner during the active phase, considering power peaks during scanning and low power phases. The black dots on the power consumption diagram exemplify the consumption in kilowatts at the respective position on the graph. The green area identifies the waiting phase and defines the area associated with the equivalent mean power demand of that phase.

Once the usage time of all imaging devices and all workstations has been calculated, the energy usages (E) (expressed in kWh) were estimate as the product of the equivalent mean power demand (Peq), (expressed in kW) declared by devices manufacturers of radiological scanners (Table 5) and workstations (Table 6) and the duration of each time (T), according to the formula:

$$\text{Energy}_i = \text{Equivalent Mean Power Demand}_i \cdot \text{Time}_i,$$

Table 5: Equivalent mean power demand (kW) and total energy used (kWh) per day during active and idle phases of all radiological scanners.

	Equivalent mean power demand (P_{eq-act}) during Active phase (kW)	Equivalent mean power demand ($P_{eq-idle}$) during Idle phase (kW)	Energy used (E_{act}) during Active period (kWh)	Energy used (E_{idle}) during Idle period (kWh)
XR 1	3.7	1.1	18.5	2.5
XR 2	3.7	1.1	24.8	0.7
XR 3	3.5	1.1	5.9	6.2
XR 4	3.5	1.1	23.4	0.7
XR 5	3.3	1.0	2.0	7.3
DXA	2.3	0.7	4.1	3.9
CBCT	1.9	1.5	3.0	3.6
CT	16.4	4.0	45.9	12.4
MRI 1	19	19	110.2	28.2
MRI 2	19	19	243.2	47.5
MG 1	4.3	1.8	21.5	11.3
MG 2	4.3	1.8	1.3	12.6
US 1	1.1	1.1	9.1	1.1
US 2	1.1	1.1	9.1	1.1
US 3	1.1	1.1	3.7	4.4
US 4	1.1	1.1	5.5	2.5
US 5	1.1	1.1	3.7	4.4
MCXR 1	2.8	0.2	4.8	4.4
MCXR 2	2.8	0.2	11.8	3.9
TOTAL			**664.2**	**201.3**

Table 6: Equivalent mean power demand (Peq) (kW) and total energy consumed (kWh) per day during active, idle and stand-by phases of all workstations.

	Equivalent mean power demand (P_{eq}) (kW) [active / idle/ stand-by]	Total energy Active period (kWh)	Total energy Idle period (kWh)	Total energy Stand-by period (kWh)
RW (n = 10)	0.5 / 0.28 / 0.02	37.0	5.8	2.9
WS (n= 27)	0.3 / 0.17 / 0.02	55.0	46.8	4.3
TOTAL		**100.5**	**58.8**	**8**

3.2.4. Methodology adopted in Paper V

ICM usage was estimated retrospectively by reviewing 4441 consecutive Contrast Enhanced Computed Tomography (CECT) examinations performed in a Radiology Emergency Department from 1 May 2023 to 30 April 2024. If a subject had undergone more than one CECT exams during the observation period, all the examinations were considered. Also, only the studies conducted in the CT suite equipped with the Centargo injector (Bayer Healthcare) were included in the analysis. The injector analysed in this study is a dual head programmable automatic piston-based injector which use the same ICM vial and saline bag across multiple patients, requiring only the replacement of the patient line between exams. The CECT examinations included in the study involved the cranio-cervical region, the thoraco-abdominal area, the upper and lower body extremities.

The volume of ICM administered is automatically recorded on the data report available in hospital's PACS (Enterprise Imaging Platform, Agfa Healthcare) by the automatic injector and was used to calculate the average mL of ICM administered/study. ICM injected to each patient was subtracted from total ICM loaded into the automatic injector to calculate average mL of ICM wasted/study. ICM waste was defined as the difference between the volume of ICM loaded into the injector and the volume administered to the patient. We considered ICM wasted also ICM remaining in the vials and in the automatic injector's syringe before changing the daily kit. Any unused ICM is typically discarded in the trash. 200- and 500-mL vials of ICM with different concentrations (320 mg/mL, 350 mg/mL, 370 mg/mL and 400 mg/mL) were emptied of contrast and weighed. The weight of each of these and of plastic, paper, syringes and patient lines were measured on a digital weighing scale with graduations of 1 g to calculate the total annual weight of glass, paper and plastic waste of disposable materials. The reported values in the results reflect a single measurement performed by two researchers.

All data were collected and organized using Microsoft Excel and subsequently analysed descriptively using IBM SPSS Statistics, version 30.0.0. Descriptive statistics were computed to summarize the characteristics of the dataset, including the number of CECT examinations, ICM volumes administered, ICM wasted and the distribution of disposable materials. Continuous variables, such as ICM volume per examination, were reported as mean, median and interquartile range. Categorical variables, including the ICM's concentrations and vials' size, were presented as absolute frequencies and percentages.

3.2.5. Methodology adopted in Paper VI

In Paper VI, 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: (i) the distribution of energy consumption across different scanner activity states; (ii) the differences in energy consumption between two MRI scanners of different generations; (iii) the estimation of the cumulative primary energy consumption over a typical 10-year system lifespan (Figure 4); (iv) the consistency between energy values declared by the manufacturers in the EPDs and those measured during actual clinical operation.

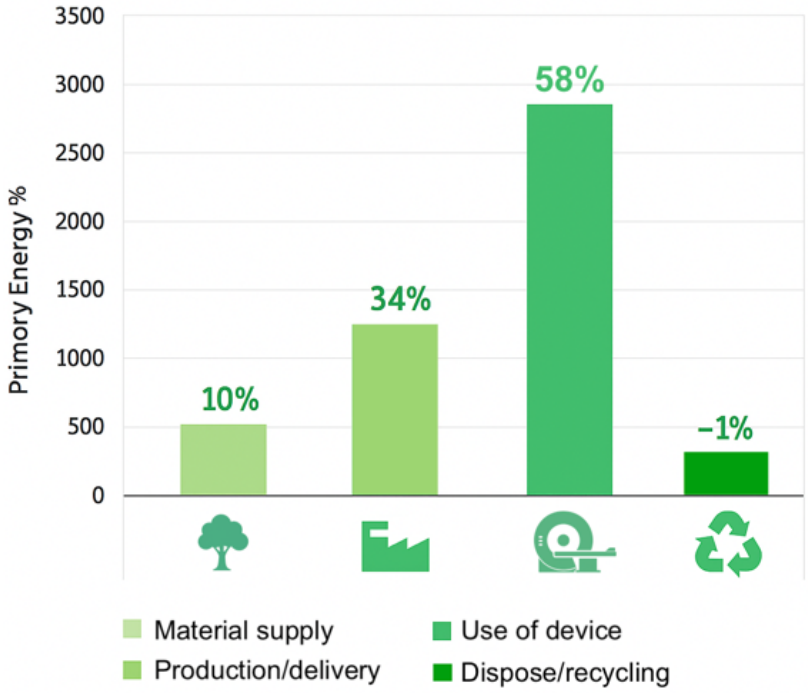


Figure 4: Distribution of primary energy demand across the life cycle stages of an MRI system. The clinical use represents the largest share of total energy consumption (58%), followed by production and delivery (34%), material supply (10%), and end-of-life disposal/recycling, which provides an energy recovery benefit (−1%). These values highlight the predominant impact of operational energy use in the overall environmental performance of the device. (Source: siemens-healthineers.com/sola)

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 two weeks prior to the decommissioning of the old model 1.5T MRI (Magnetom Aera, Siemens Healthineers, software version VA50A, with a gradient of 625A/2000 V, a radiofrequency amplifier peak root mean square power of 26.1 kW) and in October 2024, in the first two weeks of full operation of the new model 1.5T MRI (Magnetom Sola, Siemens Healthineers, software version XA61, with gradient of 625A/2000 V, 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 hours from Monday to Friday, occasionally 8 hours on Saturdays and emergency examinations on Sundays. Over the course of two weeks, 153 examinations were performed on the Magnetom Aera (old MRI model) and 180 on the Magnetom Sola (new MRI model). Both monitoring periods were fully comparable in terms of scanner utilisation, 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 optimisation 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 non-invasively with a power quality analyser (GSC59, HT Instruments), commonly used in hospital infrastructure energy audits (Figure 5).



Figure 5: Measurement setup for on-site energy monitoring. Power consumption was measured non-invasively with a power quality analyser (GSC59, HT Instruments) connected to the incoming power line of the MRI electrical cabinet. The analyser continuously measured voltage, current and power parameters during routine scanner operation, allowing real-time assessment of energy demand without interfering with clinical workflow.

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 analysed in a 30-second 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. 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 to 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. Using the data collected by the power quality analyser, 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: Active state, Idle state and Stand-by state (Figure 6). 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 (Siemens Healthcare; n.d.) and Magnetom Sola (Siemens Healthineers; n.d.) 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.

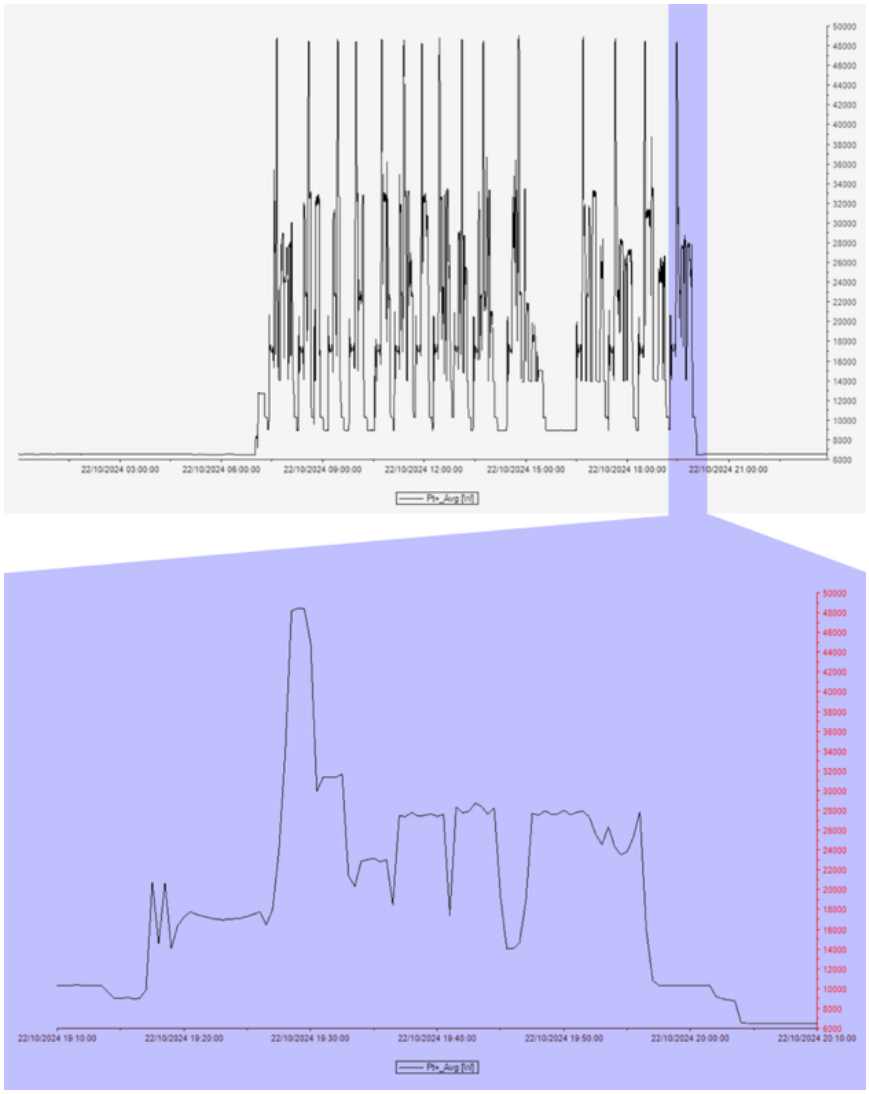


Figure 6: The figure shows the consumption profile in watts (W) of an MRI working day recorded by the power quality analyser in which an MRI scan is zoomed in to show the footprint of energy consumption in the active state.

Finally, to estimate the primary energy consumption of the two MRI 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 ten years. To convert this value into primary energy, various PEFs for domestic electricity were considered. The European PEF of 1.9, established in European Union Directive 2023/807 (European Union n.d.), 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 (European Commission for Energy Directorate-General *et al.* 2023).

3.2.6. Methodology adopted in Paper VII

For Paper VII, 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 [^{18}F]FDG PET/CT whole-body examinations performed on the same PET/CT system, with a standard scan range from head to pelvis, were included. 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. An LCA was performed to estimate the GHG emissions associated with a single [^{18}F]FDG PET/CT whole-body scan. A cradle-to-grave approach, compliant with ISO 14040 standards (The International Organization for Standardization 2006), was adopted.

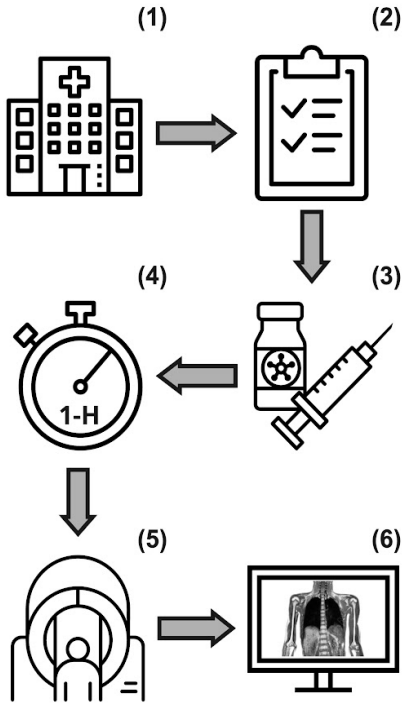


Figure 7: Patient pathway for a [^{18}F]FDG PET/CT Whole-Body Scan.

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 Figure 7: (1) patient arrival at the hospital, (2) patient reception and registration, (3) intravenous injection of [^{18}F]FDG with a radiopharmaceutical injector, (4) 60-minute uptake period, (5) Execution of [^{18}F]FDG PET/CT whole-body scan, (6) image acquisition and patient discharge. The total average duration of a single session was estimated at approximately two hours. This pathway served as the basis for the system boundaries considered in the LCA (Figure 8).

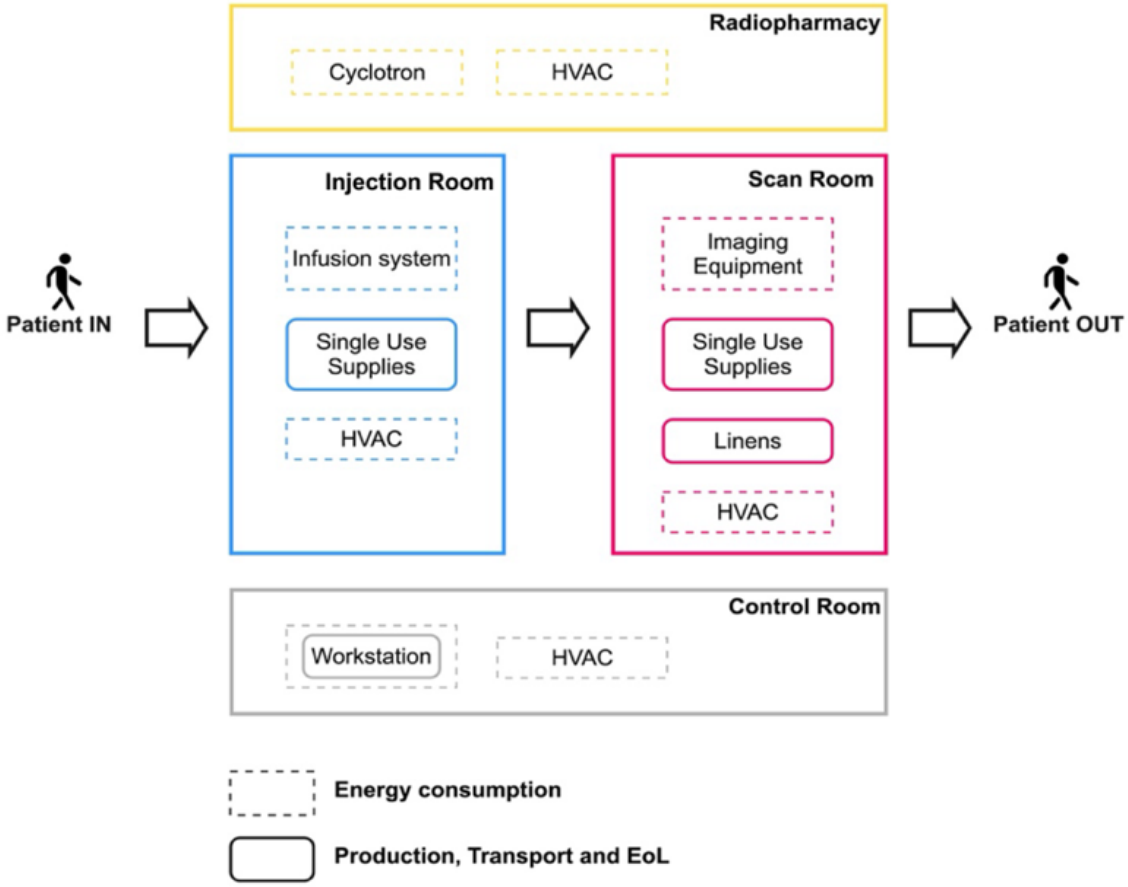


Figure 8: System Boundaries and Functional Areas for [¹⁸F]FDG PET/CT Life Cycle Assessment. Diagram showing the main functional spaces involved in a [¹⁸F]FDG PET/CT scan: Radiopharmacy, Injection Room, Scan Room, and Control Room. The elements contributing to the life cycle environmental impacts are 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.

The life cycle inventory was modelled using SimaPro software (version 9.6.0.1, Pré Consultants, Amersfoort, The Netherlands) (PRé Sustainability n.d.) in combination with the Ecoinvent 3.10 database (Frischknecht *et al.* 2005).

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-second 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 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). 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 [¹⁸F]FDG PET/CT whole-body 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, assuming continuous operation (24/7). Computers, 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-hour 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 HVAC systems was estimated using official data relating to the trigeneration plant at the San Raffaele Hospital in Milan, available through environmental statements(I.R.C.C.S. Ospedale San Raffaele 2020), energy audits (GKSD ESCo. 2023) and technical reports on the facility's energy requirements (Marzocchi & Piemonte 2017). The plant, located 600 m from the hospital, produces and distributes electricity, hot water, superheated water and chilled water, covering the air conditioning needs of a total area of approximately 290,000 m². In 2020, total consumption for heating and cooling amounted to 214,125 MWh, corresponding to an average requirement of 738 kWh/m² per year, or approximately 2.02 kWh/m² per day. In particular, thermal energy in the form of hot water amounted to 71,843 MWh (247.7 kWh/m² per year), that in the form of superheated water to 74,225 MWh (255.9 kWh/m² per year), while the cooling energy requirement reached 68,057 MWh (234.7 kWh/m² 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 Figure 8. 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 whole-body [^{18}F]FDG PET/CT 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 (I.R.C.C.S. Ospedale San Raffaele 2020).

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-hour 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 categorized by material composition using manufacturer data

when available or estimated based on scientific literature and specialized databases. 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 sterilization 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.

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 timestamped data retrieved from the RIS and 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. Similarly, the transportation of patients and hospital staff to and from the facility was not considered in this analysis.

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 (Huijbregts *et al.* 2017). Finally, 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, recognizing variability in operation across different clinical settings. LCA does not lend itself to statistical methods commonly used in medicine.

Chapter 4

Result and analyses

In this chapter the results from the appended papers are presented in relation of research questions (see section 1.1)

4.1 European survey on radiology staff perceptions of environmental and energy sustainability

A total of 253 valid responses were obtained from a total of 27 European countries. Invalid respondents (n = 82), including participants who did not complete the survey and those who worked in non-European countries, were excluded from the data analysis. The frequency of responses per country is outlined in Table 7.

Table 7: Frequency of survey responses per country with four or more respondents.

Country	No. of Respondents	Responses
Italy	132	52,17%
United Kingdom	16	6,32%
Ireland	15	5,93%
Switzerland	14	5,53%
Portugal	9	3,56%
Malta	8	3,16%
Denmark	7	2,77%
France	5	1,98%
Spain	5	1,98%
Lithuania	4	1,58%
Netherlands	4	1,58%
Slovenia	4	1,58%
Sweden	4	1,58%
Other	26	10,28%
Total	**253 respondents**	**100,00%**

Demographic information of respondents

Most respondents were aged between 18 and 30 years of age (30.4%, n = 77) and between 31 and 40 years of age (30.4%, n = 77), as indicated in Table 8. Professional experience varied; 79 (31.2%) respondents had more than 20 years of professional experience, 68 (26.9%) respondents had 11-20 years' experience, 44 (17.4%) respondents had 6-10 years' experience, 29 (11.5%) respondents had 3-5 years' experience and the remainder (13.0%, n = 33) had less than 2 years' professional experience.

Table 8: Demographic age categories of respondents.

Age	No. of Respondents	Responses
18–30 years	77	30,43%
31–40 years	77	30,43%
41–50 years	47	18,58%
51–60 years	40	15,81%
61–70 years	10	3,95%
Prefer not to say	2	0,79%

Qualifications and specialisations of respondents

All participants were radiographers, therapeutic radiographers or radiographers in training. The majority of respondents were clinical (43.9%, n = 111), followed by specialist (12.7%, n = 32) and student (11.9%, n = 30). The remaining participants were divided between coordinator/service manager, academic/teacher and researchers. Regarding their primary clinical specialties, most respondents (78.8% n = 197) specialise in diagnostic/interventional radiography. This is succeeded by radiotherapy, with 8% (n = 20) of respondents, and nuclear medicine, accounting for 4% (n = 10). Others reported not working in a clinical setting. Diagnostic and therapeutic techniques mainly practiced by respondent were detailed in Table 9.

Table 9: Techniques mainly practiced by respondents.

Country	No. of Respondents	Responses
Computer Tomography	165	65,22%
Conventional radiography	162	64,03%
Magnetic Resonance Imaging	114	45,06%
Angiography/Fluoroscopy	85	33,60%
Mammography	53	20,95%
DXA	33	13,04%
Dental radiography	32	12,65%
Ultrasound	23	9,09%
PET	23	9,09%
External beam Radiotherapy	22	8,70%
Hybrid imaging	18	7,11%
SPECT	16	6,32%
Experimental imaging (phantom/animal models)	5	1,98%
Brachytherapy	5	1,98%
Proton therapy	4	1,58%
I do not work in a clinical setting	16	6,32%

Regarding the employment settings of respondents, 63.2% (n = 168), were employed in public hospitals. This is followed by 19.4% (n = 49) who worked in private hospitals, and 5.5% (n = 14) in research centres. Excluding students (11.9%, n = 30), for most respondents, the highest qualification held was a master's degree (35.2%, n = 89),

with 32.8% (n = 83) holding a bachelor's degree, 15.4% (n = 39) holding a postgraduate diploma or certificate, and 4.7% (n = 12) qualified to doctoral level.

Healthcare system sustainability

Through a VAS, interest in issues related to climate change was investigated, with a minimum range (0) corresponding to the response "Not at all interested" and a maximum range (100) corresponding to "Very interested". Using the same methodology, the importance associated with the issue of environmental sustainability in healthcare was investigated, with a minimum range (0) corresponding to "Not at all important" and a maximum range (100) corresponding to "Very important". The results of these two questions are summarized in Figure 9 and Figure 10, where the data for the second question (median "94", interquartile range "75–100") tend to have higher ratings with slightly less variability than the first set (median "88", interquartile range "70–100"). This could indicate a higher degree of consensus or a generally more positive opinion among the participants regarding the second question.

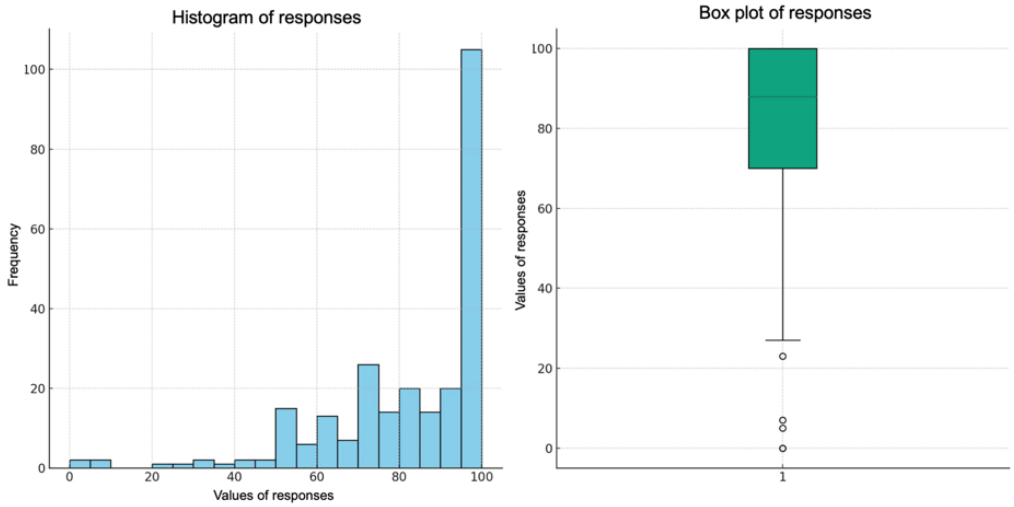


Figure 9: Participants' interest in climate change issues.

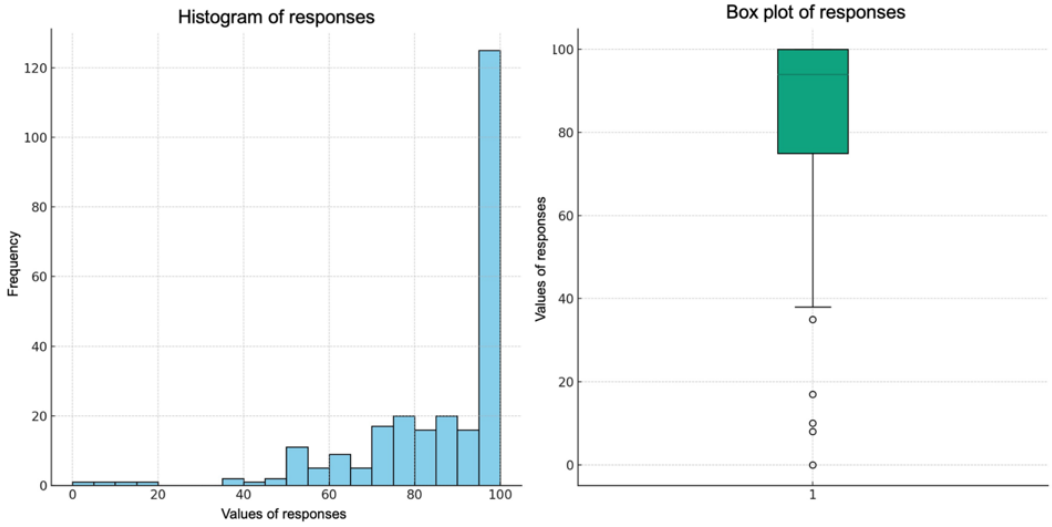


Figure 10: Participants' opinion on the importance for the health system to be environmentally sustainable.

3. Result and analyses

The results from the age-based model indicate that interest in the topic of climate change varies according to age groups. The mean and standard deviations (Mean ± SD) of interest level for the 18-30 age group was 78.84 ± 22.26, and for the 41–50 age group, it was 85.98 ± 16.12. Similarly, concerning the importance attributed to sustainability in healthcare, the mean importance level in the 18-30 age group was 85.62 ± 19.17, while in the 41–50 age group, it was 87.94 ± 14.86. In terms of education level, the lowest mean interest level in climate change was observed among participants with doctoral degrees, at 75.92 ± 13.26, while the highest mean interest level was observed among those with a bachelor's degree, at 83.78 ± 20.07. Regarding the importance of sustainability in healthcare, the lowest mean value was reported by students, at 79.83 ± 23.26, and the highest mean value was associated with participants who have a bachelor's degree, at 88.23 ± 18.52. When asked, “Which of these sources of greenhouse gas emissions from the healthcare sector do you think has the greatest impact on the environment?”, with a maximum of three answers to choose from, the option “Waste generation during operations” was chosen by 79.3% (n = 187) of participants. This was followed by “Processing, use, and end-of-life treatment of solid products or equipment” with 47.3% (n = 120) of participants, and “Direct emissions from company facilities and vehicles” with 41.5% (n = 105) of participants. Asking the same question but narrowing the focus exclusively to the radiological area, the most chosen option was “Energy consumption for lighting, heating, and cooling of work environments” with 67.6% (n = 171) of the participants. This was followed by “Energy consumption of radiological equipment during its use” with 63.6% (n = 161) of the participants, and “Waste generation during operations” with 50.2% (n = 127) of the participants.

Energy consumption of radiology departments

Below 50% participants (41.5%, n = 105) self-reported that they turn off their radiology equipment at the end of their work activity, except for equipment in the emergency department. Meanwhile, 34.4% (n = 87) of participants turn them off every day, and 13.0% (n = 33) do not turn off their equipment at the end of the workday. On the other hand, regarding computers and reporting stations, 40.7% (n = 103) of participants reported that they turn them off at the end of the workday, except for equipment in the emergency department. A total of 31.6% (n = 80) of the participants turn them off every day, and 18.6% (n = 47) do not turn off computers and reporting stations at the end of the workday. The investigation also covered whether radiological equipment is turned off during idle periods (devices “on” but non-productive). 63 participants (24.9%) answered “No, automatic standby”, followed by “No” (24.5%, n = 62) and “Yes, all equipment I use” (22.5%, n = 57). In contrast, almost all participants (81%, n = 205) answered “Yes” when asked if they switch off lights in their work area at the end of the day. Finally, the survey explored participants’ personal perception on what the barriers to switching off equipment in their department might be. The frequency of responses is outlined in Figure 11.

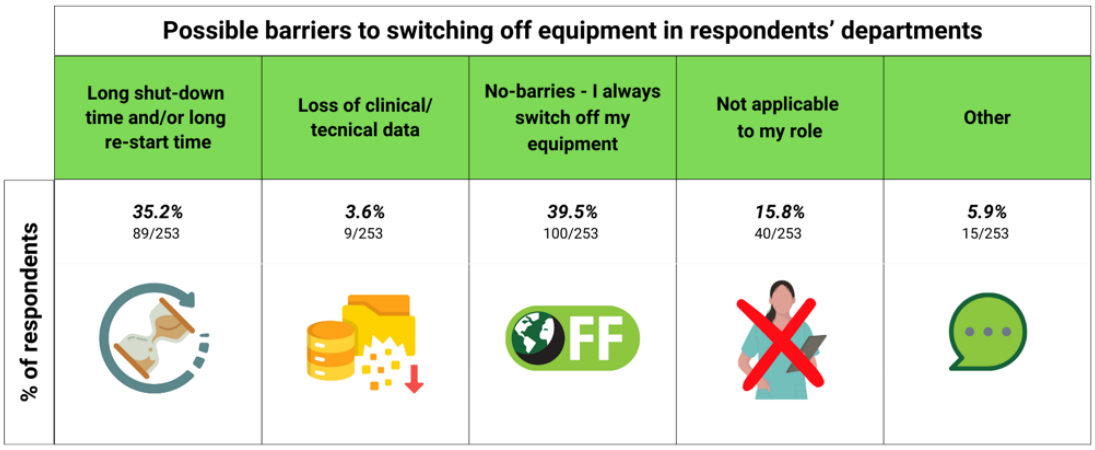


Figure 11: Possible barriers to switching off equipment in respondents' departments.

Emissions from radiography staff travel

The commuting and work-related travel habits of the participants were closely examined. A large portion of the respondents (43.5%, n = 110) travel between 0 and 10 kilometres daily to and from work. A smaller segment, 18.2% (n = 46) of participants, commute more than 41 kilometres each day. The most common modes of transportation among them are public transport (32.0%, n = 81), petrol cars (31.6%, n = 80), diesel cars (24.1%, n = 61), walking (19.7%, n = 50), and bicycles (15.0%, n = 38). When it comes to business travel, such as attending congresses, conferences, seminars, or activities in other hospitals, over half of the participants (50.2%, n = 127) report making between 1 and 2 travels per year. The preferred methods of travel for congresses or conferences are by car (56.9%, n = 144), train (51.4%, n = 130), and airplane (34.8%, n = 88). Specifically, regarding attendance at congresses and conferences, a significant majority, 65.2% (n = 165) of participants, prefer to attend these events in person. Conversely, 28.1% (n = 71) of participants would rather participate virtually. A large portion of the radiographers surveyed (76.8%, n = 194) believe that virtual attendance at conferences can contribute positively to environmental sustainability. The feasibility of working from home within the radiography sector was scrutinized. A substantial majority, over 81% (n = 205) of participants, expressed that remote work was not applicable to their roles. Only 2% (n = 5) cited the main barriers to remote work as being due to inadequate technology at home or an unsuitable home environment. Additionally, participants were queried about the potential for conducting CT and MRI examinations remotely. More than half of the participants (56.1%, n =142) were unaware of such possibilities. Despite the lack of awareness, 51.4% (n = 130) of respondents reported the personal perception that conducting MRI and CT examinations remotely would not be feasible or practical within their departments. Conversely, 44.7% (n = 113) participants believe that remote execution of these examinations could beneficially impact the climate footprint in the radiology sector (Figure 12).

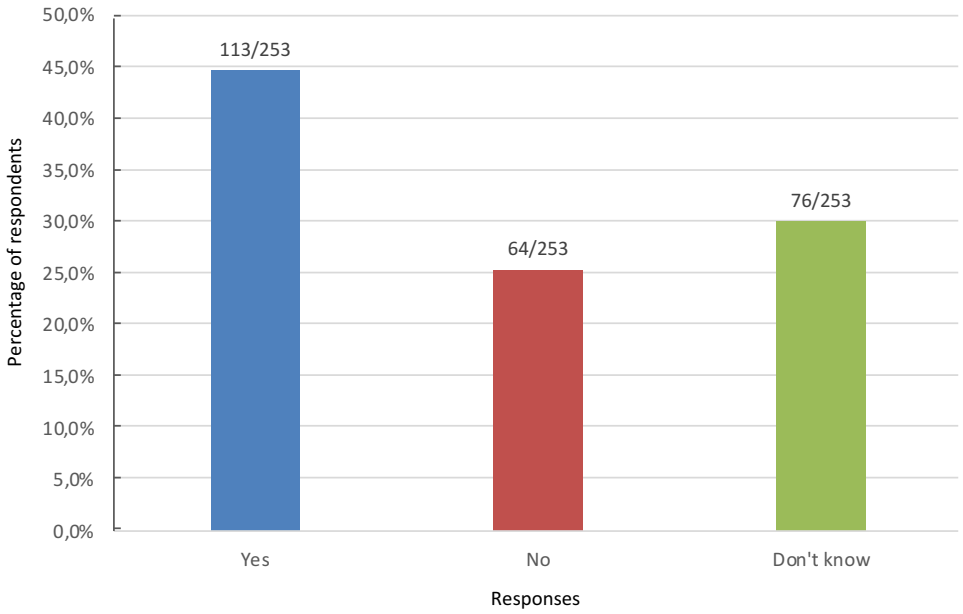


Figure 12: Participants' responses to the question "Do you think remote CT and MRI examinations can help reduce the climate footprint in the radiology area?"

Waste generation from radiological activities

Personal perception of what the primary sources of waste generation are in the respondents' departments were analysed, as depicted in Figure 13.



Figure 13: Main sources of waste generation in the respondents' departments.

Furthermore, opinion of what are the categories of waste most frequently recycled within these departments are illustrated in Figure 14. The primary obstacles preventing radiology and radiotherapy departments from implementing waste recycling programs, as identified by the participants' opinions, include the non-availability of

recycling bins in departments (41.5%, n = 105), a lack of staff training (36.0%, n = 91), and product packaging that is not conducive to recycling (28.9%, n = 73). Respondents were surveyed about their views on the recovery and recycling of contrast agents from waste and patients. 63.6% (n = 161) of the survey participants were unaware of the potential to reclaim iodine- and gadolinium-based contrast agents used in CT and MRI procedures. Nevertheless, a significant majority, 78.7% (n = 199), believed that programs aimed at recovering contrast agents from waste and patients could enhance the environmental sustainability of radiology. Furthermore, 52.6% of the participants (n = 133) considered that a contrast agents recovery program could be viable within their departments.

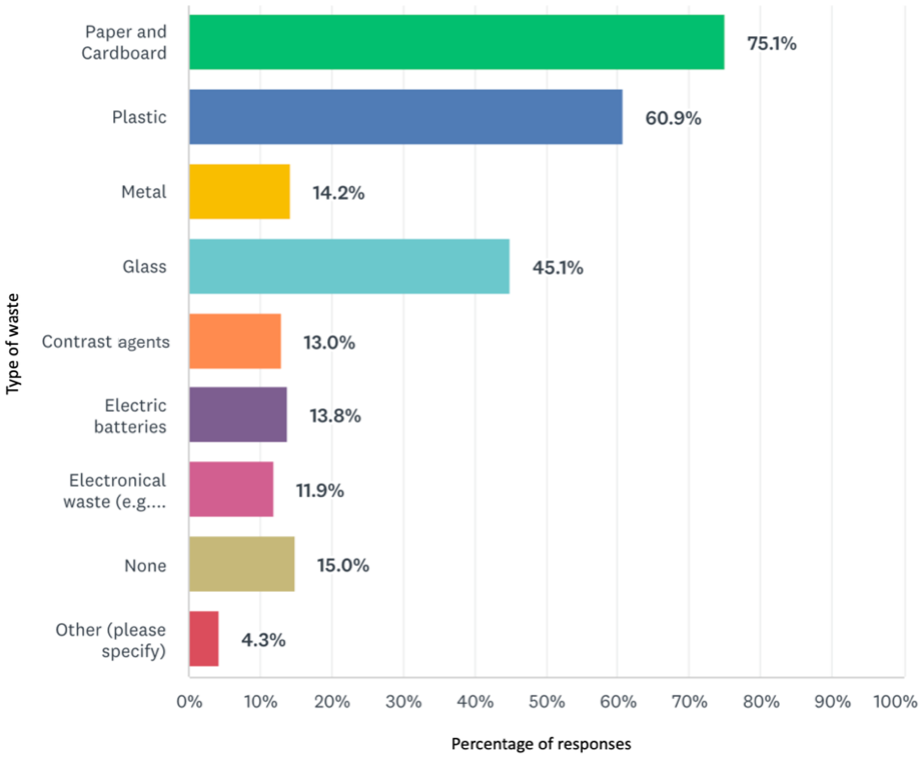


Figure 14: Types of waste most frequently recycled in respondents' departments.

Radiographers' and therapeutic radiographers' role

Regarding the various topics of environmental sustainability examined (energy consumption, staff travel, and waste generation), participants were asked about their perceived contribution of these aspects to the total emissions of their departments. For "energy consumption", the option "over 40%" was the most selected by the participants (17.8%, n = 45). In the case of "staff travel", the most chosen option was "0-10%" (24.5%, n = 62), and for "waste generation", the option "21-30%" was most frequently selected by the respondents (17.0%, n = 43). The majority (66.0%, n = 167) of the participants perceived that environmental sustainability procedures or protocols are either absent in their workplace or that they are unaware of their existence. However, 30% (n = 76) believed that introducing such protocols might be beneficial. A further 8.3% (n = 21) of the participants indicated that although protocols are in place, they are not followed by the staff. Among the environmental sustainability actions implemented, where present, participant self-reported that the most common include reducing energy consumption (39.5%, n = 100), improving waste recycling (38.7%, n = 98), and reducing waste production (24.9%, n = 63).

Almost all survey participants (96.1%, n = 243) believe that radiographers can play an active role in environmental sustainability programs within their departments. The perception of their importance is practically divided, with opinions nearly evenly split between “a limited role” and “a primary role”. Among the actions identified where radiographers could significantly contribute to reducing environmental emissions, “reducing energy consumption” was recognised by 80.6% (n = 204) of participants, “improving waste recycling” by 73.5% (n = 186) of participants, and “reducing waste production” by 58.9% (n = 149) of participants.

4.2 Energy consumption assessment and savings estimation in a radiology department in northern Italy

First, the energy usage of radiology department was estimated. The total number of daily imaging examinations is 489, divided into 2.0% CBCT, 16.4% CT, 2.3% DXA, 6.5% MG, 6.5% MRI, 72% MCXR, 17.4% US and 41.7% XR. All imaging equipment in the department stayed in idle mode for a portion of the working time (Table 1) ranging from 8% time in idle period for XR2 and XR4 to 96% for MG2. The equipment that showed very dense schedules with idle periods of less than 20% during daily work were XR2, XR4 and MRI2. The imaging scanners that spend a significant amount of working time in idle periods are MCXR2 (84%), XR5 (92%), MCXR1 (93%) and MG2 (96%). Among the workstations, those with the most time spent in idle period are the RIS/PACS workstations with an average of 43%. The estimation of the energy usage of each imaging scanners can be found in detail in the Table 2. In operational unit of radiology, MG2 is the scanner that used the least energy per day during the active period (1.3 kWh). Regarding idle period, XR2 and XR4 used the least energy (0.7 kWh). MRI2 is the scanner that used the highest amount of energy during both the active period (243.2 kWh) and idle period (47.5 kWh), followed by MRI1 (110.2 kWh during active period and 28.2 kWh during idle period) and CT (45.9 kWh during active period and 12.4 kWh during idle period).

Furthermore, when analysing the impact of the energy used during idle periods compared to the total daily energy usage of each device, the imaging modalities with the highest non-productive energy usage were MG2 (91 %), XR5 (78 %), CBCT (55 %) and DXA (49 %) (Figure 15).

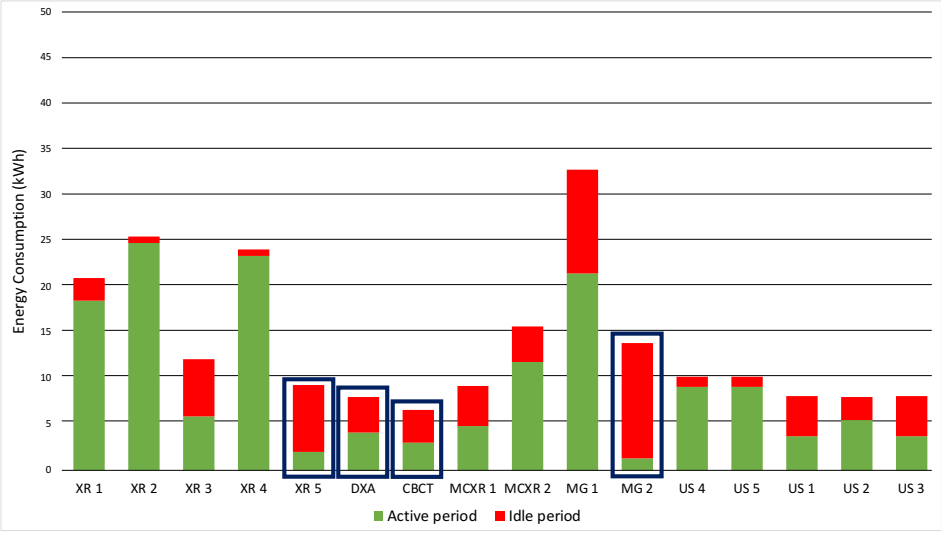


Figure 15: Energy usage for each imaging modality (active period and idle period during a working day). Modalities with high energy waste during idle period are contoured.

Mean energy usage for each imaging modality for the active period and idle periods is summarized in Figure 16.

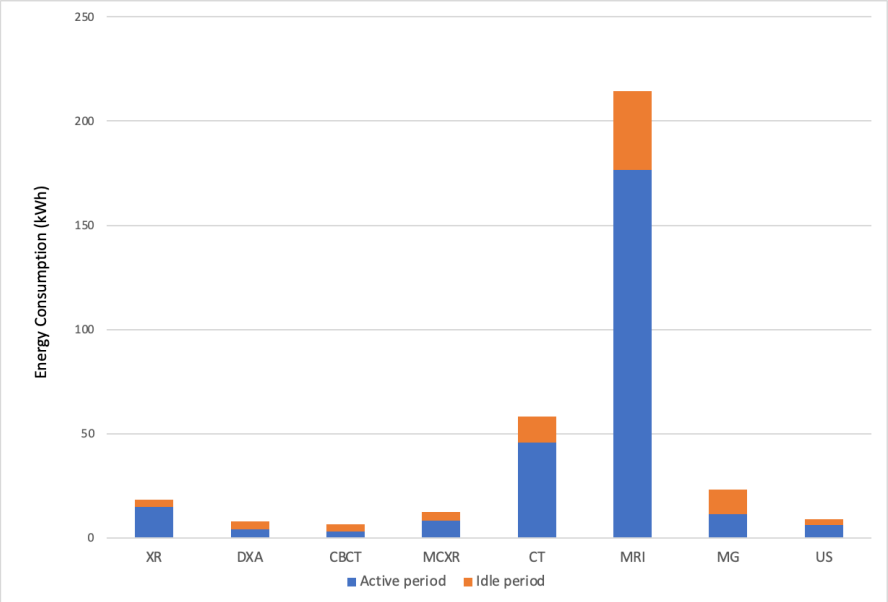


Figure 16: Mean energy consumption (kWh) for each imaging modality (active period and idle period during a working day).

Considering the mean energy consumption for each diagnostic modalities, CBCT modality has the lowest daily energy usage (6.6 kWh), followed by DXA (8 kWh), US (8.9 kWh), MCXR (12.5 kWh), XR (18.4 kWh) and MG (23.4 kWh). The diagnostic modalities with the highest mean daily energy usage are CT (58.3 kWh) and MRI (214.6 kWh). In total, it was estimated that all radiological device modalities in the department consume 710.2 kWh per day, divided in 551.5 kWh (78 %) during the active period and 158.7 kWh (22%) during the non-productive idle period.

The energy used by the workstations was considered for all devices in the department (Table 4, section 3.2.2.). Overall, the highest energy usage is associated to the RIS/PACS workstations in the operating unit of radiology (active period = 55.0 kWh; idle period = 46.8 kWh; stand-by period: 4.3 kWh). Concerning the workstations, the total energy usage during daily work is estimated at 167.3 kWh, divided into 100.5 kWh (60.1%) during active period, 58.8 kWh (35.1%) during idle period and 8 kWh (4.8%) during standby period. In total, the department's energy usage was estimated at 877.5 kWh during the daily work activity.

Mitigation strategies

Based on the energy usage data estimated, in March 2023, three different mitigation strategies were proposed and evaluated by an audit committee composed by radiographers, radiologists and clinical engineers of the hospital in the radiology department, considering the needs of the radiology staff. Proposed mitigations strategies were summarized in Figure 17.

3. Result and analyses

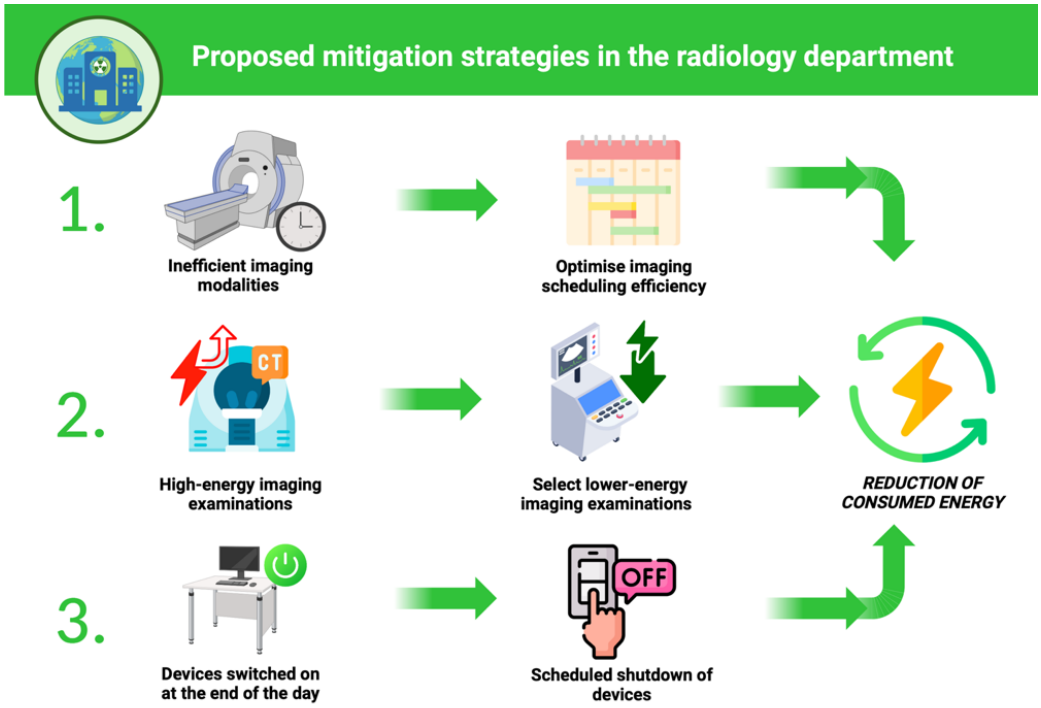


Figure 17: Proposed mitigation strategies in the radiology department.

Mitigation strategy 1: Optimize imaging scheduling efficiency

Based on the results of the energy usage analysis of the imaging modalities for active and idle periods, the most energy inefficient imaging modalities will be identified, and energy waste mitigation strategies will be formulated to optimize the efficiency of imaging scheduling. In the ratio of active period to idle period, as shown above, the greatest energy inefficiencies concern the imaging modalities XR5, CBCT, MCXR1, MG2. In response, four direct interventions to optimize imaging scheduling efficiency were identified:

1. Reduction of XR5 activity from 5 to 3 working days, redistributing exams on scheduled days.
2. Reduction of CBCT activity times based on the number of patients booked and early closure of diagnostics at the end of scheduled activity.
3. Redistribution of MG1 mode activity to MG2, keeping both modes active.
4. Exclusive use of MCXR2, keeping MCXR1 switched off, concentrating activity on a single device.

The results of this mitigation strategy can be seen in Table 10. In summary, an increase of 3.0% in energy used during the active period, a reduction of 38.3% in energy usage during the non-productive idle phase, and a total reduction of 16.6% in the total energy used per day were achieved.

Table 10: Results of mitigation strategy 1: optimize imaging scheduling efficiency.

	Active period before (kwh)	Active period after (kwh)	Δ active period (%)	Idle period before (kwh)	Idle period after (kwh)	Δ idle period (%)	Total energy before (kwh)	Total energy after (kwh)	Δ total energy (%)
XR5	**2**	**3.6**	**80.0%**	**7.3**	**6.2**	**-15.1%**	**9.3**	**9.8**	**5.4%**
CBCT	**3**	**3.7**	**23.3%**	**3.6**	**0.0**	**-100%**	**6.6**	**3.7**	**-44.0%**
MG1	21.5	11.6	-46.0%	11.4	8.3	-27.2%	32.9	19.9	
MG2	1.3	11.6	792.3%	12.6	8.3	-34.1%	13.9	19.9	
Total MG	**22.8**	**23.2**	**1.8%**	**24**	**16.6**	**-30.8%**	**46.8**	**39.8**	**-15.0%**
MCXR2	11.8	16.3	38.1%	3.9	3.6	-7.7%	15.7	19.9	
MCXR1	4.8	0.0	-100 %	4.4	0.0	-100 %	9.2	0.0	
Total MCXR	**16.6**	**16.3**	**-1.8%**	**8.3**	**3.6**	**-56.6%**	**24.9**	**19.9**	**-20.1%**
Total Modalities	**83.8**	**86.3**	**3.0%**	**75.5**	**46.6**	**-38.3%**	**159.3**	**132.9**	**-16.6%**

Mitigation strategy 2: Select lower-energy imaging examinations

Considering emergency activities of the unit of radiology, it was identified that for patients affected by abdominal pain, both XR and CT scans were frequently used for diagnosis. However, according to the guidelines of the American College of Radiology Appropriateness Criteria (American College of Radiology 2024), ultrasound imaging could serve as an equally appropriate diagnostic alternative. A retrospective evaluation was conducted to explore the feasibility of substituting US imaging for XR and CT in these cases, to achieve a potential reduction in energy usage. For this analysis, a sample of 41 diagnostic investigations performed for different types of abdominalgia was taken, identifying the diagnostic strategy performed and its low-energy alternative with equal diagnostic appropriateness, and identifying total energy usage. The results of this mitigation strategy are shown in Table 11. In overview, the adoption of low-energy diagnostic strategies with equal diagnostic appropriateness can lead to a -80.4% reduction in energy used in 41 different diagnostic investigations.

Table 11: Results of mitigation strategy 2: Select lower-energy imaging examinations.

Num. Exams	Clinical Question	Diagnostic strategy performed	Low-energy alternative	Actual energy consumption (kWh)	Alternative energy consumption (kWh)	Δ Total energy (%)
22	Generic abdominal pain	XR	US	77	24.2	-68.6%
5	Renal colic	XR + CT	US + XR	99.5	23	-76.9%
6	Air-fluid levels	XR + CT	US + XR	119.4	27.6	-76.9%
8	Chronic hepatitis	CT	US	131.2	8.8	-93.3%
Total: 41				**427.1**	**83.6**	**-80.4%**

Mitigation strategy 3: Scheduled shutdown of devices

Based on the results of the analysis of the energy usage of the workstations, the energy waste mitigation strategy will be planned through the scheduled switch-off of all workstations at the end of the working day in the radiology unit. Among the calculated energy usage, one of the critical issues is the high energy usage of the RIS/PACS workstations during the non-productive idle and stand-by periods. The results of this energy waste mitigation strategy can be seen in the Table 7. After implementation of the mitigation strategy, there was a 43.3 % reduction in energy used by RIS/PACS workstations in the radiology unit.

Table 12: Results of mitigation strategy 3: Scheduled shutdown of devices.

	Active Before (kWh)	Active After (kWh)	Idle Before (kWh)	Idle After (kWh)	Stand-by Before (kWh)	Stand-by After (kWh)	Total energy Before (kWh)	Total energy After (kWh)	Δ Total energy (%)
WS (n= 27)	55.0	45.3	46.7	5.5	4.3	9.3	**106.0**	**60.1**	**-43.3%**

4.3 Replacement of magnetic resonance imaging equipment and validation of environmental product declarations

Old model MRI

In the last two weeks of its decommissioning, a total of 153 MRI diagnostic examinations were performed with the Siemens Healthineers MRI scanner 1.5T Magnetom Aera. For one day, clinical activity was suspended to perform quality checks by the department's medical physics (not included in the energy calculations). The total energy consumption for a two-week of activity was 4309.6 kWh. The peak power consumption of the scanner, analysed per aggregated daily maxima, was 48.7 kW ± 13.4 (range 7.3 – 60.5 kW), while the minimum power measured 11.8 kW ± 0 during idle state and was 7.3 kW ± 0 during stand-by state. The average daily energy consumption for the scanner was 307.8 kWh. In total, the MRI scanner consumed 2284.9 kWh during the active state, 633.5 kWh during the idle state, and 1391.2 kWh during the stand-by state, over the two weeks of the observation (Table 13). Stand-by state accounted 32% of the total energy consumption owing to the continuous operation of the cold head cooling system. MRI idle state energy consumption accounted 15% of the total energy consumption.

New model MRI

In the first two weeks of its installation, a total of 180 MRI examinations were performed with the Siemens Healthineers MRI scanner 1.5T Magnetom Sola. The total energy consumption for a two-week of activity was 3886.0 kWh. The peak power consumption of the scanner, analysed per aggregated daily maxima, was 47.8 kW ± 7.7 (range 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, the MRI scanner consumed 2243.1 kWh during the active state, 384.1 kWh during the idle state, and 1258.8 kWh during the stand-by state, over the two weeks of the observation (Table 13). Stand-by state accounted 32% of the total energy consumption owing to the continuous operation of the cold head cooling system. MRI idle state energy consumption accounted 10% of the total energy consumption.

Table 13: Distribution of MRI energy consumption and power according to type activity states of scanners, with additional technical and operational characteristics.

Model	Characteristics	Energy consumption (kWh)							Power (kW)					
						Daily			Power peak demand				Idle State Minimum power	Standby State Minimum power
		Active state	Idle state	Standby state	Total	Median	Mean	SD	Maximum	Median	Mean	SD		
1.5T MRI scanner Magnetom Aera	Software: VA50A Gradient: 625A/2000 V RF amplifier: 26.1 kW Commercial release: 2010 Installed at hospital: 2013	2284.9	633.5	1391.2	4309.6	321.0	307.8	66.1	60.5	52.3	48.7	13.4	11.8	7.3
1.5T MRI scanner Magnetom Sola	Software: XA61 Gradient: 625A/2000 V RF amplifier: 29.2 kW Commercial release: 2018 Installed at hospital: 2024	2243.1	384.1	1258.8	3886.0	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%**

Comparison between different activity states of two models

The comparison between the two MRI scanner models is summarised in Table 13. Overall, during different operating states, the reduction is -2% in the active phase, -39% in the idle phase, and -10% in the standby phase. Similarly, when looking at average daily consumption, there is an -10% decrease between the two MRI scanner models. 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 54,4kW). The minimum power in waiting mode decreases by -19% and in standby mode by -11%.

10-years 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 1206.7 MWh for the old MRI model and 1010.4 MWh for the new model. However, to account for the presence of a routine physical quality check interval during the monitoring of the old MRI model, 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 ten years amounts to 2,292.7.0 MWh for the old model and 1,919.7 MWh for the new model. When applying the individual national PEFs reported across EU member states, the ten-year primary energy consumption for the old model ranges from 1448.0 MWh (minimum) to 4223.4 MWh (maximum), with an average value of 2775.4MWh. For the new model ten-year primary energy consumption ranges from 1212.4 MWh (minimum) to 3536.3 MWh (maximum), with an average value of 2323.8 MWh. This results 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 contextualise the results, Table 14 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 Aera to -33.2% for the 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.

Table 14: 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). 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.

Model	Source	PEF	10-year primary energy demand (MWh)	Difference from EPD (%)
MAGNETOM AERA	EPD	N/A	3680.0	Reference
	Field data	1.20 (min)	1448.0	-60.7%
	Field data	1.90 (EU)	2292.7	-37.7%
	Field data	2.30 (avg)	2775.4	-24.6%
	Field data	3.50 (max)	4223.4	+14.8%
MAGNETOM SOLA	EPD	N/A	2874.0	Reference
	Field data	1.20 (min)	1212.4	-57.8%
	Field data	1.90 (EU)	1919.7	-33.2%
	Field data	2.30 (avg)	2323.8	-19.2%
	Field data	3.50 (max)	3536.3	+23.0%

4.4 Life cycle assessment of PET/CT imaging with [^{18}F]FDG in a nuclear medicine department

In paper III, through the results of the literature review, a LCA framework, depicted in Figure 18, 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 (Andrews *et al.* 2013), 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.

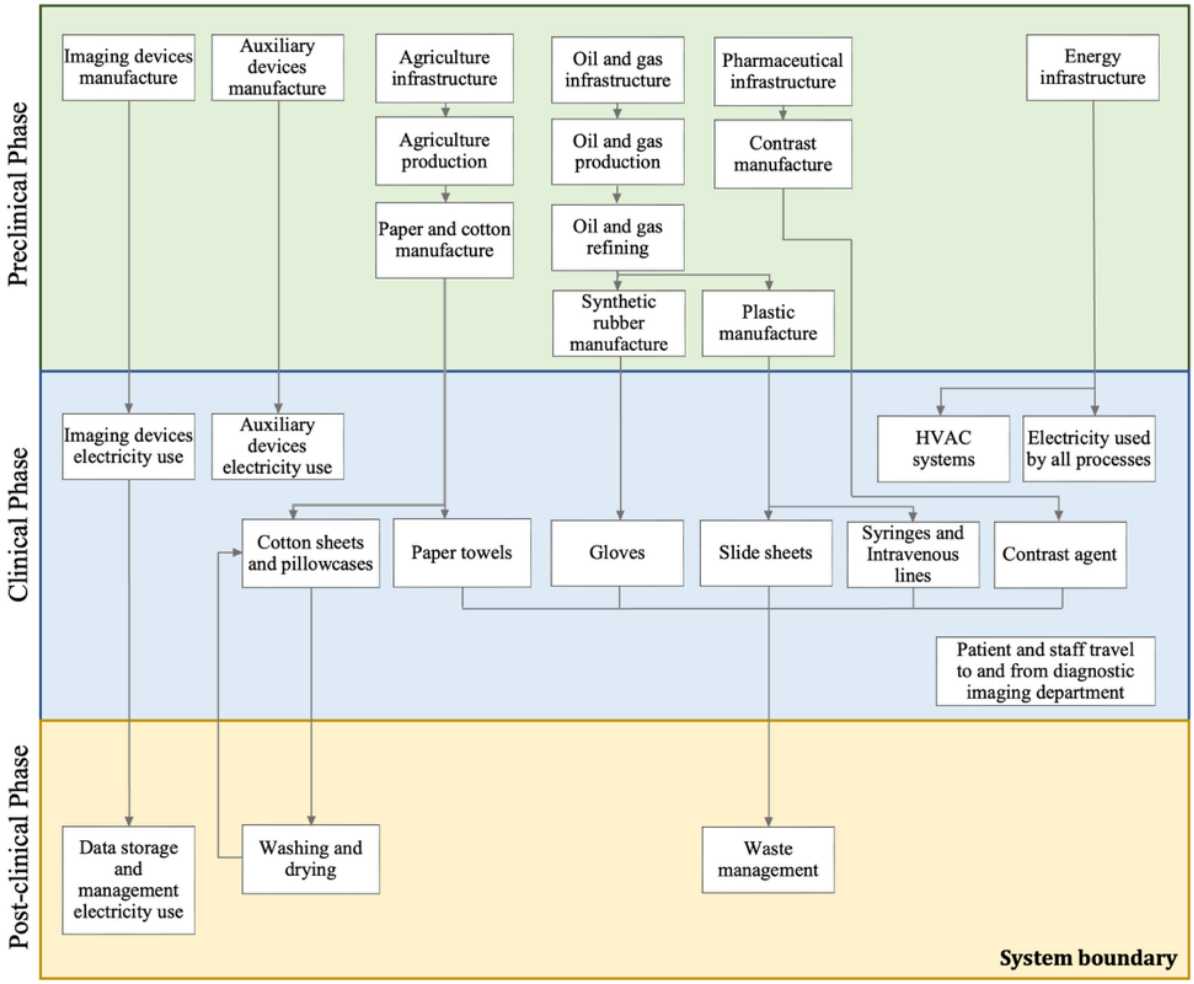


Figure 18: Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging.

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 (Gardezi *et al.* 2021; Sartori *et al.* 2021; Schneider *et al.* 2023; Wu *et al.* 2023). 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.

The LCA framework developed and formalized in *Paper III* was subsequently applied in *Paper IV*, adapting it to the specific context of the Nuclear Medicine Department at San Raffaele Hospital. This application enabled a detailed quantification of the environmental impact associated with a standard whole-body [^{18}F]FDG PET/CT

procedure, encompassing both the direct phases of the examination (radiopharmaceutical production, image acquisition, and reporting) and the indirect contributions related to departmental infrastructure and organizational aspects. The purpose of this study was to validate the proposed LCA framework in a real-world clinical setting, to identify the main hotspots within the diagnostic process, and to explore potential mitigation strategies aimed at reducing the environmental burden of hybrid nuclear medicine imaging.

Life Cycle Impact Assessment per Scan

Each whole-body [18F]FDG PET/CT scan has a life cycle Global Warming Potential (GWP) of approximately 7.6 kg CO_2 eq (Table 15). This GHG emission per scan falls within the broad range reported for advanced imaging modalities in the literature and underscores the importance of understanding emissions 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.

Table 15: Life Cycle Impact Assessment Results per [18F]FDG PET/CT Scan. Environmental impact results for a single [18F]FDG PET/CT VMT scan, based on the ReCiPe 2016 Midpoint (H) method. eq: equivalent; kg: kilograms; m³: 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; m²a 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

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. Result and analyses

Component Contributions to GWP

A detailed breakdown of the GWP per scan by component was provided in Table 16. As illustrated in Figure 19, 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.

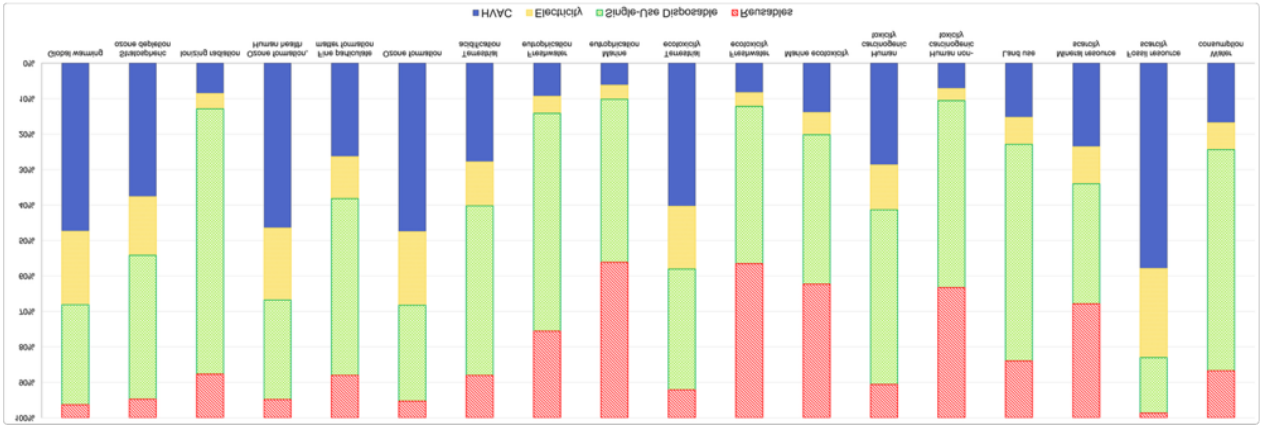


Figure 19:Life cycle impact category contributions by major component for a single [^{18}F]FDG PET/CT scan. Stacked bar chart showing the percentage contribution of four main components: HVAC (plain blue), Electricity (yellow horizontal lines), Single-Use Disposable (green grid), and Reusables (red diagonal lines), to each impact category assessed using the ReCiPe 2016 Midpoint (H) method.

Among all the components, building operational energy, particularly the HVAC required to maintain climate control within the PET/CT suite, emerged as the dominant contributor to GWP and most other midpoint indicators (Tables 17). 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 (Figure 20, Tables 17, Tables 18). 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 (Table 19).

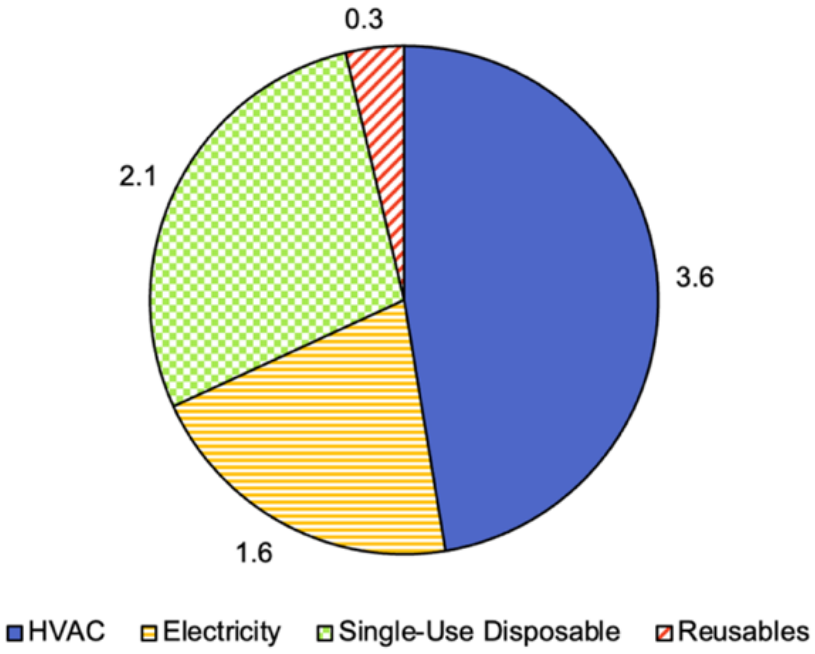


Figure 20: Breakdown of life cycle GHG emissions, expressed in kg CO_2-equivalent, per [18F]FDG PET/CT scan. The chart shows the relative contributions of major system components: HVAC (plain blue), Electricity (yellow horizontal lines), Single-Use Disposables (green grid), and Reusables (red diagonal lines).

In contrast, the direct electricity consumption by imaging equipment during the scan represents a comparatively minor share of total impacts. The total energy consumed by PET/CT scanner during the week of the study amounted to 964.5 kWh, of which 87.8 kWh per week was consumed during the scanning phases for all full-body [18F]FDG PET/CT considered (Table 20). Each individual scan uses approximately 1.6 kWh, equating to roughly 3.7% (0.6 kg CO_2 eq.) of GWP. 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% (Figure 20, Tables 17, Tables 18). This distribution of impact is largely consistent across other environmental categories. Energy consumption, especially from HVAC and cyclotron-related processes, not only dominates GWP but also drives impacts in fine particulate matter formation, photochemical ozone creation, and fossil resource depletion. In comparison, impacts related to material inputs and waste management were relatively modest, highlighting the predominant roles of building energy use and radiotracer production in the scan's overall carbon footprint.

3. Result and analyses

Table 16: Full LCA results for the [^{18}F]FDG PET/CT whole body scan; upper=absolute numbers, lower= % of modality total.

Impact Category	Unit	Total	Sterile gauze	Gloves	Electricity, GE OMNI legend PET/CT	Hypodermic needle with cannula	Sterile physiological saline solution	Packaging disposable	Disposable lancet and glucometer needle	Needle securing tape	Lancet	3-way stopcock	Disposable syringe	Disposable spiral INTEGO	Climate system Injection room	Climate system PET room	Coflex bandage	Computers	Electricity computers, monitors and printer
Global warming	kg CO2 eq	7,623	0,042	0,079	0,415	0,015	0,163	0,058	0,026	0,034	0,019	0,153	0,042	0,268	0,249	1,249	0,128	0,081	0,059
Stratospheric ozone depletion	kg CFC11 eq	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ionizing radiation	kBq Co-60 eq	0,162	0,002	0,008	0,002	0,001	0,010	0,003	0,002	0,001	0,001	0,010	0,002	0,015	0,001	0,005	0,007	0,007	0,000
Ozone formation, Human health	kg NOx eq	0,015	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,000	0,000	0,000
Fine particulate matter formation	kg PM2.5 eq	0,005	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,017	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,003	0,000	0,000	0,000
Terrestrial acidification	kg SO2 eq	0,011	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,001	0,000	0,000	0,000
Freshwater eutrophication	kg P eq	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Marine eutrophication	kg N eq	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Terrestrial ecotoxicity	kg 1,4-DCB	58,412	0,252	0,676	2,708	0,325	0,872	0,372	0,327	0,311	0,127	3,633	0,307	2,643	1,625	8,158	0,829	2,049	0,387
Freshwater ecotoxicity	kg 1,4-DCB	0,258	0,004	0,008	0,002	0,001	0,005	0,003	0,003	0,002	0,001	0,007	0,002	0,011	0,001	0,007	0,004	0,043	0,000
Marine ecotoxicity	kg 1,4-DCB	0,397	0,004	0,011	0,006	0,002	0,008	0,005	0,004	0,002	0,001	0,012	0,004	0,017	0,004	0,019	0,007	0,058	0,001
Human carcinogenic toxicity	kg 1,4-DCB	1,320	0,005	0,013	0,044	0,020	0,017	0,008	0,081	0,004	0,014	0,020	0,044	0,032	0,026	0,131	0,022	0,061	0,006
Human non-carcinogenic toxicity	kg 1,4-DCB	4,497	0,072	0,163	0,037	0,019	0,119	0,077	0,037	0,035	0,018	0,142	0,042	0,241	0,022	0,111	0,105	0,624	0,005
Land use	m2a crop eq	0,153	0,024	0,004	0,003	0,000	0,004	0,002	0,001	0,001	0,000	0,004	0,001	0,006	0,002	0,008	0,003	0,005	0,000
Mineral resource scarcity	kg Cu eq	0,020	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,002	0,000	0,003	0,000
Fossil resource scarcity	kg oil eq	4,946	0,009	0,036	0,329	0,004	0,053	0,024	0,007	0,009	0,006	0,049	0,013	0,079	0,197	0,990	0,044	0,020	0,047
Water consumption	m3	0,073	0,018	0,001	0,001	0,000	0,002	0,001	0,000	0,000	0,000	0,001	0,000	0,002	0,001	0,004	0,001	0,001	0,000

Impact Category	Unit	Total	Electricity, MEDRAD® Intego PET Infusion System	INTEGO Source administration set	Keyboard	Laundering	Lighting	Linens	Climate system control room	Monitor	Mouse	Blood filter needle	Plastic and Glass container	Printer	Radiotracer vial	Saniwipes	Electricity cyclotron	Climate system cyclotron
Global warming	kg CO2 eq	7,623	0,012	0,098	0,011	0,019	0,039	0,016	0,438	0,159	0,002	0,204	0,672	0,014	0,037	0,108	1,037	1,677
Stratospheric ozone depletion	kg CFC11 eq	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ionizing radiation	kBq Co-60 eq	0,162	0,000	0,005	0,001	0,001	0,000	0,001	0,002	0,011	0,000	0,011	0,034	0,000	0,002	0,006	0,004	0,006
Ozone formation, Human health	kg NOx eq	0,015	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,000	0,002	0,000	0,000	0,000	0,002	0,003
Fine particulate matter formation	kg PM2.5 eq	0,005	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,001
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,017	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,000	0,002	0,000	0,000	0,000	0,002	0,004
Terrestrial acidification	kg SO2 eq	0,011	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,002	0,000	0,000	0,000	0,001	0,001
Freshwater eutrophication	kg P eq	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Marine eutrophication	kg N eq	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Terrestrial ecotoxicity	kg 1,4-DCB	58,412	0,081	0,895	0,166	0,134	0,252	0,099	2,860	2,102	0,032	1,341	5,964	0,165	0,217	0,786	6,770	10,950
Freshwater ecotoxicity	kg 1,4-DCB	0,258	0,000	0,006	0,006	0,001	0,000	0,001	0,003	0,056	0,001	0,010	0,030	0,004	0,005	0,012	0,006	0,010
Marine ecotoxicity	kg 1,4-DCB	0,397	0,000	0,008	0,008	0,001	0,001	0,001	0,007	0,075	0,002	0,015	0,045	0,005	0,007	0,016	0,016	0,026
Human carcinogenic toxicity	kg 1,4-DCB	1,320	0,001	0,092	0,005	0,003	0,004	0,002	0,046	0,051	0,001	0,139	0,118	0,005	0,004	0,017	0,109	0,176
Human non-carcinogenic toxicity	kg 1,4-DCB	4,497	0,001	0,099	0,092	0,014	0,003	0,023	0,039	0,859	0,022	0,192	0,692	0,033	0,100	0,218	0,092	0,150
Land use	m2a crop eq	0,153	0,000	0,002	0,001	0,001	0,000	0,010	0,003	0,008	0,000	0,005	0,032	0,000	0,002	0,002	0,007	0,011
Mineral resource scarcity	kg Cu eq	0,020	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,003	0,000	0,001	0,002	0,000	0,000	0,000	0,001	0,002
Fossil resource scarcity	kg oil eq	4,946	0,010	0,030	0,003	0,006	0,031	0,003	0,347	0,039	0,001	0,065	0,281	0,002	0,009	0,054	0,822	1,329
Water consumption	m3	0,073	0,000	0,001	0,000	0,000	0,000	0,008	0,001	0,001	0,000	0,001	0,006	0,000	0,000	0,011	0,004	0,006

Impact Category	Unit	Total	Sterile gauze	Gloves	Electricity, GE OMNI legend PET/CT	Hypodermic needle with cannula	Sterile physiological saline solution	Packaging disposable	Disposable lancet and glucometer needle	Needle securing tape	Lancet	3-way stopcock	Disposable syringe	Disposable spiral INTEGO	Climate system Injection room	Climate system PET room	Coflex bandage	Computers	Electricity computers, monitors and printer
Global warming	kg CO2 eq	100,00%	0,55%	1,04%	5,44%	0,20%	2,14%	0,76%	0,34%	0,45%	0,25%	2,01%	0,55%	3,51%	3,26%	16,39%	1,68%	1,06%	0,78%
Stratospheric ozone depletion	kg CFC11 eq	100,00%	5,36%	0,78%	4,33%	0,17%	1,41%	0,38%	0,21%	1,51%	0,15%	1,12%	0,32%	2,50%	2,60%	13,03%	0,80%	0,86%	0,62%
Ionizing radiation	kBq Co-60 eq	100,00%	1,40%	4,66%	0,98%	0,57%	6,27%	2,06%	0,98%	0,83%	0,59%	6,29%	1,29%	9,30%	0,59%	2,96%	4,31%	4,03%	0,14%
Ozone formation, Human health	kg NOx eq	100,00%	0,72%	1,02%	5,34%	0,17%	1,62%	0,69%	0,28%	0,38%	0,19%	1,61%	0,42%	2,76%	3,20%	16,07%	1,37%	1,61%	0,76%
Fine particulate matter formation	kg PM2.5 eq	100,00%	1,72%	1,66%	3,03%	0,44%	2,80%	1,09%	0,61%	0,77%	0,36%	2,88%	0,79%	4,95%	1,82%	9,12%	2,38%	3,73%	0,43%
Ozone formation, Terrestrial ecosystems	kg NOx eq	100,00%	0,64%	1,03%	5,45%	0,16%	1,56%	0,69%	0,26%	0,36%	0,19%	1,55%	0,40%	2,65%	3,27%	16,43%	1,36%	1,47%	0,78%
Terrestrial acidification	kg SO2 eq	100,00%	2,69%	1,68%	3,20%	0,31%	2,73%	0,98%	0,47%	0,72%	0,31%	2,82%	0,68%	4,55%	1,92%	9,63%	2,26%	3,41%	0,46%
Freshwater eutrophication	kg P eq	100,00%	2,69%	1,89%	1,07%	0,43%	2,91%	4,40%	0,67%	1,04%	0,40%	4,17%	0,89%	5,87%	0,64%	3,23%	3,19%	7,52%	0,15%
Marine eutrophication	kg N eq	100,00%	29,58%	0,55%	0,71%	0,10%	0,58%	2,26%	0,16%	0,27%	0,08%	0,75%	0,19%	1,27%	0,43%	2,15%	0,54%	0,78%	0,10%
Terrestrial ecotoxicity	kg 1,4-DCB	100,00%	0,43%	1,16%	4,64%	0,56%	1,49%	0,64%	0,56%	0,53%	0,22%	6,22%	0,53%	4,52%	2,78%	13,97%	1,42%	3,51%	0,66%
Freshwater ecotoxicity	kg 1,4-DCB	100,00%	1,43%	3,02%	0,96%	0,44%	2,13%	1,30%	1,04%	0,64%	0,38%	2,70%	0,93%	4,37%	0,57%	2,88%	1,70%	16,59%	0,14%
Marine ecotoxicity	kg 1,4-DCB	100,00%	1,02%	2,72%	1,60%	0,45%	2,01%	1,21%	1,00%	0,61%	0,36%	3,09%	0,89%	4,31%	0,96%	4,81%	1,64%	14,56%	0,23%
Human carcinogenic toxicity	kg 1,4-DCB	100,00%	0,36%	1,00%	3,30%	1,55%	1,30%	0,60%	6,11%	0,34%	1,05%	1,52%	3,30%	2,39%	1,98%	9,93%	1,64%	4,60%	0,47%
Human non-carcinogenic toxicity	kg 1,4-DCB	100,00%	1,59%	3,61%	0,82%	0,41%	2,64%	1,71%	0,81%	0,78%	0,41%	3,15%	0,94%	5,36%	0,49%	2,48%	2,34%	13,87%	0,12%
Land use	m2a crop eq	100,00%	15,81%	2,43%	1,76%	0,30%	2,55%	1,08%	0,45%	0,58%	0,30%	2,39%	0,64%	4,11%	1,05%	5,29%	2,00%	3,04%	0,25%
Mineral resource scarcity	kg Cu eq	100,00%	0,49%	1,40%	2,71%	1,60%	1,52%	0,68%	1,33%	0,46%	0,35%	2,05%	0,95%	3,08%	1,63%	8,16%	1,68%	13,68%	0,39%
Fossil resource scarcity	kg oil eq	100,00%	0,17%	0,73%	6,65%	0,09%	1,07%	0,48%	0,15%	0,18%	0,12%	0,98%	0,26%	1,60%	3,99%	20,02%	0,88%	0,40%	0,95%
Water consumption	m3	100,00%	24,62%	1,55%	1,93%	0,16%	2,13%	0,77%	0,26%	0,35%	0,17%	1,35%	0,37%	2,45%	1,16%	5,82%	1,61%	0,93%	0,28%

Impact Category	Unit	Total	Electricity, MEDRAD® Intego PET Infusion System	INTEGO Source administration set	Keyboard	Laundering	Lighting	Linens	Climate system control room	Monitor	Mouse	Blood filter needle	Plastic and Glass container	Printer	Radiotracer vial	Saniwipes	Electricity cyclotron	Climate system cyclotron
Global warming	kg CO2 eq	100,00%	0,16%	1,29%	0,14%	0,25%	0,51%	0,21%	5,75%	2,08%	0,03%	2,68%	8,82%	0,19%	0,49%	1,41%	13,60%	22,00%
Stratospheric ozone depletion	kg CFC11 eq	100,00%	0,13%	18,62%	0,11%	0,23%	0,40%	2,28%	4,57%	1,82%	0,02%	1,63%	4,15%	0,17%	0,47%	0,95%	10,81%	17,49%
Ionizing radiation	kBq Co-60 eq	100,00%	0,03%	3,33%	0,48%	0,60%	0,09%	0,52%	1,04%	7,01%	0,12%	6,79%	20,92%	0,15%	1,20%	4,01%	2,46%	3,98%
Ozone formation, Human health	kg NOx eq	100,00%	0,16%	1,11%	0,20%	0,22%	0,50%	0,29%	5,64%	2,93%	0,05%	2,16%	11,77%	0,10%	0,53%	1,22%	13,34%	21,58%
Fine particulate matter formation	kg PM2.5 eq	100,00%	0,09%	2,05%	0,49%	0,44%	0,28%	0,72%	3,20%	6,71%	0,11%	3,87%	20,80%	0,26%	0,95%	1,64%	7,57%	12,24%
Ozone formation, Terrestrial ecosystems	kg NOx eq	100,00%	0,16%	1,07%	0,18%	0,21%	0,51%	0,26%	5,76%	2,69%	0,04%	2,11%	11,25%	0,09%	0,49%	1,25%	13,64%	22,06%
Terrestrial acidification	kg SO2 eq	100,00%	0,10%	1,77%	0,46%	0,36%	0,30%	1,13%	3,38%	6,65%	0,11%	3,33%	19,58%	0,23%	1,08%	1,79%	7,99%	12,93%
Freshwater eutrophication	kg P eq	100,00%	0,03%	2,13%	1,02%	0,76%	0,10%	1,13%	1,13%	14,25%	0,24%	4,20%	24,08%	0,30%	0,59%	1,84%	2,68%	4,34%
Marine eutrophication	kg N eq	100,00%	0,02%	0,46%	0,09%	1,33%	0,07%	12,78%	0,75%	30,11%	0,02%	0,92%	7,60%	0,06%	0,15%	0,47%	1,78%	2,88%
Terrestrial ecotoxicity	kg 1,4-DCB	100,00%	0,14%	1,53%	0,28%	0,23%	0,43%	0,17%	4,90%	3,60%	0,05%	2,30%	10,21%	0,28%	0,37%	1,35%	11,59%	18,75%
Freshwater ecotoxicity	kg 1,4-DCB	100,00%	0,03%	2,14%	2,45%	0,28%	0,09%	0,45%	1,01%	21,81%	0,54%	3,97%	11,70%	1,63%	1,96%	4,47%	2,39%	3,86%
Marine ecotoxicity	kg 1,4-DCB	100,00%	0,05%	2,09%	2,10%	0,25%	0,15%	0,30%	1,69%	18,86%	0,47%	3,76%	11,32%	1,38%	1,71%	3,97%	3,99%	6,46%
Human carcinogenic toxicity	kg 1,4-DCB	100,00%	0,10%	6,95%	0,40%	0,24%	0,31%	0,14%	3,48%	3,87%	0,05%	10,51%	8,96%	0,35%	0,33%	1,30%	8,24%	13,33%
Human non-carcinogenic toxicity	kg 1,4-DCB	100,00%	0,02%	2,20%	2,05%	0,31%	0,08%	0,50%	0,87%	19,09%	0,49%	4,28%	15,39%	0,72%	2,21%	4,85%	2,06%	3,32%
Land use	m2a crop eq	100,00%	0,05%	1,58%	0,43%	0,96%	0,16%	6,81%	1,85%	5,52%	0,09%	3,15%	21,14%	0,18%	1,07%	1,51%	4,39%	7,10%
Mineral resource scarcity	kg Cu eq	100,00%	0,08%	2,09%	1,73%	0,19%	0,25%	0,20%	2,86%	15,63%	0,36%	3,60%	10,62%	0,55%	0,38%	1,58%	6,77%	10,95%
Fossil resource scarcity	kg oil eq	100,00%	0,20%	0,61%	0,06%	0,12%	0,62%	0,07%	7,02%	0,78%	0,01%	1,32%	5,67%	0,03%	0,18%	1,09%	16,62%	26,88%
Water consumption	m3	100,00%	0,06%	0,98%	0,12%	0,28%	0,18%	10,61%	2,04%	1,53%	0,03%	2,03%	8,34%	0,07%	0,42%	14,76%	4,83%	7,82%

Table 17: Full LCA results for the [18F]FDG PET/CT whole body scan divided by categories (by percent contribution).

Impact Category	Unit	HVAC	Electricity	Single-Use Disposable	Reusables
Global warming	**%**	47%	21%	28%	4%
Stratospheric ozone depletion	**%**	38%	17%	41%	5%
Ionizing radiation	**%**	9%	4%	75%	12%
Ozone formation, Human health	**%**	46%	20%	28%	5%
Fine particulate matter formation	**%**	26%	12%	50%	12%
Ozone formation, Terrestrial ecosystems	**%**	48%	21%	27%	5%
Terrestrial acidification	**%**	28%	12%	48%	12%
Freshwater eutrophication	**%**	9%	5%	61%	24%
Marine eutrophication	**%**	6%	4%	46%	44%
Terrestrial ecotoxicity	**%**	40%	18%	34%	8%
Freshwater ecotoxicity	**%**	8%	4%	44%	43%
Marine ecotoxicity	**%**	14%	6%	42%	38%
Human carcinogenic toxicity	**%**	29%	13%	49%	9%
Human non-carcinogenic toxicity	**%**	7%	3%	53%	37%
Land use	**%**	15%	8%	61%	16%
Mineral resource scarcity	**%**	24%	10%	34%	32%
Fossil resource scarcity	**%**	58%	25%	16%	1%
Water consumption	**%**	17%	8%	62%	13%

Table 18: Total GHG emission (values) for the [18F]FDG PET/CT whole body scan divided by categories

Impact Category	Unit	HVAC	Electricity	Single-Use Disposable	Reusables	Total
Global warming	**Kg CO_2 eq**	3.6	1.6	2.1	0.3	7.6

Table 19: Relative GHG emission (values and percent contribution) of each functional phase to the total global warming potential (GWP) per [^{18}F]FDG PET/CT scan.

Impact Category	Unit	Total	Scan Room – Scan execution	Radiopharmacy - Radiopharmaceutical production	Injection Room - Patient preparation	Control Room - Data management
Global warming	**%**	**100%**	22%	36%	32%	10%
	kg CO_2 eq	**7,62**	1.71	2.71	2.42	0.78

Table 20: Energy consumption (kWh) and duration (min) per [^{18}F]FDG PET/CT whole body scan.

	Energy consumption (kWh)				Duration (min)		
N. Examinations	**Total**	**Average**	**Median**	**SD**	**Average**	**Median**	**SD**
56	87.8	1.6	1.6	0.2	12.7	13.2	2.5

Process-Level Environmental Hot Spots

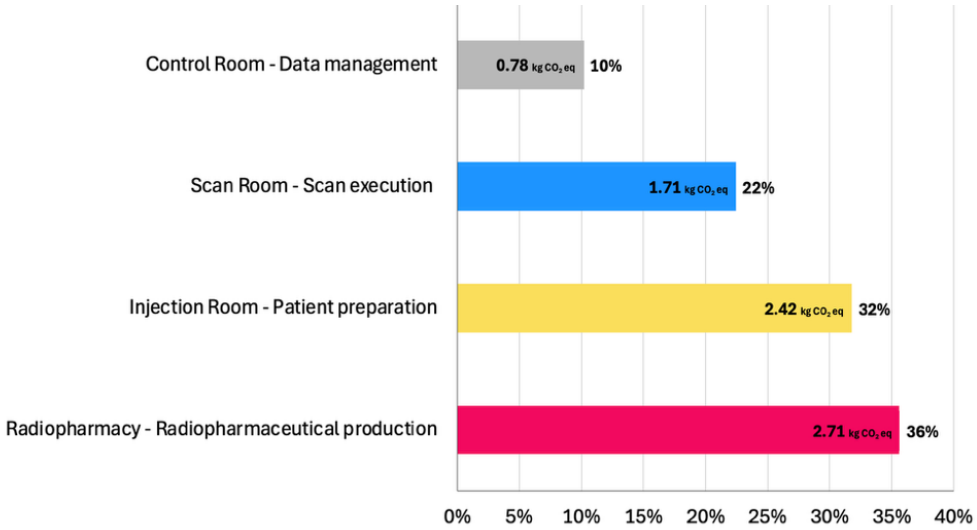


Figure 21: Process-Level Contribution to Life Cycle GHG Emissions per PET/CT Scan. Relative contribution of each functional phase to the total GWP per [18F]FDG PET/CT scan.

Evaluating the results by individual process steps along the patient care pathway (Figure 21) 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 [18F]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 (computers, monitors, and PACS servers) represented less than 10% of the total GWP per scan.

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 16, Figure 20). 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 minimizing unnecessary consumable use, can yield meaningful reductions without compromising clinical safety.

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 decarbonization 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 (European Environment Agency 2025). In 2024, the share of electricity generated from renewable sources in Italy has increased from 31% to 41.2% (Terna - Rete Elettrica Nazionale 2025). This transition towards renewables is leading to the progressive decarbonization 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 decarbonization 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.

4.5 Impact of waste from the injection of multidose contrast media in an emergency radiology department

Data from all CECT examinations were retrieved from the hospital's PACS from May 2023 to April 2024. The dataset consisted of 4,441 consecutive CECT acquisitions, of which 4,418 were included in the analysis; 23 examinations (0.5%) were excluded due to missing information on injected ICM volumes.. The mean number of CECT examinations performed was 12 per day and 368 per month. A total of 600.9 L of ICM were loaded into the injector, of these, 456.2 L were injected, with an average dose per examination of 103.3 mL (median 110 mL, IQR 70-127). The distribution of ICM loaded and ICM wasted monthly is shown in Figure 22.

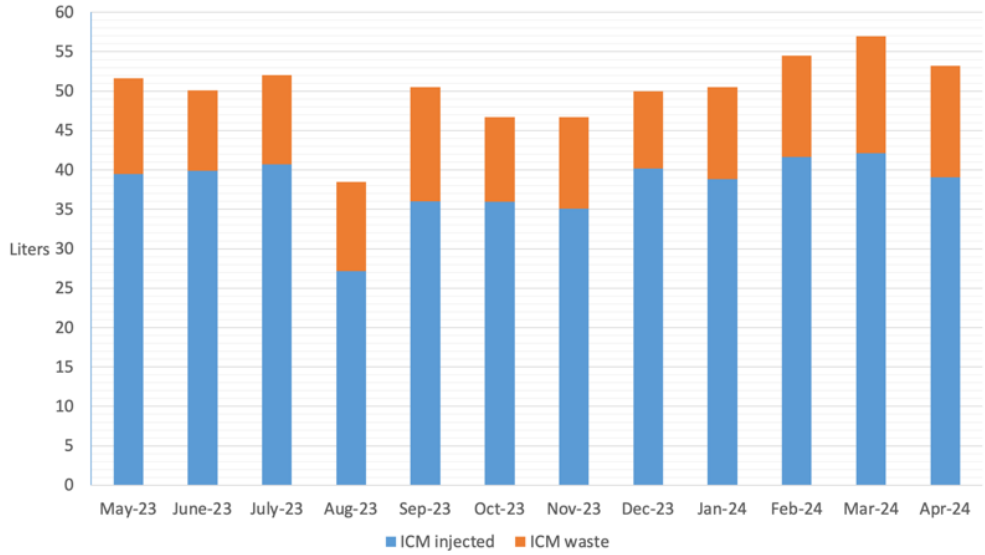


Figure 22: Monthly volumes of iodinated contrast media (ICM) used in the Emergency Radiology Department over the 12-month study period. Blue bars represent ICM administered to patients, while orange bars indicate ICM wasted, including residual volumes remaining in vials and in the automatic injector syringe. Volumes are expressed in litres.

ICM wasted amounted to 144.7 L (32.7 mL per exam), corresponding to n=290 500 mL vials (a total of 76.9 kg of glass and 14.2 kg of paper) and 31.7% of the total ICM loaded into the automatic injector. The specific quantities of ICM wasted are illustrated in Table 21.

Table 21: Type of ICM used in the radiology department, their relative concentrations and the quantity of ICM wasted.

ICM concentration (mg/mL)	ICM waste (L)	ICM waste %
320	4.7	3.2
350	9.8	6.8
370	130.1	89.9
400	0.1	0.1

The ICM volume administered for examination ranging from 25 to 155 mL are shown in Figure 23.

3. Result and analyses

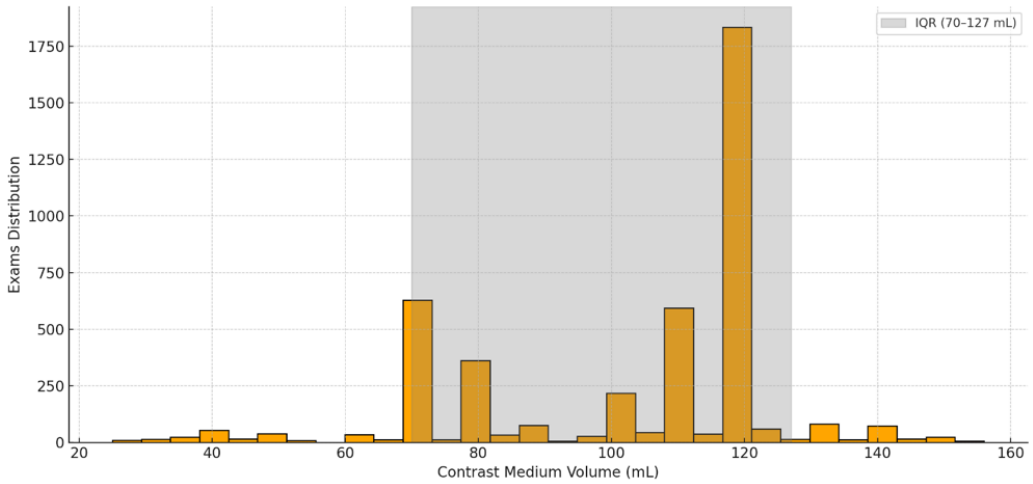


Figure 23: Distribution of ICM injected with the relative frequencies. The average dose for examination amount of 103.3 mL with an interquartile range between 70 mL and 127 mL.

Waste production of disposal materials was categorised into three streams: recyclable plastic, recyclable paper and recyclable glass. In one year, 1,362 ICM vials are used, more precisely 267 200-ml glass vials and 1,095 500-ml vials, of which 1,075 are glass and 20 are plastic. We also used 411 daily kits, for a total of 34 per month, and 4,803 patient lines, for a total of 13 per day. All individual weights of disposable materials are analysed in Table 22.

Table 22: Weights (g) of the single disposable materials used for one CECT examinations.

	Plastic (g)	*Glass (g)*	*Paper packaging (g)*	*Plastic packaging (g)*	***Total waste (g)***
Daily kit	414	-	7	190	**611**
Patient line kit	30	-	3	3	**36**
500-mL glass ICM vial	-	256	49	-	**305**
500-mL plastic ICM vial	300	-	38	-	**338**
200-mL glass ICM vial	-	104	35	-	**139**

The total weight of the waste generated from these 4,418 CECT examinations is outlined in Figure 24. In particular, the total waste amount was 736.2 kg divided as follows: 81.1 kg (11 %) of recyclable paper, 342.5 kg (46.5 %) of recyclable plastic and 312.6 kg (42.5 %) of glass.

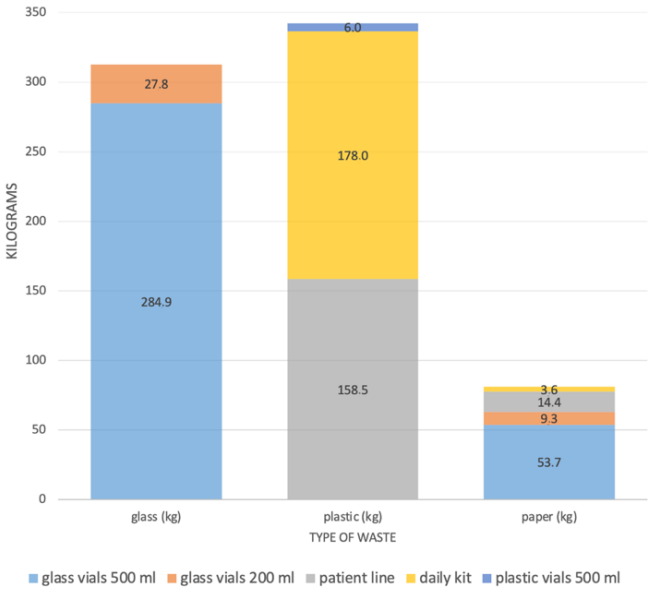


Figure 24: Total weight (kg) of glass, plastic, and paper waste generated by contrast-enhanced CT (CECT) examinations during the study period. Stacked bars illustrate the contribution of individual disposable components, colour coded as follows: glass vials 500 m L (light blue), glass vials 200 mL (orange), patient lines (grey), daily injector kits (yellow), and plastic vials 500 mL (blu

Chapter 5

Concluding remarks

The chapter contains a discussion of the results and conclusions in relation to the research questions.

5.1 Discussion

The overall aim of this doctoral thesis was to quantify the environmental impact and energy consumption of diagnostic imaging departments, to assess how environmental sustainability issues are perceived by professionals working in this field, and to identify strategies capable of effectively mitigating these impacts. The research was structured around four main research questions (RQ1–RQ4), addressing both the awareness dimension of sustainability among radiology staff and the quantitative dimension of energy and environmental performance in diagnostic imaging. Accordingly, the discussion of this thesis is organized around the answers provided to these research questions through the seven appended papers. Taken together, they offer an integrated view of radiology's environmental impact, exploring the operational and technological factors that determine environmental footprint of imaging activities, and proposing evidence-based mitigation pathways aligned with the transition of hospital energy systems toward sustainability.

By analysing the attitudes and perceptions of radiology staff towards issues relating to energy and environmental sustainability (RQ1), a crucial aspect of the green radiology paradigm is identified: the implementation of sustainable practices within radiology departments fundamentally depends on the awareness, training and commitment of radiology professionals. As highlighted in *Paper II*, radiographers from different parts of Europe, different ages and degrees of study, a high level of concern regarding climate change and recognize the importance of environmental sustainability in healthcare. Interestingly, concern about climate change issues does not peak among younger participants, but instead increases with age, contrary to other studies involving broad population segments (Milfont *et al.* 2021). This finding, however, is confirmed by other studies in which older people were more likely to believe that climate change is real, to express concern about the impact of the changing climate, and to be more likely to adopt pro-environmental behaviour (Ayalon 2024). Similar findings were also highlighted by Gendy et al. 41whose survey study, conducted exclusively among radiology staff in the United Kingdom, found a ninety-two per cent of respondents were either "very" or "fairly" concerned about climate change (Gendy *et al.* 2022). However, a strong consensus on the importance of environmental issues was highlighted. Those results suggest that the exclusive focus on raising awareness of the climate crisis may not be as high a priority. Among the three primary subjects investigated, energy consumption, travel by staff, and waste generation, respondents considered the environmental impact of energy consumption associated with radiology activities as the most significant. Regarding energy sustainability practices, excluding equipment employed for emergency diagnostics, over 70% of respondents reported shutting off devices and workstations after their work activities. These energy conservation measures are crucial not only for reducing environmental impact but also for their potential to save

significant amounts of energy annually and to achieve cost reductions per device (McKee *et al.* 2024). Participants identified the primary obstacle to powering down equipment as the extended duration required to turn devices off and then back on, which could dissuade the practice of switching off during idle periods. Noteworthy findings emerged from queries regarding staff travel as well. The surveyed radiographers reported an average daily commute of approximately 21.1 kilometres, totalling around 6,330 kilometres annually (based on 300 working days). Given that 55.7% of respondents indicated they commute in petrol or diesel vehicles, each radiographer contributes to the release of approximately 2 tons of CO2 into the atmosphere. This outcome is consistent with the findings reported by Peters et al. (Peters *et al.* 2021). This underscored the need for greener travel policies, the adoption of virtual platforms, the implementation of telemedicine where possible, and the encouragement of the use of public transportation or low-emission vehicles (Sánchez-Barroso *et al.* 2022). A direct approach involves opting for greener travel alternatives (e.g. public transport, walking, biking). Additionally, adopting remote operation for diagnostic equipment like CT or MRI scanners, could enabling radiographers to work without travel to the hospital (Deistung *et al.* 2024). Despite over half of the survey participants being unaware of radiological remote operations, 44.7% of them believe that remote diagnostics could positively influence the radiology sector's climate footprint. This perspective highlights remote operations not only as a potential solution to staff shortages (Quinsten *et al.* 2023) but also as a beneficial strategy for environmental sustainability according to respondents. Regarding waste management in radiology departments, paper and cardboard, plastic and glass were identified as the most frequently recycled materials. However, although 58.1% of respondents recognized contrast agents as a significant waste source, only 13% reported recycling it. Furthermore, many participants were unaware of existing recovery programs for contrast agents in some radiology departments (Rengier *et al.* 2024). This lack of awareness underscores the importance of educating European radiographers on emerging opportunities for enhancing environmental sustainability.

The second research question (RQ2) of this thesis addresses the quantification of the environmental impact and GHG emissions of radiology departments, aiming to identify the main contributors to the ecological footprint of diagnostic imaging and to assess how methodological choices influence the comparability of results across different contexts. While energy consumption in radiological operations dominates, in the perception of radiology staff, as the main contributor to the environmental impact of imaging activities, the theoretical framework developed in *Paper III* and its application in *Paper VII* reveal a more complex reality than it may initially appear.

In fact, the analysis in *Paper VII* 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 (Chua *et al.* 2021; Leapman *et al.* 2023). Chua et al. (Chua *et al.* 2021), who calculated the volume of GHG associated with interventional radiology procedures, identify the climate control system as responsible for 49% of the emissions. It is important to emphasize that the performance of HVAC systems depends mainly on external seasonal conditions, where hot summer or cold winter conditions significantly alter the environmental impact (Pachano *et al.* 2022). 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 of healthcare activities

(Aparicio-Ruiz *et al.* 2025; García-Sanz-Calcedo *et al.* 2018). 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 (Rizan *et al.* 2020). 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 (Heye *et al.* 2020; Vosshenrich *et al.* 2025). However, it highlights the importance of adopting operational strategies aimed at reducing scanner downtime and optimizing patient flows (Woolen *et al.* 2023b). 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. (Godard *et al.* 2025), where, however, the production of radiopharmaceuticals is associated with the environmental impact of transport from the external production facility and the nuclear medicine department. Furthermore, going deeper into radiological activities, *Paper V* demonstrated that material waste, particularly that associated with ICM constitutes a significant contributor to the overall environmental impact of diagnostic imaging procedures. The results show that CECTs represent a significant source of waste production and resource consumption, with the total quantity of iodine wasted correspond to 53.1 kg. This waste is not negligible, both economically and environmentally, considering the number of CECTs performed (n = 4418) during the period under consideration, the cost of producing iodine, a scarce natural resource and the implications in terms of waste generated, particularly glass, paper and plastic. Due to excretion via the patients' urine, ICM enter many water surfaces, groundwater systems and in the last years concerns have grown over the impact of these substances on the aquatic environment and the water cycle. Consequently, an increasing amount of evidence highlights the environmental problem caused by the breakdown of ICM's products (Sengar & Vijayanandan 2021). High concentrations of ICM were found in rivers and lakes in many regions of world such as Sydney estuary in Australia (Birch *et al.* 2015) and Madrid in Spain (Mendoza *et al.* 2016). Although ICMs are inherently low in toxicity, the by-products resulting from their transformation in wastewater treatment plants and in the environment can pose a threat to aquatic ecosystems and to the safety of drinking water (Dekker *et al.* 2022; Pichler *et al.* 2025).

The energy consumption of diagnostic imaging equipment is consistently identified as a key factor in the environmental impact of radiology departments (RQ3). This research question was addressed through the studies conducted in *Papers IV* and *Paper VI*, and was part of *Paper VII*, which quantified total and specific electricity consumption under real clinical operating conditions and examined the impact of technology replacement on efficiency and primary energy demand.

In particular, in Paper IV the total energy usage of imaging department was estimated at 877.5 kWh per day. Analysing the usage data of individual devices during a working day, the results of this study showed that CT and

4. Concluding remarks

MRI scanners has a greater impact in terms of both energy usage than individual imaging devices such as XR or US, confirming results already reported by other authors (Malik *et al.* 2021). Considering the energy used during idle periods by imaging equipment, it accounts for 22% of the total energy usage daily, with devices that is mostly inactive due to organisational reasons, some with 90% of energy usage associated with idle periods. These aspects underline the importance of reducing energy waste through mitigation strategies, while maintaining the department's diagnostic effectiveness. Although the energy used during the activity period is necessary for patient care, the idle periods must be the main target of these energy-saving actions.

When analysing energy consumption at the single-scanner level, as performed in *Paper VI*, and comparing two different generations of the same equipment, the results further highlight the importance of having a concrete understanding of energy use and of how it manifests within the specific operational context in which the equipment is installed. The results of *Paper VI* 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 (Vosshenrich & Heye 2023). 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 isn't in use (Luo *et al.* 2025). 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 (Kravchenko *et al.* 2025; Qu *et al.* 2023). 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 (Akhmetov *et al.* 2025). 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. 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 (Moré *et al.* 2022; Moshood *et al.* 2024; Olanrewaju *et al.* 2025). Although EPDs are built on standardized methodologies

and provide a valuable framework for comparing products, they often rely on assumptions that don't always reflect what happens in practice. Usage patterns, climate conditions, and hospital operating schedules vary widely across facilities. Another limitation is that EPDs don't 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 (European Commission for Energy Directorate-General *et al.* 2023). 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 are 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.

Finally, the strategies that can be implemented to mitigate the energy consumption and environmental impact of the radiological area (RQ4) were investigated in *Papers IV, V, VI, and VII*. In *Paper IV*, several mitigation strategies were hypothesized, exploring both organizational and technological approaches to reduce the environmental footprint of diagnostic imaging operations. Through optimised scheduling efficiency, it was possible to achieve an 16.6% reduction in total electricity usage and 38,3% reduction during idle periods maintaining and increasing the use of the equipment, as already demonstrated in the literature with MRI (Esmaeili *et al.* 2018). The scheduled shutdown of devices during the non-productive idle and stand-by periods, finds confirmation in the literature, still with workstations and other imaging modalities (Brown *et al.* 2022; Büttner *et al.* 2021; Hainc *et al.* 2020; Woolen *et al.* 2023a). The energy-waste mitigation strategies considered are just a few of those that can be implemented in a radiology department. For example, implementable mitigation strategies may include shortening imaging protocols, for examinations with low environmental impact but the same diagnostic value (Ibrahim *et al.* 2024), using energy-efficient technologies in the construction and operation of radiological services (Heye 2024; Klein 2023; Schoen *et al.* 2024), using artificial intelligence to optimise examination times (Ayde *et al.* 2022; Doo *et al.* 2024), and optimizing data storage, which is associated with high energy usage (Jia *et al.* 2025). Radiology departments of different sizes can implement strategies similar to those proposed or adapt them according to their own workflows and resources, either by identifying and reducing unnecessary examinations (Kopparam & Redberg 2023) or by rescheduling activity and redistributing the necessary resources, also with the help of new technologies (Shahbandegan *et al.* 2022). On the other hands, sensitivity analysis of *Paper VII* 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. (Thiel *et al.* 2024), 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.

5.2 Limitations

The present thesis integrates evidence and methodological elements from seven studies focusing on environmental sustainability and energy efficiency in diagnostic imaging. Therefore, several limitations must be acknowledged. First, many studies were conducted in single-center settings, often within a single hospital and, in some cases, using equipment from a single vendor. This limits the generalizability of the findings, as workflows, infrastructures, energy mixes, organizational models, and clinical practices may vary substantially across institutions, countries, and healthcare systems.

By focusing specifically on energy mixes, it is possible to identify a further limitation, which specifically concerns the high variability of electricity emission factors between different countries. Since emissions associated with energy consumption depend heavily on the national energy mix, which can include very different proportions of fossil fuels, renewables or nuclear power, the same consumption in kWh can result in extremely different environmental impacts. This variability has a significant impact on the results, making it difficult to directly compare studies conducted in national and international regions with heterogeneous energy mixes.

Moreover, several analyses relied on short observation periods, ranging from one to two weeks for radiology department activities, or on limited time windows for the retrospective assessment of energy consumption and waste generation. Although consistent with previously published sustainability studies, such timeframes may not fully capture seasonal fluctuations, holiday periods, exceptional workload variations, emergency-driven activity, or changes in case mix. Retrospective estimations and extrapolations (e.g., over ten-year life cycles) also introduce assumptions which, while aligned with scientific literature, require cautious interpretation.

From a data-collection perspective, when direct measurements were not feasible, some studies relied on indirect measurements or estimated parameters, such as manufacturer-declared power consumption, planned examination times, or average activity durations. In such cases, the absence of continuous energy monitoring using certified power meters may lead to under- or over-estimation of actual consumption. Similarly, manual measurements, such as waste weighing, may be subject to operator-dependent variability.

It is also important to highlight the engineering-oriented nature of this thesis project, as most studies focused primarily on technical or environmental performance, without assessing clinical parameters such as image quality or diagnostic efficiency. Although these aspects do not directly affect energy consumption, they are essential for contextualising sustainability within everyday clinical practice.

Another aspect not considered in several analyses concerns the full life cycle of radiological equipment. Key stages, including manufacturing, transport, installation, disposal, and equipment construction, were often excluded. This partial definition of system boundaries, largely due to the unavailability of proprietary industrial data held by vendors, may lead to an underestimation of the total environmental impact.

Studies based on survey methodologies also present intrinsic limitations typical of qualitative research, including self-reporting issues, response bias, and participant selection bias. Dissemination methods (online platforms, conference promotion) likely favoured the participation of individuals already interested in sustainability. Furthermore, the limited sample size and geographical imbalance reduce the representativeness of radiology staff perceptions at the European level. Finally, it is important to emphasise that the heterogeneity of the literature on environmental sustainability in diagnostic imaging, in terms of study design, measurement units (kWh, kg CO_2-eq, economic metrics), data-collection methods, and clinical or engineering approaches, limits the direct comparability of the results of this thesis with part of the existing scientific literature.

5.3 Conclusion

The seven studies developed during this doctoral project collectively construct a multidimensional framework for understanding, quantifying, and mitigating the environmental impact of diagnostic imaging, according to the four research questions defined at the beginning of this thesis. Each study represents a distinct key through which the ecological footprint of radiology can be analysed; together, they outline a roadmap towards a decarbonised and resource-efficient diagnostic service. One of the key findings to emerge from this doctoral research is that the environmental footprint of radiology is not dominated by a single factor, but by the intersection of three interdependent domains: energy, materials and human behaviour. Energy consumption, particularly during the idle states of MRI and CT scanners, remains the most significant contributor to the overall footprint, but also the most easily improved. At the same time, the material dimension reveals that consumables and contrast media represent an important and often underestimated component of the environmental burden. The methodological pillar linking these studies is the progressive adoption of LCA as an integrative framework. By adopting LCA principles, energy audits, waste analyses and perceptual studies are no longer isolated exercises, but components of a single coherent sustainability model. The results presented in all studies converge towards a crucial institutional insight: environmental sustainability in radiology cannot be delegated to individual actors or isolated projects; it requires systemic governance. Hospitals must integrate sustainability metrics into procurement, accreditation, and performance evaluation processes. This doctoral research demonstrates that the environmental sustainability of diagnostic imaging is not a peripheral concern but an intrinsic component of radiology modernisation. The results reveal that the ecological footprint of radiology is both measurable and reducible. The evidence gathered provides concrete pathways for decarbonising imaging services without compromising diagnostic performance or patient safety.

Chapter 6

Further work

This chapter gives suggestions for further research.

The research developed in this doctoral thesis has posed the methodological foundations for measuring and mitigating the environmental impact of diagnostic imaging. However, several areas remain open for further exploration, both from methodological and practical perspectives.

Future research may broaden the methodological tools employed. The proposed LCA framework could be expanded to include additional impact categories and to extend its boundaries to the entire pathway of diagnostic imaging, covering logistics, maintenance, and end-of-life management of radiological devices. In line with the most recent developments in dynamic LCA, it will also be appropriate to integrate into the model the temporal variability of electricity mixes, equipment usage patterns and seasonal loads of HVAC systems, thus overcoming the static approach based on average conditions (Slavkovic & Stephan 2025). A key evolution will involve shifting from single-scanner to multi-scanner and department-level analyses, to capture the energy interactions between different imaging systems, HVAC networks, and digital infrastructures (Zong *et al.* 2025). This would allow a more realistic representation of the energy dynamics of a radiology department.

Future studies should also assess the environmental performance of emerging imaging technologies such as photon-counting CT, low-field MRI, and artificial intelligence (AI). AI can contribute to environmental mitigation by enabling workflow optimisation, reducing repeat scans, improving image quality with lower acquisition parameters and potentially shortening examination times (Kocak *et al.* 2025). However, the environmental impact of AI in radiology remains highly variable and depends on factors such as AI model size, training requirements, data management practices, and the characteristics of the underlying computational infrastructure (Doo *et al.* 2024). Strategies such as lightweight AI model architectures and the use of pre-trained AI models specific to certain tasks have been shown to significantly reduce energy consumption and CO_2eq emissions during AI model training (Champendal *et al.* 2026). These developments indicate that optimisation based on emerging technologies has excellent prospects for sustainability in the future but will also require rigorous assessment frameworks to quantify the actual environmental benefits.

Another promising direction involves the use of mathematical models or simulation to represent the radiology department as a dynamic system (González-Domínguez *et al.* 2022; Javadi *et al.* 2023). These tools can simulate equipment scheduling, energy flows, and patient throughput, enabling the testing of efficiency scenarios before their real-world implementation.

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A further keystone of a sustainable transition lies in the source of the energy itself. Future analyses should explore the integration of renewable energy systems within hospital infrastructures, potentially combined with trigeneration and energy storage solutions (Kamarajah *et al.* 2025; Pascale & Achour 2024).

At the institutional level, it will also be valuable to investigate how sustainability indicators are currently incorporated into radiological management and procurement processes (Rockall *et al.* 2025). Collaboration among healthcare facilities, industry partners, and policymakers will be essential to define standardized environmental performance criteria for diagnostic imaging equipment and to align purchasing policies with broader decarbonization goals.

In summary, this PhD project represents a starting point for further work integrating technical measurements, system simulations and behavioural changes. The convergence of multi-machine analysis, renewable energy integration and predictive modelling will be key to designing truly sustainable imaging departments, where clinical excellence and environmental sustainability can coexist in synergy.

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Part II

Included Papers

PAPER I

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EUROPEAN SOCIETY OF RADIOLOGY
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EXPERIMENTAL

SYSTEMATIC REVIEW

Open Access

The environmental impact of energy consumption and carbon emissions in radiology departments: a systematic review

Andrea Roletto[1*], Moreno Zanardo[2], Giuseppe Roberto Bonfitto[3], Diego Catania[4], Francesco Sardanelli[2,5] and Simone Zanoni[6]

Abstract

Objectives Energy consumption and carbon emissions from medical equipment like CT/MRI scanners and workstations contribute to the environmental impact of healthcare facilities. The aim of this systematic review was to identify all strategies to reduce energy use and carbon emissions in radiology.

Methods In June 2023, a systematic review (Medline/Embase/Web of Science) was performed to search original articles on environmental sustainability in radiology. The extracted data include environmental sustainability topics (*e.g.*, energy consumption, carbon footprint) and radiological devices involved. Sustainable actions and environmental impact in radiology settings were analyzed. Study quality was assessed using the QualSyst tool.

Results From 918 retrieved articles, 16 met the inclusion criteria. Among them, main topics were energy consumption (10/16, 62.5%), life-cycle assessment (4/16, 25.0%), and carbon footprint (2/16, 12.5%). Eleven studies reported that 40–91% of the energy consumed by radiological devices can be defined as "nonproductive" (devices "on" but not working). Turning-off devices during idle periods 9/16 (56.2%) and implementing workflow informatic tools (2/16, 12.5%) were the sustainable actions identified. Energy-saving strategies were reported in 8/16 articles (50%), estimating annual savings of thousand kilowatt-hours (14,180–171,000 kWh). Cost-savings were identified in 7/16 (43.7%) articles, ranging from US $9,225 to 14,328 per device. Study quality was over or equal the 80% of high-quality level in 14/16 (87.5%) articles.

Conclusion Energy consumption and environmental sustainability in radiology received attention in literature. Sustainable actions include turning-off radiological devices during idle periods, favoring the most energy-efficient imaging devices, and educating radiological staff on energy-saving practices, without compromising service quality.

Relevance statement A non-negligible number of articles — mainly coming from North America and Europe — highlighted the need for energy-saving strategies, attention to equipment life-cycle assessment, and carbon footprint reduction in radiology, with a potential for cost-saving outcome.

Key points

• Energy consumption and environmental sustainability in radiology received attention in the literature (16 articles published from 2010 to 2023).

• A substantial portion (40–91%) of the energy consumed by radiological devices was classified as "non-productive" (devices "on" but not working).

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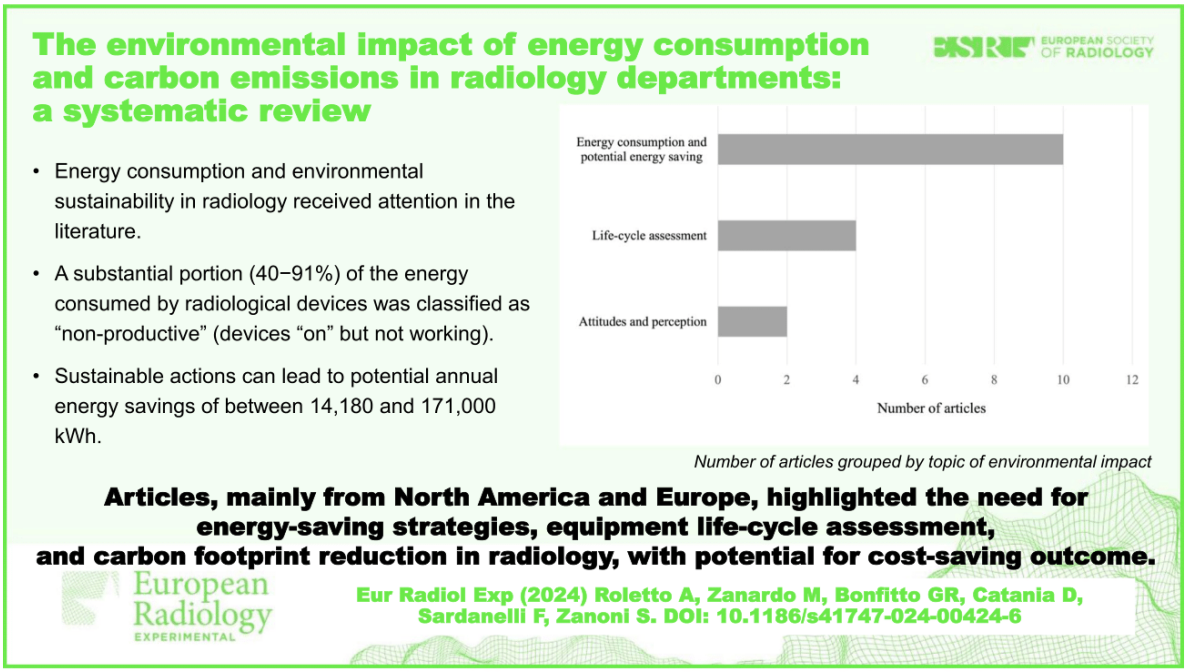
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• Sustainable action such as shutting down devices during idle periods was identified, with potential annual energy savings ranging from 14,180 to 171,000 kWh.

Keywords Carbon emissions, Electricity, Energy savings, Environmental sustainability, Radiology

Graphical Abstract



Introduction

In recent years, there has been a growing recognition of the urgent need for environmental sustainability across various sectors of society. As a result, individuals, organizations, and industries are taking proactive steps to minimize their ecological footprint, to ensure not only environmental benefits but also substantial economic savings [1]. Climate change is causing a range of impacts on communities such as more frequent extreme weather, air pollution, changing distribution of infectious diseases, mental health impacts, and others [2].

Within the healthcare sector, environmental sustainability has emerged as a critical concern [3–5]. Healthcare facilities, including radiology departments, have traditionally been associated with high-energy consumption, carbon emissions, waste generation, and the use of potentially harmful substances. However, the realization of the healthcare sector's substantial contribution to environmental degradation has spurred a transformative shift toward sustainability [6, 7].

In this context, the Greenhouse Gas (GHG) Protocol Corporate Standard [8] establishes standards and guidance for organizations in preparing GHG emissions inventories, outlined by the Kyoto Protocol. Its objectives include ensuring a true and fair representation of emissions, simplifying inventory compilation, providing data for strategic emissions management, facilitating participation in GHG programs, and enhancing consistency and transparency in accounting and reporting across companies and programs.

In addition, considering the categorization of the GHG Protocol Corporate Standard [8] for carbon emissions associated with companies (Scope 1 for "direct GHG emissions"; Scope 2 for "electricity indirect GHG emissions"; and Scope 3 for "other indirect GHG emissions"), health care facilities play a role in all three of these categories.

Radiology departments, crucial in the diagnosis and treatment of various medical conditions, have a particular responsibility to align their practices with

environmental sustainability principles. Studies show that diagnostic departments account for about 9% of the carbon emission footprint in medicine [9, 10]. The health sector is responsible for a part of the global greenhouse gas emissions of about 4–10% [10–12]. Other studies have shown that computed tomography (CT) and magnetic resonance imaging (MRI) equipment account for a large portion of the hospital's total energy consumption and carbon emissions (Scope 2) [10, 13–17]. In radiology departments, the main contributor to climate change is high electricity consumption caused by using energy-intensive medical devices such as CT scanners, MRI systems, and workstations [16, 17]. Additionally, a significant portion of medical equipment remains on and nonproductive for nearly one-third of the day [14]. Furthermore, the cooling processes of radiology equipment and the energy consumption generated by the enterprise picture archiving and communication system (PACS) contribute significantly to the energy consumption and carbon emission (Scope 1 and Scope 2) for hospitals, especially when these systems are left on overnight, as commonly practiced in radiology departments [16].

In an intermediate-size or large radiology department, a considerable number of workstations always remain in operation, regardless of their actual use. This prevalent practice is particularly evident in hospital facilities, where hundreds of workstations contribute significantly to unnecessary energy consumption. As a result, excessive energy waste exacerbates the environmental footprint associated with radiology [18]. For those reasons, hospital radiology departments have great potential in reducing energy consumption, which is accessible by developing workflow optimization processes, using control systems, and improving and optimizing the utilization of used equipment of imaging departments.

To our knowledge, the only systematic reviews published so far in the radiological area have focused on interventional radiology [19] and radiation oncology [20]. Therefore, the purpose of this systematic review was to identify all strategies and approaches to minimize energy use and carbon emissions in radiology departments.

Materials and methods

No ethics committee approval was needed to perform this systematic review, and it was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [21].

Systematic search

In June 2023, a systematic search was conducted on MEDLINE (PubMed), Embase (Elsevier), and Web of Science to find original articles on environmental sustainability in radiology department. The search was limited to original studies written in English, published on peer-reviewed journals, with an available abstract. The search strings were built using the following strategy, based on the Population, Intervention, Comparison, and Outcome (PICO) model and adjusted for each database considering their own unique indexing systems, terminology, and search algorithms:

- 'Environmental sustainability'/exp + synonyms
- 'Radiology'/exp + synonyms OR 'radiology department'/exp
- 'Energy consumption'/exp + synonyms OR 'carbon emission'/exp OR 'recycling'/exp OR 'waste'/exp"

The full search strings were reported in Supplementary file 1.

Three researchers (A.R., G.R.B., and M.Z., with 1 to 7 years of experience in diagnostic imaging research) performed in consensus an initial screening of the retrieved articles, excluding reviews, case reports, and studies that only comprised automatic computer analyses. The full text was downloaded for all studies included at this first selection, and a second screening was performed. Finally, references of included articles and reviews were manually searched to check for further eligible studies.

We included a study if it was as follows: (1) focused on environmental sustainability strategies and (2) had sustainability endpoint in diagnostic radiology departments, radiology imaging services, or in diagnostic radiology medical school. We excluded the following: (1) studies focused on hospitals in general or in setting different from diagnostic radiology department; (2) reviews, editorials, and viewpoints; and (3) abstracts or conference proceedings.

Data extraction

For all articles included at the final selection, the same researchers who selected articles performed independently data extraction. In case of disagreement among readers, arbitration was performed in consensus. For each study, the extracted data (when present) were as follows: year of publication; continent and country of publication; study design (prospective or retrospective); environmental sustainability topic (energy consumption, carbon footprint, life-cycle assessment); type of carbon emission or energy consumption (direct carbon emission/energy consumption, for diagnostic radiology activity delivery, or indirect carbon emission/energy consumption, from sources such as patients, students and workers travel, and resource life cycle); types of radiological devices involved; unit of measurements system; data collection method; and sustainable actions described.

Findings from the included studies that reported on environmental sustainability in the radiology setting are presented through a formal narrative synthesis.

Study quality appraisal

One researcher (A.R.) with 1 year of experience in diagnostic imaging research reviewed the quality of the included articles, using the QualSyst tool [22], using the checklist for qualitative studies.

Results

Study selection and methodological quality assessment

Starting from 400 records identified through search query on MEDLINE, 823 on Embase, and 474 on Web of Science and 8 identified through other sources such as references from included works, 918 were identified after duplicates removed. A total of 858 articles were excluded from title and abstract, while the remaining 60 were downloaded for individual assessment.

Finally, a total of 16 articles which matched the inclusion criteria were eligible for narrative synthesis. A flowchart of study selection is shown in Fig. 1.

Characteristics of the included publications

Baseline characteristics of articles are summarized in Table 1. Full database is published in Zenodo repository for data sharing (https://doi.org/10.5281/zenodo.10473106). Two descriptive surveys were among the included publications [23, 24]. The remaining articles reported the results of studies on carbon footprint, consumption, and energy savings in diagnostic radiology departments using various quantitative descriptive methods. Seven articles originated from the USA, three from Switzerland, and two from the UK and also included contributions from Ireland, Canada, Australia, and Germany.

Topics, settings and devices

The main topics of articles related to environmental sustainability are as follows:

- Energy consumption and nonproductive periods of radiology devices (10/16, 62.5%)
- Life-cycle assessment (4/16, 25.0%)
- Carbon footprint and environmental impact (2/16, 12.5%)

In the field of diagnostic radiology, inhospital services are the main investigation's setting (14/16, 87.5%), followed by radiology training areas (2/16, 12.5%). Diagnostic radiology devices were considered in 13 studies [13, 14, 18, 25–28, 30–35]. In particular, the devices whose energy consumption or environmental impact has been most studied are CT scanners (7/16, 43.7%), followed by MRI scanners (6/16, 37.5%), monitors and workstations (4/16, 25.0%), and ultrasound scanners (3/16, 18.7%).

In summary, as shown in Fig. 2, the main issues on which studies in the literature have focused mainly concern the electricity consumption of diagnostic radiology equipment during the period of operation. Only a small proportion of them evaluate the entire life cycle of the equipment.

Energy consumption and potential energy saving

A total of 11 studies [13, 14, 18, 25–29, 33–35] focused on energy consumption in radiology departments and identified potential areas for improvement. In 8 of these 11 studies [13, 14, 18, 25, 26, 33–35], the authors used real-time meters electricity/power consumption, as a tool of measuring the electricity consumed. Alshqaqeeq et al. [28] evaluated the appropriateness of imaging examinations in relation to energy consumption described for each type of imaging exam. Moreover, the unit of measurement adopted to describe electricity consumed is kilowatt-hour (kWh) in 9 out of 11 articles [13, 14, 18, 25, 26, 28, 33–35]. In addition to electrical energy expressed in kWh, some authors use carbon dioxide equivalent (CO_2-eq), as scope 2 emissions, to describe environmental impact (3/11) [18, 25, 27, 33] and cost (US dollars) to describe economic impact of radiology service's activity (7/11) [14, 18, 25, 28, 29, 33, 35].

In all studies about energy consumption, it was observed that the energy consumption of diagnostic radiology devices, such as MRI scanners and CT scanners, constituted a significant portion of the overall energy usage. Turning off devices during idle periods was highlighted as a sustainable action. Studies reported that a considerable percentage (ranging from 40 to 91%) [13, 14, 25–27, 34, 35] of the energy consumption by these devices was defined as non-productive, emphasizing the need for optimizing device usage and reducing idle times.

Sustainable actions aimed at energy saving and cost reduction were explored in the literature [13, 14, 18, 25–29, 33–35]. Turning off devices during idle period strategies were reported in 9/16 (56.2%) articles [13, 14, 18, 25–27, 33–35], and implementing informatic tools for workflow in 2/16 (12.2%) articles [14, 29] and optimizing operating modes in 2/16 (12.2%) articles [27, 28] were effective approaches. Significant potential energy savings were reported in 8/16 (50%) articles, with studies estimating annual savings ranging from thousands to tens of thousands of kWh (ranging from 14,180 to 171,000 kWh) [13, 14, 18, 25, 26, 33–35]. Cost savings were also identified in 7/16 (43.7%) articles [14, 18, 25, 28, 29, 33, 35], emphasizing the economic benefits of energy-efficient practices applied to the analyzed radiology devices.

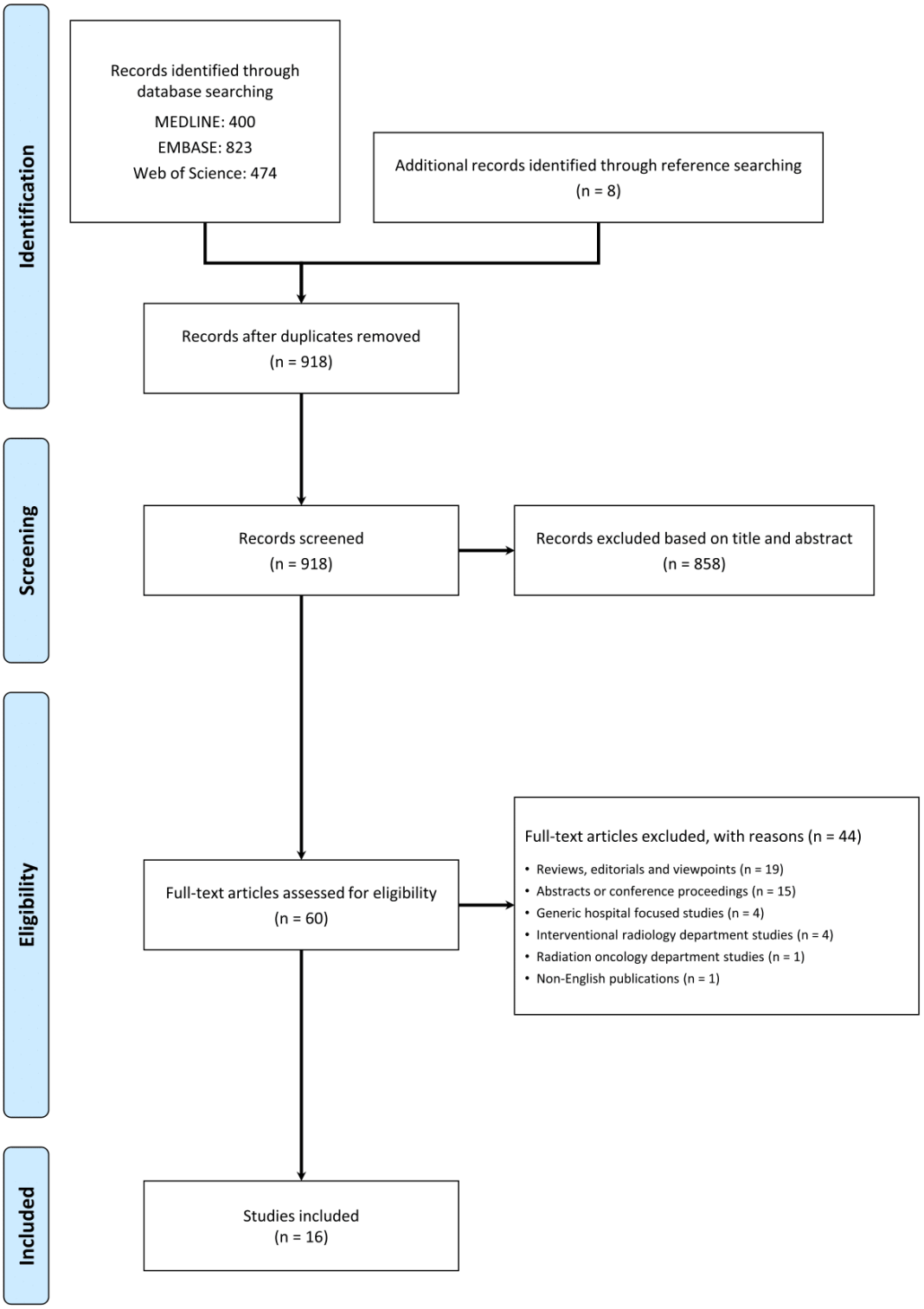


Fig. 1 Flowchart depicting the study selection process, according to the Preferred Reporting Item for Systematic Reviews and Meta-Analyses (PRISMA)

Table 1 This table provides a brief overview of the included studies, their sustainable actions, and principal results

Study	Country	Topic	GHG Protocol Corporate Standard scopes	Setting	Devices	Aim/objective	Sustainable actions	Principal results
Woolen (2023) [25]	USA	Energy consumption	Scope 2	Radiology imaging service	MRI scanners	Consumption and potential energy saving	Turning off MRI scanners during idle periods	Projected annual energy consumption per scanner: 82,700–171,100 kWh Nonproductive energy: 72–91% of total consumption
Gendy (2022) [24]	UK	Carbon footprint	Scope 1, Scope 2	Radiology imaging service	N/a	Current attitudes to environmental sustainably in radiology	Reducing travel, energy-saving measures	92% of survey participants showed high concern about climate crisis
Brown (2022) [26]	Canada	Energy consumption	Scope 2	Radiology imaging service	CT scanners	Consumption and potential energy saving	Turn off CT scanners in nonoperational hours	Potential energy saving for 1 CT scanner: 14,180 kWh per year Nonproductive energy: 40–80% of total consumption
McAlister (2022) [27]	Australia	Life-cycle assessment	Scope 2, Scope 3	Radiology imaging service	Ultrasound, x-ray, CT and MRI scanners	Greenhouse gas emissions and direct and indirect energy consumption	Reducing unnecessary imaging, choose lower energy imaging exams, turning off devices during idle periods	CO_2 emissions were 17.5 kg/scan for MRI, 9.2 kg/scan for CT, 0.8 kg/scan for x-ray, and 0.5 kg/scan for US
Peters (2021) [23]	UK	Carbon footprint	Scope 1	Radiology training	N/a	Environmental impact of radiology trainees travel	Reducing travel, teleconferencing, and distance learning	Total emissions by radiology trainees: 122.5 tonnes of CO_2
Büttner (2021) [18]	Germany	Energy consumption	Scope 2	Radiology imaging service	Monitors and workstations in radiology department	Consumption and potential energy saving	Energy-saving plan with automated shutdown/restart of workstations during idle periods	Potential energy consumption saving: 35,970 kWh (22.2 tons of CO_2 and 14,388.28 USD/year)
Hainc (2020) [13]	Switzerland	Energy consumption	Scope 2	Radiology imaging service	Monitors and workstations in Radiology department	Consumption and potential energy saving	Turning off devices during idle periods	23,692 kWh potential energy saving per year, 45% of the initial energy consumption

Table 1 (continued)

Study	Country	Topic	GHG Protocol Corporate Standard scopes	Setting	Devices	Aim/objective	Sustainable actions	Principal results
Heye (2020) [14]	Switzerland	Energy consumption	Scope 2	Radiology imaging service	CT and MRI Scanners	Consumption and potential energy saving	Energy and cost-saving during idle and system-off states can be converted to more energy-efficient operating modes	Energy consumption imaging 614,825 kWh per year CT idle period: 78% (42 867 kWh) MRI idle period: 5.5–13.4% (8,177–16 038 kWh)
Alshqaqeeq (2020) [28]	USA	Energy consumption	Scope 2	Radiology imaging service	Ultrasound, x-ray, CT and MRI Scanners	Appropriateness of imaging exams related with energy consumption	Choose lower energy imaging exams	Potential US health-care improvement: 24–240 million kWh per year (US $2.5–$25 million dollars per year)
Brodbeck (2019) [29]	Switzerland	Energy consumption	Scope 2	Radiology imaging service	N/a	Energy consumption	Development of informatic tools	Inform energy reduction strategies and improve scan protocols
Esmaeili (2018) [30]	USA	Life-cycle assessment	Scope 2, Scope 3	Radiology imaging service	MRI imaging services (MRI scanners and MRI room devices)	Greenhouse gas emissions and direct and indirect energy consumption	N/a	MRI scanner life-cycle energy: 104 kWh per patient 28% inhospital energy consumption (direct) 72% out-hospital energy consumption (indirect)
Martin (2018) [31]	USA	Life-cycle assessment	Scope 2, Scope 3	Radiology imaging service	Ultrasound, CT, and MRI scanners	Greenhouse gas emissions and direct and indirect energy consumption	N/a	Ultrasound has the least environmental impact compared to CT and MRI
Esmaeili (2015) [32]	USA	Life-cycle assessment	Scope 2, Scope 3	Radiology imaging service	CT imaging services (CT scanners and CT room devices)	Carbon footprint of CT scans by quantifying inhospital and out-of-hospital energy use	Expanding radiologists' knowledge of unseen energy impacts of CT scans	CT scan life-cycle energy: 24–34 kWh per scan 25% inhospital energy consumption (direct) 75% out-hospital energy consumption (indirect)

Table 1 (continued)

Study	Country	Topic	GHG Protocol Corporate Standard scopes	Setting	Devices	Aim/objective	Sustainable actions	Principal results
McCarthy (2014) [33]	Ireland	Energy consumption	Scope 2	Radiology imaging service	Monitors and workstations in radiology department	Consumption and potential energy saving	Turning off computers, air-conditioning units, enabling sleep mode	116.304 kWh potential energy saving per year US $11,629 potential cost-saving per year 15 metric tons of CO_2 emissions per year
Esmaeili (2011) [34]	USA	Energy consumption	Scope 2	Radiology imaging service	CT imaging services (CT scanners and CT room devices)	Energy consumed per month by CT machine in different states	Energy savings during CT idle period	Potential energy savings: 2,065 KWh per month (88% of the total)
Prasanna (2011) [35]	USA	Energy consumption	Scope 2	Radiology imaging service	Monitors and workstations in radiology department	Consumption and potential energy saving	Turn off devices at the end of workday and on weekends	Potential energy and cost savings: 76.31% (83,866.6 kWh and US $9,225.33, respectively)

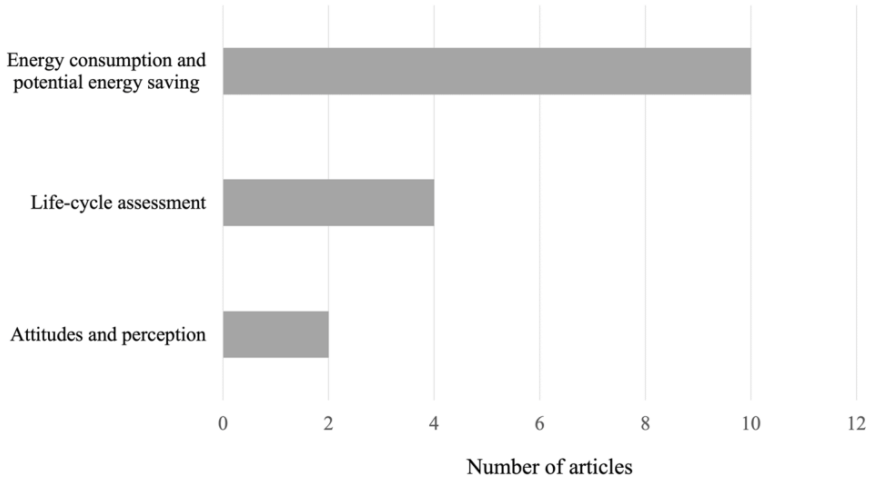


Fig. 2 Number of articles grouped by topic of environmental impact

Life-cycle assessment

Four studies [27, 30–32] conducted life-cycle assessments to evaluate the overall energy consumption and environmental impact associated with radiology services. These assessments considered both direct energy consumption within the hospital setting and indirect energy consumption associated with the manufacturing, transportation, and disposal of imaging devices. In these four studies, a transparent and detailed life-cycle assessments approach not only is used to assess the direct and indirect energy impact of radiological devices but also frequently includes the evaluation of public health implications. Among medical imaging modalities, ultrasounds are found to have the least environmental impact, significantly different from other modalities. For MRI, the carbon footprint associated with the entire individual service has been measured up to a maximum of 22.4 kg of CO_2-eq, as Scope 2 and Scope 3 emissions. This value includes both inhospital process energy (29 kWh per patient) and off-hospital energy (about 75 kWh per patient), required not only for electricity generation during its medical use but also for the manufacturing of the MRI scanner itself and disposable and reusable products used during diagnostic activities. Only approximately 28% of the total MRI life-cycle energy is used for image acquisition, suggesting potential improvements to reduce the environmental impact [27, 30]. However, there is relatively less attention given to the deactivation and disposal of radiological equipment. These analyses provide a basis for comparing environmental impacts across different imaging modalities throughout their entire life cycle, with implications for cost-effectiveness analyses and the development of sustainable policies in the medical field.

Attitudes and perception

Two studies [23, 24] provided insights into the attitudes and perceptions of radiology staff toward environmental sustainability. In both studies, the survey method was used. In the first study [23], the environmental impact of radiology students' travel during their internship was assessed. Based on the responses, the environmental impact of the students' travel was calculated (the total emissions released by all radiology trainees would be 122.5 tons of CO_2, equating to 73.8 return flights from London to New York), and suggestions were made to improve their environmental sustainability. For example, trainers and trainees were happy to use e-mail or video links, rather than face to face during the training, to reduce their environmental impact. In the second study [24], an online survey was conducted among radiology staff to assess their attitudes towards the climate emergency. The results showed a high level of concern regarding this issue. Active commuting represents only a small percentage of the travel related to radiology services. Energy-saving measures are commonly implemented in radiology departments, but they constitute only a fraction of the overall energy usage.

These two studies have shown that there is a common sensitivity among radiology staff regarding the environmental impact topic. Further surveys, including international ones, would be desirable to gain a broader understanding of the perception of the theme of energy sustainability. However, there is already significant potential to reduce the carbon footprint of radiology

services by minimizing travel, both for work and training in radiology.

Quality appraisal

QualSyst total score ranged from 50.0 [29] to 100.0% [14, 25–27] (median 90%, interquartile range 80–95%) with 14/16 (87.5%) articles [13, 14, 18, 23–28, 30, 32–35] over or equal to the 80% of high-quality level. The included studies performed poorly on the quality of data collection and analysis and on the use of verification measures in sufficient detail. Table 2 represents the full results of QualSyst quality assessment of included publications.

Discussion

This systematic review provides a comprehensive overview of various studies that explore crucial aspects such as energy consumption patterns, carbon footprint, and sustainable initiatives implemented within radiology departments in diverse countries. The key outcomes from these studies collectively illuminate the current state of environmental practices in radiology departments and may contribute valuable insights to explore and promote eco-friendly approaches in the field.

One prominent finding was the high-energy consumption associated with medical devices installed in radiology departments. The studies highlighted the need for optimizing device usage and reducing idle periods to address the nonproductive energy consumption, which accounted for a substantial portion of the overall energy usage. This nonproductive energy consumption accounted for a valuable proportion of the overall energy usage, ranging from 40 to 91% in the studies [13, 14, 25–27, 34, 35]. Studies taking into consideration shutting down MRI and CT units during idle periods [14, 25–27, 30–32, 34] have shown that it is possible to make radiology departments more energy efficient, showing significant benefits in terms of environmental sustainability, with energy savings ranging from 14,180 to 171,000 kWh per year and annual cost savings ranging from US $9,225 to 14,328 per device. The energy consumption of the reporting workstations is also not negligible and can be achieved through simple changes in device configuration, enabling for example automatic shutdown after long periods of inactivity [13, 18, 33, 35]. Other aspects reported by Woolen et al. [36] include strategies for reducing consumables, waste, heating and cooling equipment, and emissions from equipment disposal and replacement.

Additionally, four studies highlighted the importance of considering the overall life-cycle energy consumption of diagnostic units [27, 30–32]. This includes not only the energy consumed during their operational phases but also the energy expended during the manufacturing, transportation, and disposal stages, providing insights into potential areas for improvement. An unexplored topic in environmental impact in the life cycle of radiological equipment concerns their obsolescence and renewal [37, 38], in which the need for planned equipment renewal is stated to avoid failures and delays in diagnosis and patient care. Radiology devices are composed of plastics, metals, and rare-earth elements that, if not properly disposed of, can cause environmental pollution [37].

Another result was the growing concern among radiology staff regarding the climate change. Survey-based studies revealed a high level of awareness and a willingness to engage in sustainable practices. The findings highlighted the importance of promoting environmentally conscious behaviors, such as reducing travel, implementing energy-saving measures, and embracing teleconferencing and distance learning options [23, 24]. These actions not only contribute to carbon footprint reduction but also align with the broader sustainability goals of healthcare systems. For the future, there is a need to foster and promote the environmental culture even more in radiological staff healthcare workers.

The dissemination of training courses, learning groups, teleconferencing, and remote consultations must be promoted and implemented within radiology services. The goal must be to reduce the ~ 1.85 tons of CO_2, calculated by Peters et al. [23], caused by the travel of radiology staff for work and training. While online participation in health conferences or training courses may present challenges related to the perceived quality of education by learners and potential disparities in user experience due to factors such as Internet bandwidth and real-time or synchronous delivery, a thorough evaluation of the pros and cons is imperative for both environmental sustainability and the quality of ongoing education. However, findings by Vaona et al. [39] suggest that, when compared to traditional learning, e-learning may have little or no impact on patient outcomes or health professionals' behaviors, skills, or knowledge. While e-learning could be more effective in specific medical education settings, overarching claims of its inherent superiority over traditional learning may be misleading.

Two studies [14, 29] highlighted the importance of informatics tools for analyzing workflow and energy consumption. These tools offer valuable data to inform energy reduction strategies and optimize scan protocols, leading to more energy-efficient practices in radiology departments. In addition, these tools allow to reduce energy consumption considering an organizational approach (*e.g.*, turning off equipment when there is no work activity) without evaluating an engineering approach, which has been used in other published work in the healthcare field [4, 5].

Table 2 This table provides full results of QualSyst quality assessment of included publications

Criteria	Study															
	Prasanna (2011) [35]	**Esmaeili (2011) [34]**	**McCarthy (2014) [33]**	**Esmaeili (2015) [32]**	**Martin (2018) [31]**	**Esmaeili (2018) [30]**	**Brodbeck (2019) [29]**	**Alshqaqeeq (2020) [28]**	**Heye (2020) [14]**	**Hainc (2020) [13]**	**Büttner (2021) [18]**	**Peters (2021) [23]**	**McAlister (2022) [27]**	**Brown (2022) [26]**	**Gendy (2022) [24]**	**Woolen (2023) [25]**
Question/objective sufficiently described?	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2
Study design evident and appropriate?	2	2	2	2	2	2	1	2	2	2	1	2	2	2	2	2
Context for the study clear?	2	2	2	2	1	2	1	2	2	2	2	2	2	2	2	2
Connection to a theoretical framework/wider body of knowledge?	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2
Sampling strategy described, relevant, and justified?	2	2	2	2	2	2	1	2	2	2	1	2	2	2	2	2
Data collection methods clearly described and systematic?	2	1	1	1	1	1	0	2	2	2	2	2	2	2	2	2
Data analysis clearly described and systematic?	2	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2
Use of verification procedure(s) to establish credibility?	1	1	1	1	1	1	1	1	2	1	1	1	2	2	1	2
Conclusions supported by the results?	1	1	2	2	1	2	1	1	2	2	2	2	2	2	2	2
Reflexivity of the account?	2	2	2	1	1	1	2	2	2	2	2	2	2	2	1	2
Total (0–20)	**18 (90%)**	**16 (80%)**	**17 (85%)**	**16 (80%)**	**14 (70%)**	**16 (80%)**	**10 (50%)**	**18 (90%)**	**20 (100%)**	**19 (95%)**	**17 (85%)**	**19 (95%)**	**20 (100%)**	**20 (100%)**	**18 (90%)**	**20 (100%)**

On the topic of carbon emissions, there is limited analysis of the total data. No specific article identifies the type of carbon emission according to the GHG Protocol Corporate Standard [8]. When discussing space heating or cooling, vehicle travel by healthcare professionals is considered within the Scope 1 category of direct GHG emissions. On the other hand, emissions from energy consumption or the production of equipment fall under Scope 2 and Scope 3, representing electricity or other indirect GHG emissions.

Proper classification of emissions in the radiology area is important because in some cases a diagnostic activity does not always necessarily correspond to a carbon emission. For example, if the energy used to operate CT and MRI scanners was derived from production through photovoltaic panels, the carbon emissions would be close to zero.

The other side of the coin on the topic of sustainability in radiology concerns the effective management of waste generated during clinical activities [17]. These wastes can result in significant carbon emissions and financial burdens for radiology departments [40]. For example, residual and unwanted effects of iodinated and gadolinium-based contrast agents are often disposed of in wastewater systems or clinical waste streams, contributing to increased environmental pollution. However, there are virtuous examples where these contrast agents are collected and recovered, as demonstrated by initiatives such as the GREENWATER study [41] and other experiences [40, 42]. This study aims to assess the actual amounts of iodinated and gadolinium-based contrast agents recoverable from patient urine collected after CT and MRI examinations.

Different reviews on the topic of energy conservation in diagnostic radiology can be found in the literature, but none of them presents a systematic approach [10, 36, 43]. In the field of interventional radiology [19, 44], where studies related to environmental sustainability in the operating room were also considered, the same issues of equipment energy consumption, carbon footprint associated with medical activities, and staff awareness in environmental sustainability were identified. Waste generation and recycling of material used during interventional procedures were also added to these topics. Both, although not identified in the selected articles in our literature review, could also be associated with diagnostic radiology activities. Shum et al. [19] concluded that there is a need to discuss environmental awareness in their day-to-day conversation and actively contribute to the global green movement by delivering practical actions to clinical practice. In the literature review related to environmental sustainability in radiation oncology [20], the recurring themes are always carbon footprint and electricity consumption, thus demonstrating how these two themes are the most frequent throughout the literature related to the macro area of radiology. Bloom et al. [20] identify that there are several gaps in the literature which were identified including comparison of various treatment modalities such as single *versus* multifraction treatment and photon *versus* proton *versus* carbon therapy energy requirements.

Study limitations

Despite the valuable insights provided by the included studies, this systematic review has some limitations that should be taken into consideration. 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, even considering those publications that are not published in English language. Secondly, the generalizability of the findings of the included studies may be limited due to the variability in study designs, settings, and geographic locations. The included studies were conducted in different countries, with variations in healthcare systems, infrastructure, and energy sources. These contextual factors can influence energy consumption patterns and sustainability practices in radiology departments, making it challenging to draw universal conclusions. Furthermore, the heterogeneity of the data collected across studies poses a challenge for direct comparisons and synthesis. Variations in the unit of measurement, data collection methods, and outcome reporting may impact the precision and consistency of the results. The differences in measurement units (*e.g.*, kWh, kg CO_2-eq, US dollar per kWh) and data collection methods (*e.g.*, real-time metered electricity consumption, survey responses) may introduce some degree of uncertainty and make it challenging to directly compare the findings. It is also important to acknowledge the potential presence of publication bias in systematic reviews. Studies with statistically significant or positive results are more likely to be published, while studies with null or negative findings may be underrepresented [45]. This bias may affect the overall conclusions drawn from the included studies. Lastly, the review relies on the quality and rigor of the included studies. While efforts were made to ensure the inclusion of high-quality studies, variations in study design, sample size, and methodology may influence the reliability and validity of the findings. Through the QualSyst tool, the overall quality can be considered as satisfactory, with a median article quality equal to 90% (interquartile range 80–95%).

Conclusions

In conclusion, this systematic review emphasizes the importance of environmental sustainability in radiology departments and the potential for energy savings,

carbon footprint reduction, and cost optimization through sustainable actions like the following:

- Turning off devices during idle period helps to save energy and consequently reduce emissions and costs.
- Implementing power management informatic systems that automatically turn off or reduce the power consumption of idle equipment when not in use
- Investing in teleradiology and promoting remote collaboration and consultations can lead to lower carbon emissions.
- Favoring the most energy-efficient diagnostic technique and energy-efficient imaging devices in relation to the clinical question, without compromising the quality of service.
- Educating radiological staff regarding energy-saving practices and sustainability goals.

The findings provide valuable insights for healthcare providers, policymakers, and researchers to develop strategies and initiatives aimed at promoting environmental sustainability in radiology practice. By implementing these measures, radiology departments can contribute to a greener and more sustainable healthcare system, aligning with global sustainability goals and ensuring the well-being of both patients and the planet. In the future, it will be necessary to prospectively evaluate the introduction of sustainable actions in entire radiology departments, considering the life cycles of radiology equipment with a focus on the costs and environmental impact of aging and refurbishing units. In the next future, a radiology department could also be evaluated for its quantified level of environmental sustainability, opening a virtuous competition among hospitals and centers.

Abbreviations

CO_2-eq	Carbon dioxide equivalent
CT	Computed tomography
GHG	Greenhouse gas
MRI	Magnetic resonance imaging
kWh	Kilowatt-hour

Supplementary Information

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Additional file 1. Supplementary file 1. Supplementary Methods. Literature search strategy. Full search strings.

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Authors' contributions
Substantial contributions to the conception or design of the work, AR and SZ; literature search, AR and MZ; article selection, AR, MZ, and GRB; drafting of the manuscript, AR and MZ; critical revision of the manuscript for important intellectual content, MZ, GRB, DC, FS, and SZ; and supervision, DC, FS, and SZ. All authors have read and agreed to the published version of the manuscript.

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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
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Sustainable radiology departments: A European survey to explore radiographers' perceptions of environmental and energy sustainability issues

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ABSTRACT

Introduction: The environmental impact of radiology and radiotherapy activities is influenced by the energy consumption of equipment, the life cycle of consumables, waste generation, and CO_2 emissions caused by staff travel. This study aims to investigate radiographers' perception and knowledge of environmental sustainability issues.
Methods: An online survey was created and distributed to European radiographers and therapeutic radiographers. The survey questions (n = 43) include demographic data; questions on their perceptions and actions regarding environmental sustainability in healthcare, energy consumption, emissions from staff travel, waste generation from radiological procedures; the role of radiographers in addressing sustainability issues within their departments.
Results: A total of 253 responses were collected from 27 European countries. About their perception on sustainability issues, most participants considered environmental sustainability in healthcare as very important. According to 63.6% (n = 161) of respondents, the energy consumption of radiological equipment is the major source of environmental footprints from radiology activities. Additionally, 44.7% (n = 113) believe that conducting diagnostic examinations remotely could reduce environmental footprints from staff commuting About their actions at workplace, over 70% (n = 192) reported turning off devices after use. Attention to waste recycling is high, but limited to paper, plastic and glass. Contrast agents recycling procedures are implemented by 13% (n = 33). The absence or unawareness of environmental sustainability procedures in the workplace was reported by 66% (n = 167). Radiographers could play an active role in environmental sustainability programs for 243 (96.1%) participants.
Conclusion: This study provides a comprehensive overview of European radiographers' knowledge and perceptions concerning environmental sustainability issues. While radiographers recognize the importance of a green radiology department, significant gaps remain in their understanding of eco-friendly initiatives in radiology units' activities.
Implication for practice: Enhancing radiographers' skills with sustainability expertise could promote a greener culture within radiology departments.
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Introduction

The healthcare sector impacts environmental sustainability by emitting greenhouse gases (GHG) through care delivery, energy use, transportation, and product lifecycle.[1–3] In the field of radiology, the production of GHG emissions is attributed to a variety of sources and processes, reflecting the complexity and energy-intensive nature of this area.[3,4] The principal source of GHG emissions within radiology is the energy consumption associated with the activity of imaging equipment such as computed

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Abbreviations

CI	Confidence interval
CO_2	Carbon dioxide
CT	Computed tomography
EFRS	European Federation of Radiographers Societies
GHG	Greenhouse gas
MRI	Magnetic resonance imaging
VAS	Visual Analog Scale

tomography (CT)[5,6] or magnetic resonance imaging (MRI) scanners,[7,8] and auxiliary devices such as reporting workstations.[9–11] Specifically, it has been calculated that the average energy use for CT and MRI scanners in many developed countries ranges from 1200 to 3079 kWh per 1000 citizens per year, estimating a significant amount of potentially avoidable emissions each year (range 2046–175,120 CO_2 tons).[12,13] Numerous studies have explored various strategies for energy waste mitigation, focusing on reducing both environmental impact and costs within radiology departments.[8,14,15] Some of the most effective strategies to reduce energy consumption include switching off equipment when not in use and improving the efficiency of scanner programming to reduce inactivity periods[10,11,16–19] or choosing energy-efficient imaging examinations without reducing clinical appropriateness.[20,21]

The environmental impact of radiological activities extends beyond energy use as the life cycle of consumables like plastics, gloves, paper towel, and glass in medical imaging,[22–24] interventional radiology,[25–27] and radiotherapy procedures,[28,29] from production to disposal, significantly contribute to environmental degradation.[23,24] Similarly, the use and disposal of contrast agents in imaging procedures raise environmental concerns due to the impact of its discarding[30–33] and its non-renewable nature.[34,35] This situation has led to the exploration of strategies aimed at minimizing the use of contrast agents and enhancing their recovery from patient waste and disposal processes.[36,37]

Staff and patient travel for diagnostic examinations or radiotherapy treatments contribute significantly to the environmental footprint of radiology and radiotherapy departments.[38,39] In addition to patient travel, radiology staff contribute to CO_2 emissions through commuting travel[40,41] and attendance at congresses and conferences.[42,43]

These various concerns highlight significant dimensions of operations within radiology and radiotherapy departments, where radiographers form a major professional group. Analysing not only the environmental impact of radiology operations, but also the perception of sustainability issues by radiographers is important to understand whether they are ready to embrace and actively contribute to sustainability efforts. To date, only a limited number of studies have addressed this perspective in healthcare,[41,44–46] often focusing on specific aspects of a much wider issue. This research aims to assess radiographers' perspectives and understanding of environmental sustainability, energy consumption, GHG emissions, and waste management in radiology settings.

Methods

Research ethics

Ethical exemption was granted by the host institution University College Dublin for this anonymous survey (LS-LR-24-25-Catania-Rainford).

Survey design and administration

The questionnaire was initially designed using information on the main topics of environmental sustainability of the healthcare system, energy consumption of radiology departments, emissions from radiology staff travel and waste generation from radiology activities from previous literature analysis.[4,14,30,47–50] The survey was design using Survey Monkey (https://www.surveymonkey.com) to enable widespread distribution and ease of data collection.

The questionnaire comprised of closed questions or using a visual analog scale (VAS)[51] (n = 43) and were divided into five sections. The first section, concerning demographic questions, included questions on age, country of origin, professional experience, educational and professional qualifications, place of work and clinical speciality practised. Subsequent sections asked questions about their perceptions and their actions at work regarding the topic of environmental sustainability in the healthcare system and more specifically on issues of energy consumption, GHG emissions from staff travel, waste generation from radiological procedures and finally their idea on the role that radiographers and therapeutic radiographers could play regarding sustainability issues in their departments. The survey was made available in 5 different languages: English, French, German, Italian and Spanish. All survey questions are reported in Supplementary Table 1.

Pilot testing

In order to verify the appropriateness, clarity and reliability of the survey developed, a pilot study was carried out by distributing it to six external research-active radiographers, with experience in survey design, who were asked for feedback on the validity of the questions, the functionality of the online tool and the time needed to complete it. The experts provided minor recommendations regarding the mode, content, and grammar of the question text, which were then integrated into the survey. Five radiographers from each country whose mother tongue was included in the survey translations were involved in the revision of the text in their respective languages, checking its accuracy and providing minor corrections.

Survey distribution

Distribution was initially through personal and professional contacts of radiographers and therapeutic radiographers across all Europe, via a "snowballing" technique, via emails with virtual link (and subsequent reminders) and social media posts (Facebook, LinkedIn), and was also distributed using a virtual link at the European Federation of Radiographers Societies (EFRS) Research Hub during the European Congress of Radiology 2024 (February 28 – March 3, 2024, Vienna).[52] EFRS Research Hub at the European Congress of Radiology 2024 promoted a series of online questions to its member organisations and wider. The survey was intended to be completed in approximately 15 min. No incentive was offered for survey participation. All responses were collected anonymously. Participants confirmed their voluntary participation and identified themselves as radiographers, therapeutic radiographers, radiography students, or retired radiographers based in Europe.

Data analysis

Descriptive statistics were used to summarise participant demographics, current situation in Europe regarding environmental footprint of radiological activities, perceptions of European radiographers and therapeutic radiographers on environmental sustainability issues in radiology and to analyse future challenges.

Frequencies were reported together with their respective percentages. Data were visually assessed for normality and analysed using the Shapiro-Wilk test. P-values less than 0.05 from the Shapiro-Wilk test indicated non-normal distribution. For normally distributed data, the mean and standard deviation were reported, while the median and interquartile range were used for non-normally distributed data.

Results

A total of 253 valid responses were obtained from a total of 27 European countries. Invalid respondents (n = 82), including participants who did not complete the survey and those who worked in non-European countries, were excluded from the data analysis. The frequency of responses per country is outlined in Table 1, which includes countries from which four or more respondents contributed to the study.

Demographic information of respondents

Most respondents were aged between 18 and 30 years of age (30.4%, n = 77) and between 31 and 40 years of age (30.4%, n = 77), as indicated in Table 2. Professional experience varied; 79 (31.2%) respondents had more than 20 years of professional experience, 68 (26.9%) respondents had 11–20 years' experience, 44 (17.4%) respondents had 6–10 years' experience, 29 (11.5%) respondents had 3–5 years' experience and the remainder (13.0%, n = 33) had less than 2 years' professional experience.

Qualifications and specialisations of respondents

All participants were radiographers, therapeutic radiographers or radiographers in training. The majority of respondents were clinical (43.9%, n = 111), followed by specialist (12.7%, n = 32) and student (11.9%, n = 30). The remaining participants were divided between coordinator/service manager, academic/teacher and researchers. Regarding their primary clinical specialties, most respondents (78.8% n = 197) specialise in diagnostic/interventional radiography. This is succeeded by radiotherapy, with 8% (n = 20) of respondents, and nuclear medicine, accounting for 4% (n = 10). Others reported not working in a clinical setting. Diagnostic and therapeutic techniques mainly practiced by respondent were detailed in Table 3.

Regarding the employment settings of respondents, 63.2% (n = 168), were employed in public hospitals. This is followed by 19.4% (n = 49) who worked in private hospitals, and 5.5% (n = 14) in research centres.

Excluding students (11.9%, n = 30), for most respondents, the highest qualification held was a master's degree (35.2%, n = 89), with 32.8% (n = 83) holding a bachelor's degree, 15.4% (n = 39) holding a postgraduate diploma or certificate, and 4.7% (n = 12) qualified to doctoral level.

Healthcare system sustainability

Through a VAS, interest in issues related to climate change was investigated, with a minimum range (0) corresponding to the response "Not at all interested" and a maximum range (100) corresponding to "Very interested". Using the same methodology, the importance associated with the issue of environmental sustainability in healthcare was investigated, with a minimum range (0) corresponding to "Not at all important" and a maximum range (100) corresponding to "Very important". The results of these two questions are summarized in Figs. 1 and 2, where the data for the second question (median "94", interquartile range "75–100") tend to have higher ratings with slightly less variability than the first set (median "88", interquartile range "70–100"). This could indicate a higher degree of consensus or a generally more positive opinion among the participants regarding the second question.

The results from the age-based model indicate that interest in the topic of climate change varies according to age groups. The mean and standard deviations (Mean ± SD) of interest level for the 18–30 age group was 78.84 ± 22.26, and for the 41–50 age group, it was 85.98 ± 16.12. Similarly, concerning the importance attributed to sustainability in healthcare, the mean importance level in the 18–30 age group was 85.62 ± 19.17, while in the 41–50 age group, it was 87.94 ± 14.86.

In terms of education level, the lowest mean interest level in climate change was observed among participants with doctoral degrees, at 75.92 ± 13.26, while the highest mean interest level was

Table 1
Frequency of survey responses per country with four or more respondents.

Country	No. of Respondents	Responses
Italy	132	52,17%
United Kingdom	16	6,32%
Ireland	15	5,93%
Switzerland	14	5,53%
Portugal	9	3,56%
Malta	8	3,16%
Denmark	7	2,77%
France	5	1,98%
Spain	5	1,98%
Lithuania	4	1,58%
Netherlands	4	1,58%
Slovenia	4	1,58%
Sweden	4	1,58%
Other	26	10,28%
Total	**253 respondents 27 countries**	**100,00%**

Table 2
Demographic age categories of respondents.

Age	No. of Respondents	Responses
18–30 years	77	30,43%
31–40 years	77	30,43%
41–50 years	47	18,58%
51–60 years	40	15,81%
61–70 years	10	3,95%
Prefer not to say	2	0,79%

Table 3
Techniques mainly practiced by respondents.

Country	No. of Respondents	Responses
Computer Tomography	165	65,22%
Conventional radiography	162	64,03%
Magnetic Resonance Imaging	114	45,06%
Angiography/Fluoroscopy	85	33,60%
Mammography	53	20,95%
DXA	33	13,04%
Dental radiography	32	12,65%
Ultrasound	23	9,09%
PET	23	9,09%
External beam Radiotherapy	22	8,70%
Hybrid imaging	18	7,11%
SPECT	16	6,32%
Experimental imaging (phantom/animal models)	5	1,98%
Brachytherapy	5	1,98%
Proton therapy	4	1,58%
I do not work in a clinical setting	16	6,32%

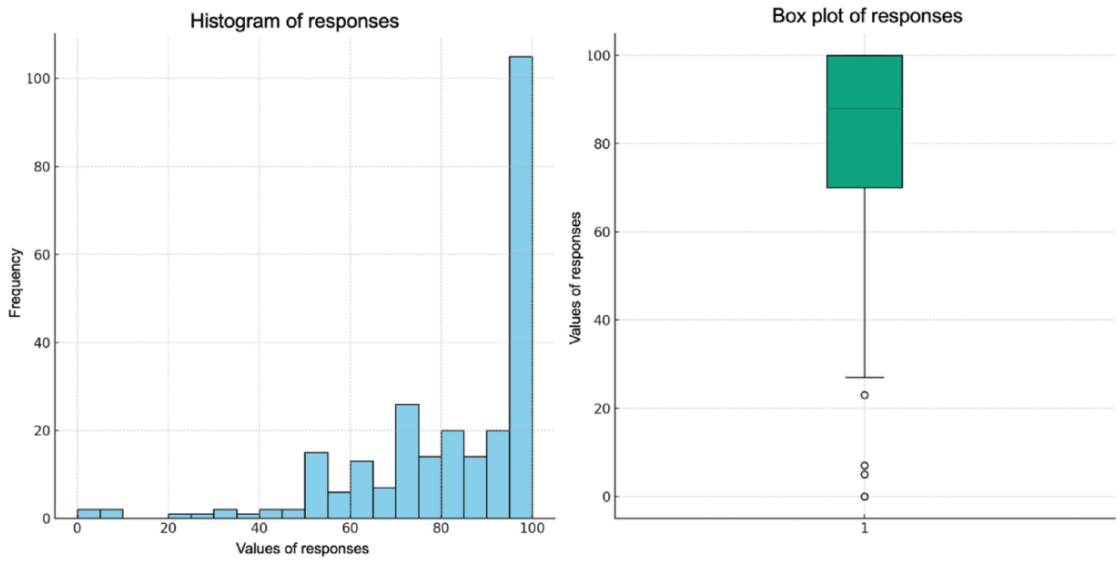


Figure 1. Participants' interest in climate change issues.

observed among those with a bachelor's degree, at 83.78 ± 20.07. Regarding the importance of sustainability in healthcare, the lowest mean value was reported by students, at 79.83 ± 23.26, and the highest mean value was associated with participants who have a bachelor's degree, at 88.23 ± 18.52.

When asked, "Which of these sources of greenhouse gas emissions from the healthcare sector do you think has the greatest impact on the environment?", with a maximum of three answers to choose from, the option "Waste generation during operations" was chosen by 79.3% (n = 187) of participants. This was followed by "Processing, use, and end-of-life treatment of solid products or equipment" with 47.3% (n = 120) of participants, and "Direct emissions from company facilities and vehicles" with 41.5% (n = 105) of participants.

Asking the same question but narrowing the focus exclusively to the radiological area, the most chosen option was "Energy consumption for lighting, heating, and cooling of work environments" with 67.6% (n = 171) of the participants. This was followed by "Energy consumption of radiological equipment during its use" with 63.6% (n = 161) of the participants, and "Waste generation during operations" with 50.2% (n = 127) of the participants.

Energy consumption of radiology departments

Below 50% participants (41.5%, n = 105) self-reported that they turn off their radiology equipment at the end of their work activity, except for equipment in the emergency department. Meanwhile, 34.4% (n = 87) of participants turn them off every day, and 13.0% (n = 33) do not turn off their equipment at the end of the workday.

On the other hand, regarding computers and reporting stations, 40.7% (n = 103) of participants reported that they turn them off at the end of the workday, except for equipment in the emergency

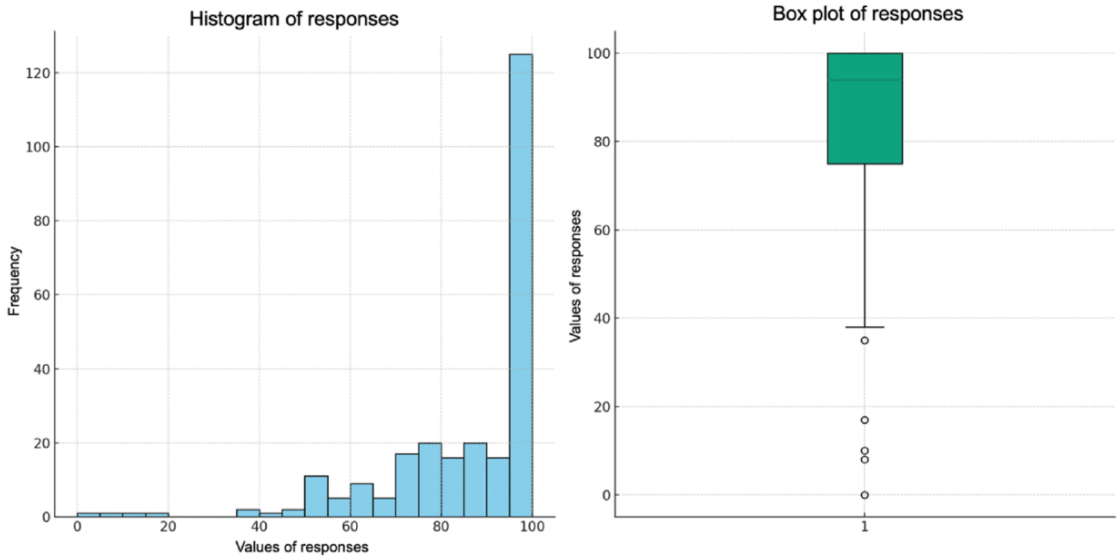


Figure 2. Participants' opinion on the importance for the health system to be environmentally sustainable.

department. A total of 31.6% (n = 80) of the participants turn them off every day, and 18.6% (n = 47) do not turn off computers and reporting stations at the end of the workday.

The investigation also covered whether radiological equipment is turned off during idle periods (devices "on" but non-productive). 63 participants (24.9%) answered "No, automatic standby", followed by "No" (24.5%, n = 62) and "Yes, all equipment I use" (22.5%, n = 57). In contrast, almost all participants (81%, n = 205) answered "Yes" when asked if they switch off lights in their work area at the end of the day. Finally, the survey explored participants' personal perception on what the barriers to switching off equipment in their department might be. The frequency of responses is outlined in Fig. 3.

Emissions from radiography staff travel

The commuting and work-related travel habits of the participants were closely examined. A large portion of the respondents (43.5%, n = 110) travel between 0 and 10 km daily to and from work. A smaller segment, 18.2% (n = 46) of participants, commute more than 41 km each day. The most common modes of transportation among them are public transport (32.0%, n = 81), petrol cars (31.6%, n = 80), diesel cars (24.1%, n = 61), walking (19.7%, n = 50), and bicycles (15.0%, n = 38).

When it comes to business travel, such as attending congresses, conferences, seminars, or activities in other hospitals, over half of the participants (50.2%, n = 127) report making between 1 and 2 travels per year. The preferred methods of travel for congresses or conferences are by car (56.9%, n = 144), train (51.4%, n = 130), and airplane (34.8%, n = 88). Specifically, regarding attendance at congresses and conferences, a significant majority, 65.2% (n = 165) of participants, prefer to attend these events in person. Conversely, 28.1% (n = 71) of participants would rather participate virtually. A large portion of the radiographers surveyed (76.8%, n = 194) believe that virtual attendance at conferences can contribute positively to environmental sustainability.

The feasibility of working from home within the radiography sector was scrutinized. A substantial majority, over 81% (n = 205) of participants, expressed that remote work was not applicable to their roles. Only 2% (n = 5) cited the main barriers to remote work as being due to inadequate technology at home or an unsuitable home environment. Additionally, participants were queried about the potential for conducting CT and MRI examinations remotely. More than half of the participants (56.1%, n = 142) were unaware of such possibilities.

Despite the lack of awareness, 51.4% (n = 130) of respondents reported the personal perception that conducting MRI and CT examinations remotely would not be feasible or practical within their departments. Conversely, 44.7% (n = 113) participants believe that remote execution of these examinations could beneficially impact the climate footprint in the radiology sector (Fig. 4).

Waste generation from radiological activities

Personal perception of what the primary sources of waste generation are in the respondents' departments were analysed, as depicted in Fig. 5.

Furthermore, opinion of what are the categories of waste most frequently recycled within these departments are illustrated in Fig. 6.

The primary obstacles preventing radiology and radiotherapy departments from implementing waste recycling programs, as identified by the participants' opinions, include the non-availability of recycling bins in departments (41.5%, n = 105), a lack of staff training (36.0%, n = 91), and product packaging that is not conducive to recycling (28.9%, n = 73).

Respondents were surveyed about their views on the recovery and recycling of contrast agents from waste and patients. 63.6% (n = 161) of the survey participants were unaware of the potential to reclaim iodine- and gadolinium-based contrast agents used in CT and MRI procedures. Nevertheless, a significant majority, 78.7% (n = 199), believed that programs aimed at recovering contrast agents from waste and patients could enhance the environmental sustainability of radiology. Furthermore, 52.6% of the participants (n = 133) considered that a contrast agents recovery program could be viable within their departments.

Radiographers' and therapeutic radiographers' role

Regarding the various topics of environmental sustainability examined (energy consumption, staff travel, and waste generation), participants were asked about their perceived contribution of these aspects to the total emissions of their departments. For "energy consumption", the option "over 40%" was the most selected by the participants (17.8%, n = 45). In the case of "staff travel", the most chosen option was "0–10%" (24.5%, n = 62), and for "waste generation", the option "21–30%" was most frequently selected by the respondents (17.0%, n = 43).

The majority (66.0%, n = 167) of the participants perceived that environmental sustainability procedures or protocols are either absent in their workplace or that they are unaware of their existence. However, 30% (n = 76) believed that introducing such protocols might be beneficial. A further 8.3% (n = 21) of the participants indicated that although protocols are in place, they are not followed by the staff. Among the environmental sustainability actions implemented, where present, participant self-reported that

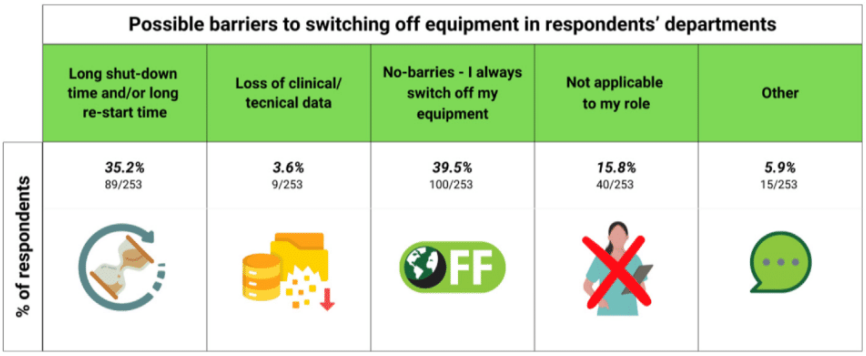


Figure 3. Possible barriers to switching off equipment in respondents' departments.

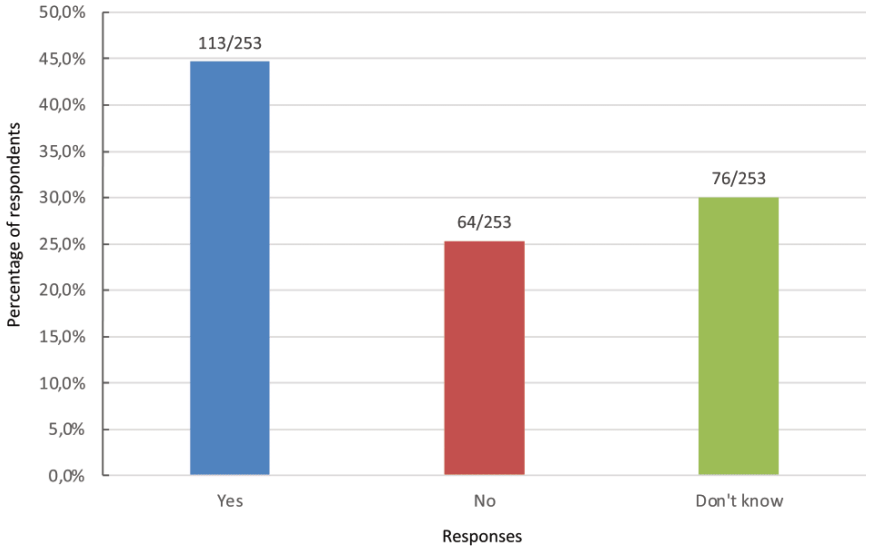


Figure 4. Participants' responses to the question "Do you think remote CT and MRI examinations can help reduce the climate footprint in the radiology area?"

the most common include reducing energy consumption (39.5%, n = 100), improving waste recycling (38.7%, n = 98), and reducing waste production (24.9%, n = 63).

Almost all survey participants (96.1%, n = 243) believe that radiographers can play an active role in environmental sustainability programs within their departments. The perception of their importance is practically divided, with opinions nearly evenly split between "a limited role" and "a primary role".

Among the actions identified where radiographers could significantly contribute to reducing environmental emissions, "reducing energy consumption" was recognised by 80.6% (n = 204) of participants, "improving waste recycling" by 73.5% (n = 186) of participants, and "reducing waste production" by 58.9% (n = 149) of participants.

Discussion

This study is the first to investigate European radiographers' perception and actions of environmental and energy sustainability issues. This study showed that European radiographers



Figure 5. Main sources of waste generation in the respondents' departments.

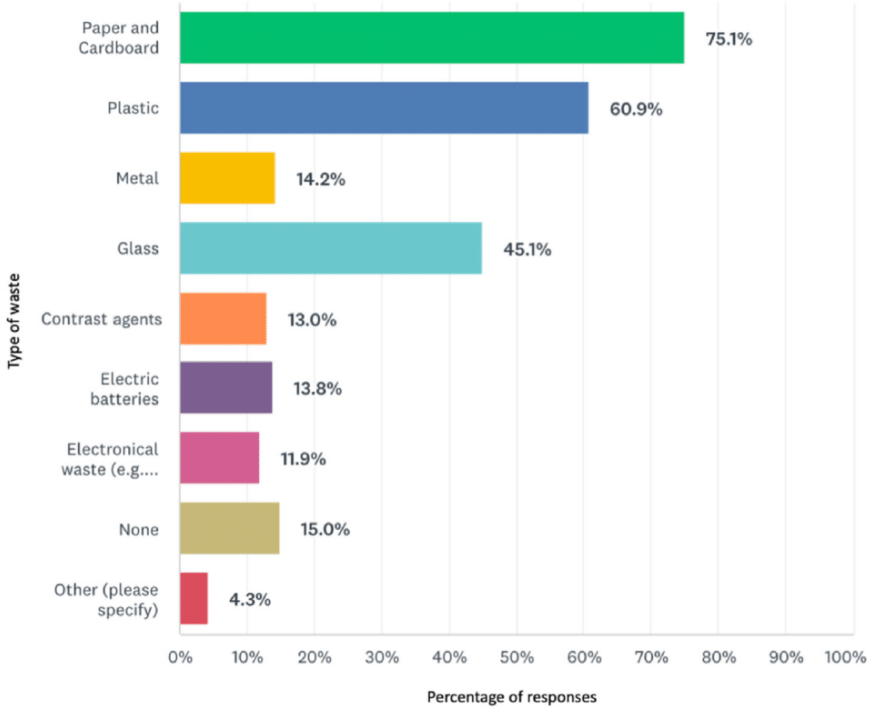


Figure 6. Types of waste most frequently recycled in respondents' departments.

acknowledge the significance of having an eco-friendly radiology and radiotherapy department, however substantial gaps persist in their understanding of green initiatives within diagnostic and therapeutic operations.

The survey illustrates those radiographers from different parts of Europe, different ages and degrees of study, have a high level of concern about climate change issues and attention to the importance of environmental sustainability in healthcare.[53] Interest in climate change issues does not peak among younger participants, but instead increases with age, contrary to other studies involving broad population segments.[53,54] This finding, however, is confirmed by other studies in which older people were more likely to believe that climate change is real, to express concern about the impact of the changing climate, and to be more likely to adopt pro-environmental behaviour.[55,56] The introduction of climate change topics in undergraduate courses in radiography, as already considered for other health professions,[45,46] could increase the involvement of young radiographers in environmental sustainability issues. Moreover, in terms of educational attainment, radiographers with doctoral degrees show less interest in climate change issues compared to those with a bachelor's degree, who demonstrate a high level of interest. This result contrasts with the idea that individuals with higher levels of education tend to be more environmentally friendly [57] and could be caused by the different sample sizes considered. More in-depth investigations on this aspect could therefore be useful. Additionally, bachelor's degree holders place significant value on the importance of sustainability in healthcare, a sentiment not as strongly shared by students. This could be attributed to the greater work experience that bachelor's degree holders typically have in radiology departments.

Similar findings were also highlighted by Gendy et al.,[41] whose survey study, conducted exclusively among radiology staff in the United Kingdom, found a ninety-two per cent of respondents were either “very” or “fairly” concerned about climate change.[41] Another survey, conducted by Soares et al.,[44] assessing the knowledge, awareness, and attitudes of European therapeutic radiographers towards environmental concepts, found a noticeable deficiency in awareness, with less than 50% of participants informed about green skills policies. However, a strong consensus on the importance of environmental issues was highlighted. Those results suggest that the exclusive focus on raising awareness of the climate crisis may not be as high a priority.

Among the three primary subjects investigated, energy consumption, travel by staff, and waste generation, respondents considered the environmental impact of energy consumption associated with radiology activities as the most significant. This perspective is further supported by the growing body of literature focusing on this topic,[5–7,9–11,14,16–19,58] in contrast to the limited research available on the environmental implications of staff travel[39–42] and waste production.[24,36,37,59,60]

Regarding energy sustainability practices, excluding equipment employed for emergency diagnostics, over 70% of respondents reported shutting off devices and workstations after their work activities. These energy conservation measures are crucial not only for reducing environmental impact but also for their potential to save significant amounts of energy annually and to achieve cost reductions per device.[14] Participants identified the primary obstacle to powering down equipment as the extended duration required to turn devices off and then back on, which could dissuade the practice of switching off during idle periods. The “wait time” cost, in terms of lost productivity, is estimated at US $36,280 per year.[10] These expenses could be mitigated through technological advancements that allow for swift transitions between power states and the automatic shift to the lowest energy mode following a predefined period of inactivity.[17]

Noteworthy findings emerged from queries regarding staff travel as well. The surveyed radiographers reported an average daily commute of approximately 21.1 km, totalling around 6330 km

annually (based on 300 working days). Given that 55.7% of respondents indicated they commute in petrol or diesel vehicles, each radiographer contributes to the release of approximately 2 tons of CO_2 into the atmosphere. This outcome is consistent with the findings reported by Peters et al.,[40] This underscored the need for greener travel policies, the adoption of virtual platforms, the implementation of telemedicine where possible, and the encouragement of the use of public transportation or low-emission vehicles.

Several strategies can be employed to decrease the CO_2 emissions associated with radiographers' commutes. A direct approach involves opting for greener travel alternatives (e.g. public transport, walking, biking). Additionally, adopting remote operation for diagnostic equipment like CT or MRI scanners, could enabling radiographers to work without travel to the hospital.[61,62] Despite over half of the survey participants being unaware of radiological remote operations, 44.7% of them believe that remote diagnostics could positively influence the radiology sector's climate footprint. This perspective highlights remote operations not only as a potential solution to staff shortages[63] but also as a beneficial strategy for environmental sustainability according to respondents. The same concept can also be applied in the training of radiography students. The use of remote education has already been successfully explored during the COVID-19 pandemic.[64,65] Applying the same principles to reduce the carbon footprint associated with student travel could prove equally effective.

Regarding waste management in radiology departments, paper and cardboard, plastic and glass were identified as the most frequently recycled materials. However, although 58.1% of respondents recognized contrast agents as a significant waste source, only 13% reported recycling it. Furthermore, many participants were unaware of existing recovery programs for contrast agents in some radiology departments.[36,37] This lack of awareness underscores the importance of educating European radiographers on emerging opportunities for enhancing environmental sustainability.

Almost all survey participants believed that radiographers can significantly contribute to environmental sustainability programs in their departments, particularly by reducing energy consumption, enhancing waste recycling, and minimizing waste production. Specifically, radiographers are well-equipped to manage energy and consumable usage in radiology departments, a capability underscored by the data collection study by McAlister et al.,[22] Their routine interaction with diagnostic equipment positions them to identify inefficiencies and recommend sustainable improvements, leading to substantial reductions in energy and waste without compromising patient care quality.[58]

Study limitations

The pilot study and the validation of the questions in this questionnaire were carried out by research-active radiographers and subsequently by the authors of the study. Potential biases may have been introduced in connection with the perceived lack of comprehensiveness of the questions or the complexity of the topics covered. The research team tried to minimise this possibility by clarifying the questions as much as possible. Sex and gender data were not included in the study minimise social desirability bias. The distribution of the survey relied on “word of mouth” and promotional efforts during the EFRS Research Hub at ECR 2024, which might have introduced selection bias. Similarly, the topic of the survey itself may have led only those interested in environmental sustainability to be more likely to respond, resulting in a possible additional selection bias. Furthermore, being disseminated online, the survey could have been more accessible to respondents from regions or countries with higher internet connectivity. A potential limitation of the study could be the relatively small sample size of participants (253 respondents in a population of over 100,000 European radiographers). Approximately 50% of the respondents are Italian. This is likely due to the Italian authors of this article having more actively disseminated the survey. However, it's important to note that the survey was based on self-reported data, potentially leading to response bias or inaccuracies due to varied interpretations and individual perspectives on the questions asked. The study's emphasis on quantitative data could also limit the depth of insight into European radiographers' views on environmental and energy sustainability. To address these limitations, future research could aim for a larger and more diverse sample, employ a broader array of recruitment methods, and integrate qualitative analyses to enrich the understanding of radiographers' attitudes towards sustainability. Despite the mentioned challenges, we believe our study offers meaningful insights into the perceptions of environmental and energy sustainability within the European radiography community.

Implication for practice

Enhancing radiographers' skills in environmental sustainability could promote a greener culture within radiology departments. Respondents showed a good awareness of environmental sustainability issues, for example perceiving energy consumption as a major source of environmental impact in radiology and stating that they already carry out mitigation actions by switching off equipment at the end of their work. They were also open to innovations in their work in favour of reducing their environmental footprint, such as the introduction of remote diagnostic activities or the recycling of contrast medium. These initiatives could not only reduce environmental impact, but also decrease costs and improve patient safety, aligning radiology activity with global sustainability goals.

Conclusion

This study provides a comprehensive analysis of European radiographers' knowledge and perceptions concerning environmental and energy sustainability within the radiology sector. While participants generally recognize the importance of an eco-friendly radiology and radiotherapy department, significant gaps remain in their understanding of methods to reduce environmental impact and energy consumption. These gaps extend to emerging procedures that could help reduce environmental pollution, such as remote operation for diagnostic imaging and recycling of used contrast agents. To bridge these knowledge gaps, it's crucial to enhance radiographers' familiarity with environmental sustainability through targeted educational initiatives. These can include residential courses, webinars, and integrating sustainability topics into university programs. By participating in these educational efforts, radiographers can become pivotal in advancing sustainability programs. By integrating expertise in supervising energy consumption, implementing sustainability initiatives, and maintaining environmentally friendly operations with their existing skills, radiographers could encourage a sustainability-oriented culture in their departments. Such an approach would not only improve departmental practices, but also motivate the broader hospital community to embrace environmentally friendly practices which go beyond the role of radiographers.

Conflict of interest statement

All authors declare that they have no competing interests directly related to this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radi.2024.06.022.

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PAPER III

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

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***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

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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.

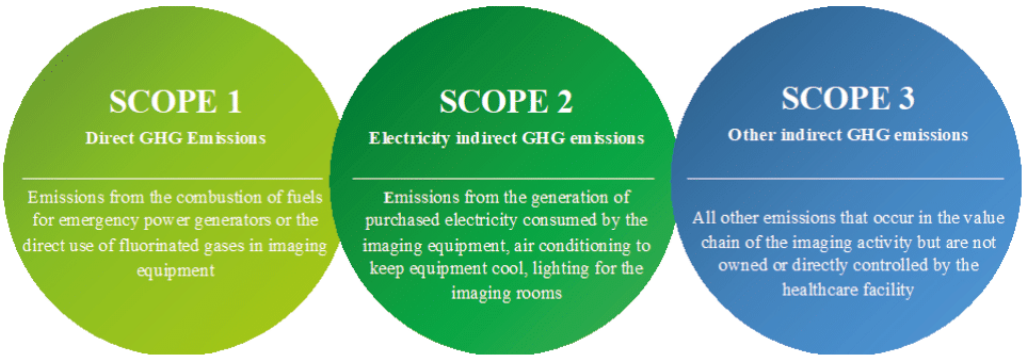


Fig. 1. Scope 1, 2 and 3 emissions in diagnostic imaging department according to the GHG protocol.

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.

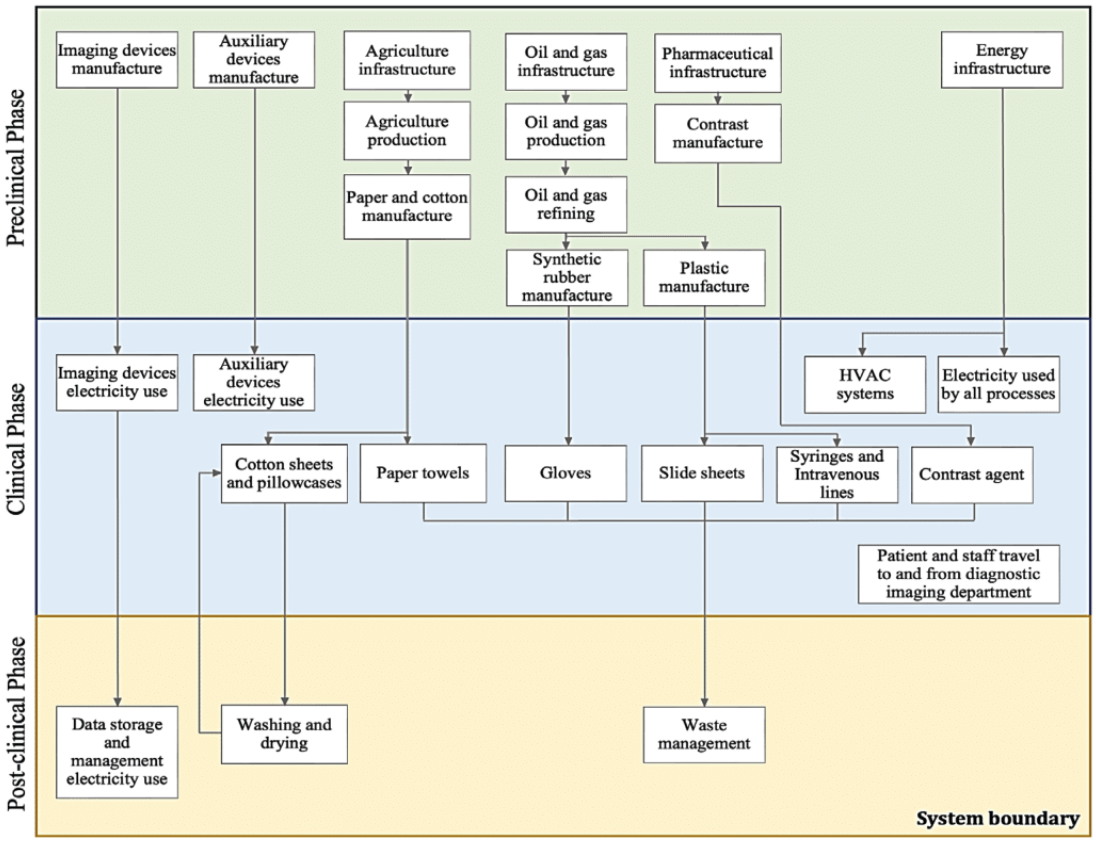


Fig. 2. Comprehensive Life Cycle Assessment Framework for Diagnostic Imaging.

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.

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PAPER IV

energies

MDPI

Article

Energy Usage Assessment and Energy Savings Estimation in a Radiology Department in Italy

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Abstract: Growing awareness of the environmental impact of radiology departments highlights the importance of adopting mitigation strategies to increase the energy sustainability of diagnostic activities. This study aims to estimate the energy usage of imaging activities in a radiology department to plan and evaluate different energy waste mitigation strategies. A retrospective analysis of the energy usage of imaging equipment, including computed tomography (CT), magnetic resonance imaging (MRI), X-ray (XR), and workstations of radiology department in Italy, was carried out. The energy used was estimated based on equivalent mean power demand values in kWh. From this analysis, mitigation strategies were planned to reduce energy waste. The daily energy usage of the department is 877.5 kWh. The cone beam CT scanner is the imaging device with the lowest daily energy usage (6.6 kWh). Modalities with the highest mean daily energy usage are XR (18.4 kWh), CT (58.3 kWh), and MRI (214.6 kWh). The proposed mitigation strategies led to a reduction in energy waste quantified between 16.6% and 80.4%. The analysis of the energy usage of all imaging devices and workstations makes it possible to assess the energy waste of a radiology department. Understanding these elements is essential to develop strategies to reduce energy waste in radiology.

Keywords: diagnostic imaging; green radiology; environmental sustainability; energy consumption; climate change

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1. Introduction

The growing global awareness of the environmental impact and energy sustainability of radiology departments is becoming increasingly evident [1–3], and radiology activities contribute significantly to energy usage and are closely linked to greenhouse gas (GHG) emissions [4–6]. It is estimated that radiology, considering the production and use of medical imaging equipment, accounts for about 1% of global GHG emissions [7,8]. Therefore, mitigation strategies to reduce these emissions in radiology departments are essential. A large part of the energy used by diagnostic imaging equipment is correlated to a nonproductive idle state [9]. Among the most effective strategies to mitigate energy usage

could include switching off equipment when not in use and improving scanner scheduling efficiency to decrease idle periods [10] or choosing lower-energy imaging examinations without reducing clinical appropriateness [11]. To see how effective these strategies are, it is necessary to calculate the energy usage related to radiological activities. The most energy-intensive radiology activities are associated with magnetic resonance imaging (MRI and computed tomography (CT) examinations [12–14], and their energy usage has often been analyzed by considering only a small part of a department's whole diagnostics imaging equipment [15–17]. It is also noteworthy that monitors and workstations, though consuming less energy than imaging equipment, still significantly impact departmental energy use [18,19]. Some studies have investigated the overall energy usage or the impact in terms of the CO_2 emissions of a radiology department's activities [12,13], or other studies have hypothesized energy-saving strategies for only single radiology equipment [9,15,18]; but, to the best of our knowledge, no studies have yet been conducted that take into account all the equipment of an entire radiology department and that assume and implement strategies in real-life settings to reduce energy waste.

This study aims to estimate the energy usage of all radiological activities within a radiology department setting: imaging modalities such as cone beam computed tomography (CBCT), computed tomography (CT), dual-energy X-ray absorptiometry (DXA), mammography (MG), magnetic resonance imaging (MRI), mobile chest X-ray (MCXR), ultrasound (US), X-ray (XR), and other equipment, specifically reporting and radiology information system (RIS) and picture archiving and communication system (PACS) workstations. From the result of this analysis, the second objective is to plan, implement, and evaluate different energy waste mitigation strategies.

2. Materials and Methods

2.1. Overview of Methods

In accordance with the energy audits of processes standard UNI CEI EN 16247-3:2022 [20] and the cycle Plan-Do-Check-Act of ISO 50001 [21], a retrospective analysis of the energy usage of all imaging equipment and reporting and RIS/PACS workstations for diagnostic activities was carried out. Through this, the areas of highest energy usage were determined, and possible energy waste mitigation strategies were planned. Figure 1 presents a graphical representation of the study's methodological flowchart.

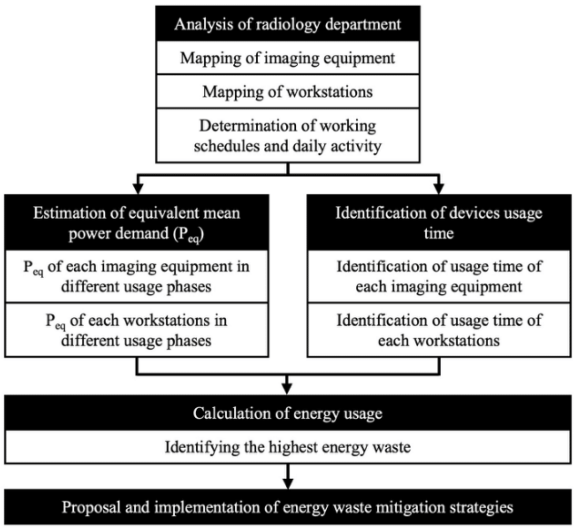


Figure 1. Study flowchart.

2.2. Study Setting

The energy usage of all imaging devices, CBCT (n = 1), CT (n = 1), DXA (n = 1), MG (n = 2), MRI (n = 2), MCXR (n = 2), US (n = 5), XR (n = 5), and all reporting (n = 10) and RIS/PACS (n = 27) workstations of the operational unit of Radiology at Ospedale Nuovo di Legnano (Legnano Hospital), a 555-bed public hospital in the metropolitan city of Milan, Italy, was evaluated. The floor plan of the department is shown in Figure 2.

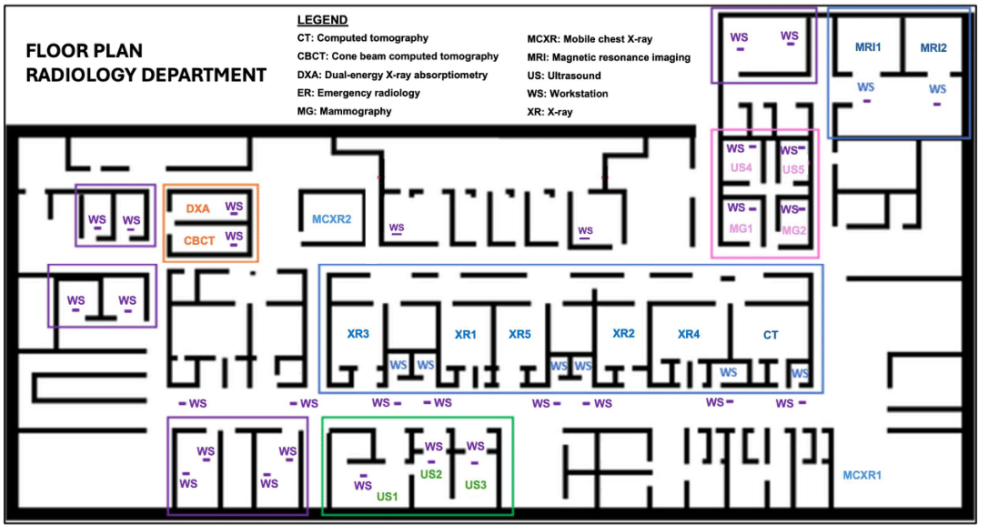


Figure 2. Floor plan of the radiology department of Ospedale Nuovo di Legnano.

The complete list of imaging equipment considered can be found in Appendix A. The working hours considered for the estimation of energy usage were from 8:10 a.m. to 3:30 p.m. (7.3 h) for all XR, DXA, MRI1, MG2, US3, US4, and US5 scanners; from 8:10 a.m. to 12:00 p.m. (4 h) for the CBCT scanner; from 8:10 a.m. to 4:30 p.m. (8.3 h) for the CT scanner; from 8:10 a.m. to 5:30 p.m. (9.3 h) for the US1 and US2 scanners; from 8:10 a.m. to 7:30 p.m. (11.3 h) for the MG1 scanner; from 8:10 a.m. to 11:30 p.m. (23.3 h) for the MRI2 scanner; and 24 h of operation for the MCXR devices of the radiology operational unit.

2.3. Study Design

The study was divided into two parts. The first part estimated the daily energy usage of each diagnostic modality and all reporting and RIS/PACS workstations in relation to the daily diagnostic activities performed, excluding when they are switched off at the end of the working day. The second part hypothesized and tested three different energy usage mitigation strategies: (1) optimizing the energy usage of reporting and RIS/PACS workstations, (2) reorganizing diagnostic activities to reduce energy waste, and (3) selecting for lower-energy imaging examinations without compromising clinical appropriateness.

2.4. Estimation of Energy Usage

In order to estimate the energy usage for each diagnostic imaging device and equipment (reporting and RIS/PACS workstations), initially the usage time (expressed in hours, h) per day was collected, considering the radiology department's activities performed between 1 January 2023 and 28 February 2023.

Regarding all imaging scanners, usage periods were divided into two states:

- Active period: the productive time, which includes patient or scanner positioning and image acquisition;

- Idle period: the non-productive waiting time interval between "active" time periods, when devices are "on" but not working.

As only the clinical operating hours of the imaging equipment were considered for this estimation, any energy consumption during the stand-by phase, i.e., when the scanner is switched off or not used after the working hours, was not estimated.

The time (T, expressed in hours) for the active period and the idle period was assessed by considering the total number of working hours per day, the total number of diagnostic examinations performed, and the allocated time duration of planned examinations (Table 1).

Table 1. Working schedules, number of examinations performed, time spent during activity, and waiting periods for each imaging modality.

	Start	End	Opening (h)	Exams per Month	Exams per Day	Exam Time (min)	Time (T)	
							Active Period (h)	Idle Period (h)
XR 1	8:10	15:30	7.3	600	30	10	5.0	2.3
XR 2	8:10	15:30	7.3	800	40	10	6.7	0.6
XR 3	8:10	15:30	7.3	200	10	10	1.7	5.6
XR 4	8:10	15:30	7.3	800	40	10	6.7	0.6
XR 5	8:10	15:30	7.3	80	4	10	0.6	6.7
DXA	8:10	15:30	7.3	88	11	10	1.8	5.5
CBCT	8:00	12:00	4.0	40	10	10	1.6	2.4
CT	8:10	16:30	8.3	350	36	10	6.2	3.1
MRI 1	8:10	15:30	7.3	248	10	35	5.8	1.5
MRI 2	8:10	23:30	15.3	500	22	35	12.8	2.5
MG 1	8:10	19:30	11.3	660	30	10	5	6.3
MG 2	8:10	15:30	7.3	40	2	10	0.3	7
US 1	8:10	17:30	9.3	500	25	20	8.3	1
US 2	8:10	17:30	9.3	500	25	20	8.3	1
US 3	8:10	15:30	7.3	200	10	20	3.3	4
US 4	8:10	15:30	7.3	300	15	20	5	2.3
US 5	8:10	15:30	7.3	200	10	20	3.3	4
MCXR 1	0:00	24:00	24.0		10	10	1.7	22.3
MCXR 2	0:00	24:00	24.0		25	10	4.2	19.8

RIS/PACS workstation usage periods were associated with three different states:

- Active period: the production time during which workstations are actively used by department staff;
- Idle period: the non-productive waiting time interval between "active" time periods, when workstations are "on" but not working;
- Stand-by period: the non-productive time that the equipment was switched on but there was no related imaging activity. During the stand-by period, workstations are able to consume less power while being able to resume its normal functions quickly.

The hours associated with these different periods can be found in Table 2.

Table 2. Number of hours for active, stand-by, and inactive periods for workstations (WSs) and reporting workstations (RWSs).

Different Energy Consumption Periods of Reporting Workstations in the Unit of Radiology			
	Active period (h)	**Stand-by period (h)**	**Idle period (h)**
RWS 1–2	6.5	2.1	15.4
RWS 3–4	5.8	2.0	16.1
RWS 5–10	9.1	2.3	12.6
Mean	7.2	2.1	14.7
Different Energy Consumption Periods of RIS/PACS Workstation in the Unit of Radiology			
	Active period (h)	**Stand-by period (h)**	**Idle period (h)**
WS (n = 27) Mean	6.8	10.2	8.0

Radiological equipment typically exhibits energy profiles characterized by short bursts of high-power demand followed by extended low-power intervals during the active phase (Figure 3) [15]. To simplify comparisons between these varying consumption patterns, the equivalent mean power demand, representing the total power supplied over the duration of a specific phase, was considered for both activity and waiting periods. This approach provides a single, easily interpretable parameter that consolidates the variable consumption profile and facilitates the straightforward comparison of different power requirements.

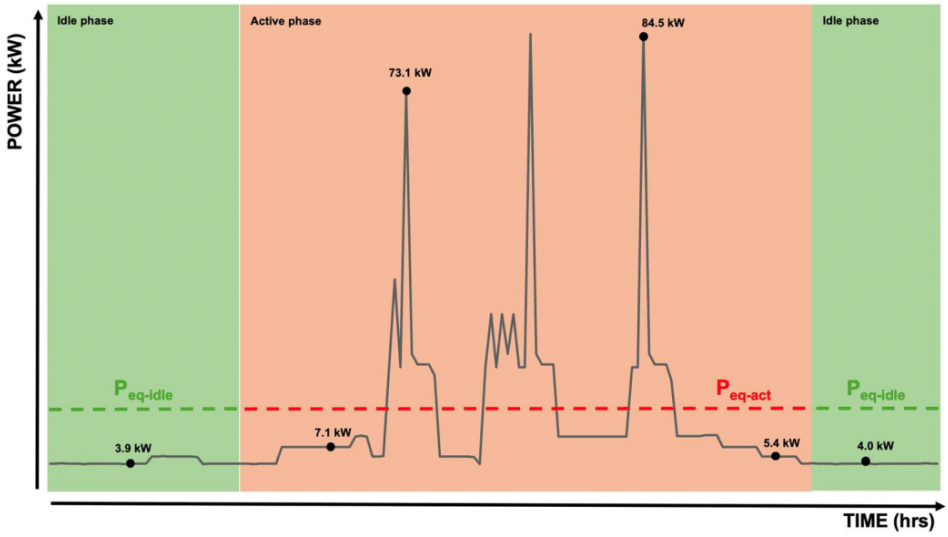


Figure 3. Diagram showing the representation of a CT scan is segmented (orange area) according to scan time. The equivalent mean power demand represents the average power required by the scanner during the active phase, considering power peaks during scanning and low power phases. The black dots on the power consumption diagram exemplify the consumption in kilowatts at the respective position on the graph. The green area identifies the waiting phase and defines the area associated with the equivalent mean power demand of that phase.

On the other hand, for MRI and ultrasound scanners, the equivalent mean power demand during the active phase and the idle phase coincides as the scan, although having some peaks during acquisition, has a rather constant active consumption, with the scanner constantly ready to scan [15,22].

Once the usage time of all imaging devices and all workstations has been calculated, the energy usages (E) (expressed in kWh) were estimated as the product of the equivalent mean power demand (P_{eq}) (expressed in kW) declared by device manufacturers of radiological scanners (Table 3) and workstations (Table 4) and the duration of each time (T), according to the formula:

$$\text{Energy}_i = \text{Equivalent Mean Power Demand}_i \cdot \text{Time}_i, \quad (1)$$

Table 3. Equivalent mean power demand (kW) and total energy used (kWh) per day during active and idle phases of all radiological scanners.

	Equivalent Mean Power Demand ($P_{eq\text{-}act}$) During Active Phase (kW)	Equivalent Mean Power Demand ($P_{eq\text{-}idle}$) During Idle Phase (kW)	Energy Used (E_{act}) During Active Period (kWh)	Energy Used (E_{idle}) During Idle Period (kWh)
XR 1	3.7	1.1	18.5	2.5
XR 2	3.7	1.1	24.8	0.7

Table 3. *Cont.*

	Equivalent Mean Power Demand ($P_{eq\text{-}act}$) During Active Phase (kW)	Equivalent Mean Power Demand ($P_{eq\text{-}idle}$) During Idle Phase (kW)	Energy Used (E_{act}) During Active Period (kWh)	Energy Used (E_{idle}) During Idle Period (kWh)
XR 3	3.5	1.1	5.9	6.2
XR 4	3.5	1.1	23.4	0.7
XR 5	3.3	1.0	2.0	7.3
DXA	2.3	0.7	4.1	3.9
CBCT	1.9	1.5	3.0	3.6
CT	16.4	4.0	45.9	12.4
MRI 1	19	19	110.2	28.2
MRI 2	19	19	243.2	47.5
MG 1	4.3	1.8	21.5	11.3
MG 2	4.3	1.8	1.3	12.6
US 1	1.1	1.1	9.1	1.1
US 2	1.1	1.1	9.1	1.1
US 3	1.1	1.1	3.7	4.4
US 4	1.1	1.1	5.5	2.5
US 5	1.1	1.1	3.7	4.4
MCXR 1	2.8	0.2	4.8	4.4
MCXR 2	2.8	0.2	11.8	3.9
Total			664.2	201.3

Table 4. Equivalent mean power demand (P_{eq}) (kW) and total energy consumed (kWh) per day during active, idle, and stand-by phases of all workstations.

	Equivalent Mean Power Demand (P_{eq}) (kW) [Active/Idle/Stand-By]	Total Energy Active Period (kWh)	Total Energy Idle Period (kWh)	Total Energy Stand-By Period (kWh)
RW (n = 10)	0.5/0.28/0.02	37.0	5.8	2.9
WS (n = 27)	0.3/0.17/0.02	55.0	46.8	4.3
Total		100.5	58.8	8

3. Results

3.1. Energy Usage

The total estimated number of daily imaging examinations is 489, divided into 2.0% CBCT, 16.4% CT, 2.3% DXA, 6.5% MG, 6.5% MRI, 72% MCXR, 17.4% US, and 41.7% XR.

All imaging equipment in the department stayed in idle mode for a portion of the working time (Table 1) ranging from 8% time in the idle period for XR2 and XR4 to 96% for MG2. The equipment that showed very dense schedules with idle periods of less than 20% during daily work were XR2, XR4, and MRI2.

The imaging scanners that spend a significant amount of working time in idle periods are MCXR2 (84%), XR5 (92%), MCXR1 (93%), and MG2 (96%). Among the workstations, those with the most time spent in the idle period are the RIS/PACS workstations with an average of 43%.

The estimation of the energy usage of each imaging scanners can be found in detail in Table 2. In the operational unit of radiology, MG2 is the scanner that used the least energy per day during the active period (1.3 kWh). Regarding the idle period, XR2 and XR4 used the least energy (0.7 kWh). MRI2 is the scanner that used the highest amount of energy during both the active period (243.2 kWh) and idle period (47.5 kWh), followed by MRI1 (110.2 kWh during the active period and 28.2 kWh during the idle period) and CT (45.9 kWh during the active period and 12.4 kWh during the idle period).

Furthermore, when analyzing the impact of the energy used during idle periods compared to the total daily energy usage of each device, the imaging modalities with the

highest non-productive energy usage were MG2 (91%), XR5 (78%), CBCT (55%), and DXA (49%) (Figure 4).

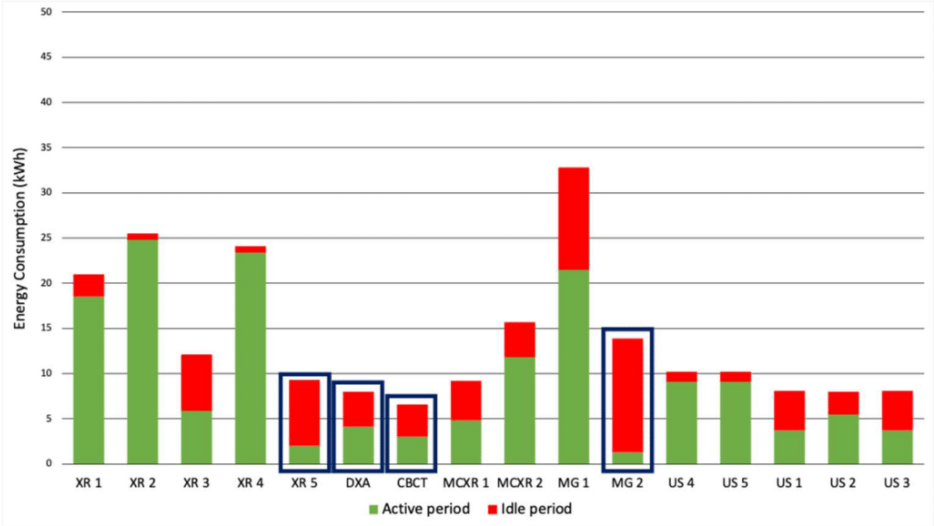


Figure 4. Energy usage for each imaging modality (active period and idle period during a working day). Modalities with high energy waste during idle period are contoured with dark blue boxes.

Mean energy usage for each imaging modality for the active period and idle periods is summarized in Figure 5.

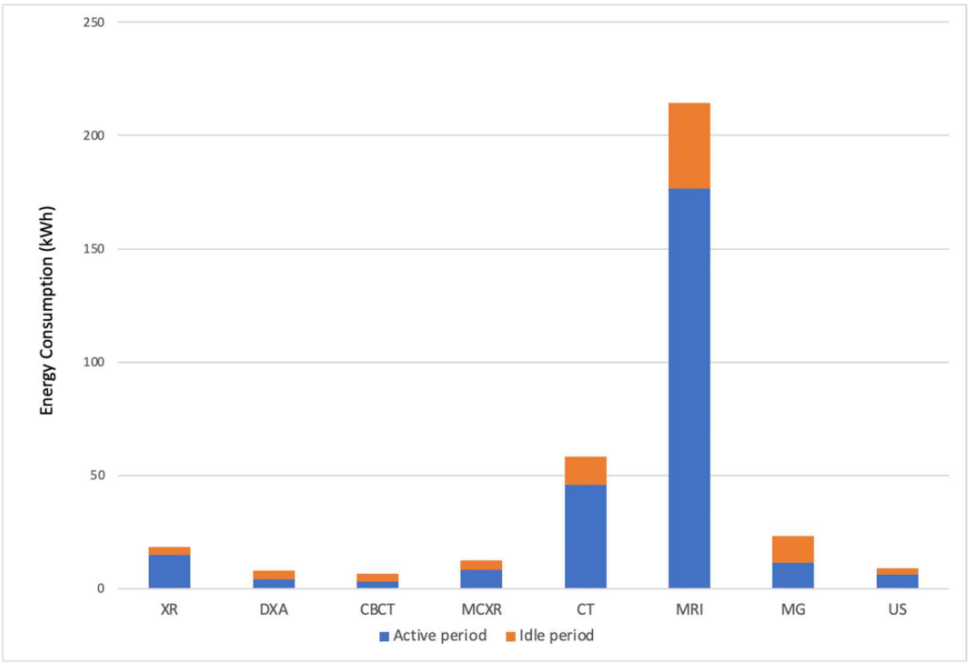


Figure 5. Mean energy consumption (kWh) for each imaging modality (active period and idle period during a working day).

Considering the mean energy consumption for each diagnostic modalities, CBCT modality has the lowest daily energy usage (6.6 kWh), followed by DXA (8 kWh), US (8.9 kWh), MCXR (12.5 kWh), XR (18.4 kWh), and MG (23.4 kWh). The diagnostic modalities with the highest mean daily energy usage are CT (58.3 kWh) and

MRI (214.6 kWh). In total, it was estimated that all radiological device modalities in the department consume 710.2 kWh per day, divided in 551.5 kWh (78%) during the active period and 158.7 kWh (22%) during the non-productive idle period.

The energy used by the workstations was considered for all devices in the department (Table 2). Overall, the highest energy usage is associated to the RIS/PACS workstations in the operating unit of radiology (active period = 55.0 kWh; idle period = 46.8 kWh; stand-by period: 4.3 kWh).

Concerning the workstations, the total energy usage during daily work is estimated at 167.3 kWh, divided into 100.5 kWh (60.1%) during the active period, 58.8 kWh (35.1%) during the idle period, and 8 kWh (4.8%) during the stand-by period. In total, the department's energy usage was estimated at 877.5 kWh during the daily work activity.

3.2. Mitigation Strategies

Based on the energy usage data estimated, in March 2023, three different mitigation strategies were proposed and evaluated by an audit committee composed by radiographers, radiologists, and clinical engineers of the hospital in the radiology department, considering the needs of the radiology staff. The proposed mitigation strategies were summarized in Figure 6.

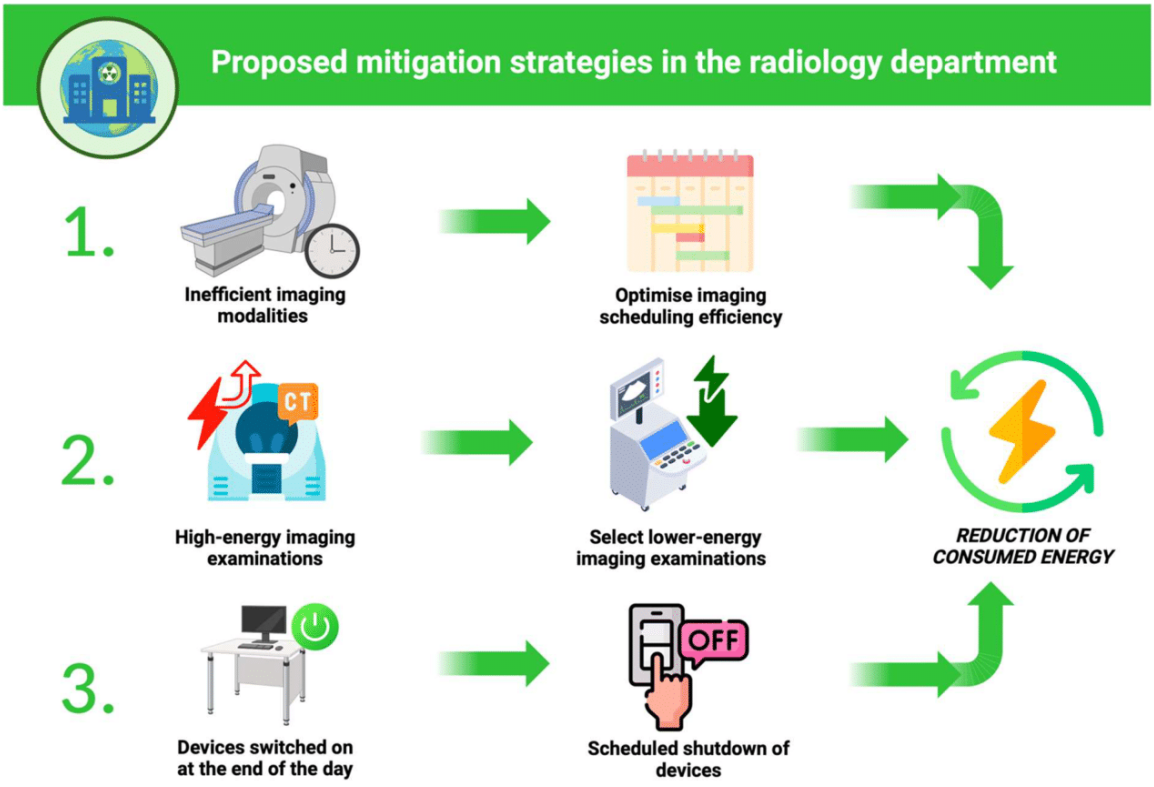


Figure 6. Proposed mitigation strategies in the radiology department.

3.2.1. Mitigation Strategy 1: Optimize Imaging Scheduling Efficiency

Based on the results of the energy usage analysis of the imaging modalities for active and idle periods, the most energy inefficient imaging modalities will be identified, and energy waste mitigation strategies will be formulated to optimize the efficiency of imaging scheduling.

In the ratio of active period to idle period, as shown above, the greatest energy inefficiencies concern the imaging modalities XR5, CBCT, MCXR1, and MG2. In response, four direct interventions to optimize imaging scheduling efficiency were identified:

1. Reduction in XR5 activity, which is exclusively ambulatory and do not include unscheduled urgent examinations, from 5 to 3 working days by redistributing exams on scheduled days.
2. Reduction in CBCT activity times based on the number of patients booked and the early closure of diagnostics at the end of scheduled activity.
3. Redistribution of MG1 mode activity to MG2, keeping both modes active.
4. Exclusive use of MCXR2, keeping MCXR1 switched off, concentrating activity on a single device.

The results of this mitigation strategy can be seen in Table 5. In summary, an increase of 3.0% in energy used during the active period, a reduction of 38.3% in energy usage during the non-productive idle phase, and a total reduction of 16.6% in the total energy used per day were achieved.

Table 5. Results of mitigation strategy 1: optimize imaging scheduling efficiency.

	Active Period Before (kWh)	Active Period After (kWh)	Δ Active Period (%)	Idle Period Before (kWh)	Idle Period After (kWh)	Δ Idle Period (%)	Total Energy Before (kWh)	Total Energy After (kWh)	Δ Total Energy (%)
XR5	2	3.6	80.0%	7.3	6.2	−15.1%	9.3	9.8	5.4%
CBCT	3	3.7	23.3%	3.6	0.0	−100%	6.6	3.7	−44.0%
MG1	21.5	11.6	−46.0%	11.4	8.3	−27.2%	32.9	19.9	
MG2	1.3	11.6	792.3%	12.6	8.3	−34.1%	13.9	19.9	
Total MG	22.8	23.2	1.8%	24	16.6	−30.8%	46.8	39.8	−15.0%
MCXR2	11.8	16.3	38.1%	3.9	3.6	−7.7%	15.7	19.9	
MCXR1	4.8	0.0	−100.0%	4.4	0.0	−100.0%	9.2	0.0	
Total MCXR	16.6	16.3	−1.8%	8.3	3.6	−56.6%	24.9	19.9	−20.1%
Total Modalities	83.8	86.3	3.0%	75.5	46.6	−38.3%	159.3	132.9	−16.6%

3.2.2. Mitigation Strategy 2: Select Lower-Energy Imaging Examinations

Considering the emergency activities of the unit of radiology, it was identified that for patients affected by abdominal pain, both XR and CT scans were frequently used for diagnosis. However, according to the guidelines of the American College of Radiology Appropriateness Criteria [23], ultrasound imaging could serve as an equally appropriate diagnostic alternative. A retrospective evaluation was conducted to explore the feasibility of substituting US imaging for XR and CT in these cases to achieve a potential reduction in energy usage.

For this analysis, a sample of 41 diagnostic investigations performed for different types of abdominalgia was taken, identifying the diagnostic strategy performed and its low-energy alternative with equal diagnostic appropriateness and identifying total energy usage.

The results of this mitigation strategy are shown in Table 6. In overview, the adoption of low-energy diagnostic strategies with equal diagnostic appropriateness can lead to a −80.4% reduction in energy used in 41 different diagnostic investigations.

Table 6. Results of mitigation strategy 2: select lower-energy imaging examinations.

Num. Exams	Clinical Question	Diagnostic Exams Performed	Low-Energy Alternative	Actual Energy Consumption (kWh)	Alternative Energy Consumption (kWh)	Δ Total Energy (%)
22	Generic abdominal pain	XR	US	77	24.2	−68.6%
5	Renal colic	XR + CT	US + XR	99.5	23	−76.9%
6	Air-fluid levels	XR + CT	US + XR	119.4	27.6	−76.9%
8	Chronic hepatitis	CT	US	131.2	8.8	−93.3%
Total: 41				427.1	83.6	−80.4%

3.2.3. Mitigation Strategy 3: Scheduled Shutdown of Devices

Based on the results of the analysis of the energy usage of the workstations, the energy waste mitigation strategy will be planned through the scheduled switch-off of all workstations at the end of the working day in the radiology unit.

Among the calculated energy usage, one of the critical issues is the high energy usage of the RIS/PACS workstations during the non-productive idle and stand-by periods.

The results of this energy waste mitigation strategy can be seen in Table 7. After the implementation of the mitigation strategy, there was a 43.3% reduction in energy used by RIS/PACS workstations in the radiology unit.

Table 7. Results of mitigation strategy 3: scheduled shutdown of devices.

	Active Before (kWh)	Active After (kWh)	Idle Before (kWh)	Idle After (kWh)	Stand-By Before (kWh)	Stand-By After (kWh)	Total Energy Before (kWh)	Total Energy After (kWh)	Δ Total Energy (%)
WS (n = 27)	55.0	45.3	46.7	5.5	4.3	9.3	106.0	60.1	−43.3%

4. Discussion

In this single-center study of a medium-sized Italian radiology department, radiology activity volumes were evaluated, and the total electricity usage of all diagnostic imaging equipment and workstations over a full working day was estimated. The total energy usage of the imaging department was estimated at 877.5 kWh per day. Analyzing the usage data of individual devices during a working day, the results of this study showed that more advanced individual imaging equipment (CT and MRI) has a greater impact in terms of both energy usage than individual imaging devices such as XR or US, confirming results already reported by other authors [13,24]. These results underline the importance of choosing the most suitable diagnostic method both for the clinical question and from the point of view of the energy usage required to perform it. This was the focus of the second mitigation strategy proposed by the study, namely, the choice of lower-energy imaging examinations, when clinically appropriate, which showed promising results, ensuring not only energy savings but also benefits in terms of reduced waiting times, patient satisfaction, and lower costs, as confirmed in other studies [25,26].

Considering the energy used during idle periods by imaging equipment, it accounts for 22% of the total energy usage daily, with devices that is mostly inactive due to organizational reasons, some with 90% of energy usage associated with idle periods. These aspects underline the importance of reducing energy waste through mitigation strategies while maintaining the department's diagnostic effectiveness. Although the energy used during the activity period is necessary for patient care, the idle periods must be the main target of these energy-saving actions.

This study showed that through different energy waste mitigation approaches, encouraging results can be achieved. Through optimized scheduling efficiency, it was possible to achieve an 16.6% reduction in total electricity usage and 38.3% reduction during idle periods maintaining and increasing the use of the equipment, as already demonstrated in the literature with MRI [16]. The third energy waste mitigation strategy considered, the scheduled shutdown of devices during the non-productive idle and stand-by periods, finds confirmation in the literature, still with workstations and other imaging modalities [9,10,18,19]. The results of this study highlight the importance of a systematic approach to energy management. This study has shown that the adoption of energy performance monitoring and identification practices allows inefficiencies to be identified and resource use to be improved. This is consistent with the energy planning principle of ISO 50001, which encourages organizations to identify significant energy consumption and define energy performance indicators to drive continuous improvement [21].

The energy-waste mitigation strategies considered are just a few of those that can be implemented in a radiology department. For example, implementable mitigation strategies may include shortening imaging protocols for examinations with low environmental impact but the same diagnostic value [25], using energy-efficient technologies in the construction and operation of radiological services [27], using artificial intelligence to optimize examination times [28,29], and optimizing data storage, which is associated with high energy usage [29]. Radiology departments of different sizes can implement strategies similar to those proposed or adapt them according to their own workflows and resources, either by identifying and reducing unnecessary examinations [30] or by rescheduling activity and redistributing the necessary resources, also with the help of new technologies [31].

This study shows how decisive it is in the radiology context to consider an entire radiology department and not only individual equipment to be able to introduce energy waste mitigation strategies and achieve an increase in environmental sustainability and energy savings of diagnostic activities.

It is important to emphasize that energy usage is only one aspect of the environmental sustainability of medical radiology departments. CO_2 emissions associated with radiology activities also relate to the use of consumables and contrast media [32,33], waste generation [34,35], the sustainable management of helium in MRI [22], and the travelling of patients and staff to and from radiology facilities [36,37]. In the context of a more comprehensive analysis of the radiology department's environmental impact and the identification of best practices for a more sustainable radiology, it would be useful to also consider all these aspects beyond the energy usage of equipment, through tools designed to calculate carbon emissions, such as life cycle assessment [12,38,39].

This study has limitations. To identify the energy usage of all diagnostic modalities and workstations in the department, work activity over a limited time window (January–February 2023) was considered. Other similar studies have carried out data collection over longer time windows [12,40]. Furthermore, energy usage was estimated as the product of the equivalent mean power demand declared by scanner manufacturers and the duration of each activity, following examples described in the literature [13,16]. The use of power meters would allow a calculation of the real usage considering all variables associated with the activity of a radiology department [9,41]. In addition, the allotted time duration of a planned examination was considered to estimate the duration of the daily examinations of each equipment to obtain the most reproducible data possible. The effective duration of the examinations performed in the time frame considered was not considered because it varies according to the type of patient and the clinical demand. Another limitation is that the study only considered radiological activities in a single hospital environment. Differences in the energy usage of diagnostic modalities were identified

due to both variations between the devices, the type of use, and the varying number of examinations per month and per day within a modality and between modalities [15]. Due to this variability, absolute levels of energy usage and emissions in other contexts may differ. Energy usage associated with the non-working time of day and heating, ventilation, and air conditioning systems and ward lighting systems are not included in the study. The effect of these omissions is only to underestimate the total amount of energy usage of the entire department, which is outside the purpose of this study. Mitigation strategy 1 focused on specific equipment within the radiology unit as mitigation actions needed to align with the unit's normal day-to-day operations. Lastly, the results of mitigation strategy 2 are associated with a retrospective estimate. No patients were included in the study; therefore, it was not possible to actively evaluate the strategy of choice lower-energy imaging examinations. Through an update of the ethics committee approval, the efficacy could be verified prospectively in future studies. It is important to emphasize that all energy waste mitigation strategies can cause inconvenience from an organizational and patient feedback perspective. These aspects must also be considered when planning and possibly introducing mitigation strategies in daily clinical practice.

5. Conclusions

Analyzing the energy usage of all imaging devices and workstations is critical to assessing energy waste in a radiology department. This study highlights energy-intensive diagnostic imaging practices and helps identify potential energy inefficiencies in a radiology department. Energy waste mitigation strategies can help reduce energy usage and can generate effective results such as those described:

- Optimize imaging scheduling efficiency −16.6% of energy usage;
- Select lower-energy imaging examinations −80.4% of energy usage;
- Scheduled shutdown of devices −40.9% of energy usage.

Introducing these strategies could help radiology departments that aspire to become greener, reducing their environmental footprint without compromising the quality of patient care.

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

Abbreviations

The following abbreviations are used in this manuscript:

CT	Computed tomography
CBCT	Cone beam computed tomography
DXA	Dual-energy X-ray absorptiometry
E	Energy
GHG	Greenhouse gas
MG	Mammography

MCXR	Mobile chest X-ray
MRI	Magnetic resonance imaging
P_{eq}	Equivalent mean power demand
PACS	Picture archiving and communication system
RIS	Radiology information system
RWS	Reporting workstation
US	Ultrasound
WS	Workstation
XR	X-ray

Appendix A

The full list of radiological equipment examined is as follows:

XR1	Samsung AccE GC85A (Samsung Healthcare, Seoul, Republic of Korea)
XR2	Samsung AccE GC85A (Samsung Healthcare, Seoul, Republic of Korea)
XR3	Carestream DRX-Compass (Carestream Health, Rochester, NY, USA)
XR4	Carestream DRX-Compass (Carestream Health, Rochester, NY, USA)
XR5	Discovery RF180 Radiography and Fluoroscopy System (GE HealthCare, Chicago, IL, USA)
CT	Discovery HD750 CT scanner (GE HealthCare, Chicago, IL, USA)
MRI1	Philips Ingenia 1.5-T MRI scanner (Philips Healthcare, Best, Netherlands)
MRI2	Philips Ingenia 1.5-T MRI scanner (Philips Healthcare, Best, Netherlands)
CBCT	Cone Beam 3D imaging New Tom Giano HD (NewTom Official, Imola, Italy)
DXA	GE Lunar iDXA (GE HealthCare, Chicago, IL, USA)
MG1	Hologic 3D Dimensions (Hologic Inc, Marlborough, MA, USA)
MG2	Hologic 3D Dimensions (Hologic Inc, Marlborough, MA, USA)
MCXR1	Carestreams DRX-Revolution (Carestream Health, Rochester, NY, USA)
MCXR2	Carestreams DRX-Revolution (Carestream Health, Rochester, NY, USA)
US1	Esaote MyLab X8c (Esaote SpA, Genoa, Italy)
US2	Esaote MyLab X8c (Esaote SpA, Genoa, Italy)
US3	Esaote MyLab X8c (Esaote SpA, Genoa, Italy)
US4	Samsung Ultrasound system RS85 (Samsung Healthcare, Seoul, Republic of Korea)
US5	Samsung Ultrasound system RS85 (Samsung Healthcare, Seoul, Republic of Korea)
Reporting workstations (RWS) (n = 10)	Barco Nio Gray 5.8 MP (Branco NV, Kortrijk, Belgium)
RIS/PACS workstations (WS) (n = 27)	HP z600 computer (HP Inc., Palo Alto, CA, USA)

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PAPER V

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Research Article

Analysis of waste generation and environmental impact of a multi-dose iodinated contrast media injection system in an emergency radiology department

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ABSTRACT

Introduction: The introduction of automatic multi-dose injectors has revolutionised contrast media management in Computed Tomography (CT) imaging, affecting both workflow efficiency and waste production. However, there is limited evidence regarding their environmental performance in high-turnover emergency settings. This study provides a quantitative assessment of contrast media waste and of materials associated with a multi-dose injector in an emergency radiology department.

Methods: All iodinated contrast media (ICM) administrations for CT examinations performed between May 2023 and April 2024 were retrospectively analysed using data extracted from the injector's digital reports. For each examination, administered volume, unused ICM, number of vials, and associated plastic, glass, and paper waste were recorded and aggregated monthly.

Results: A total of 4,418 contrast-enhanced CT scans were reviewed. Overall, 1,362 vials of ICM were used, corresponding to 600.9 L loaded and 456.2 L administered. The average injected dose was 103.3 mL per scan (median 110; IQR 70–127), while 144.7 L (31.7%) of ICM were wasted, equivalent to 290 vials and 53.1 kg of iodine. Additionally, 411 daily injector kits and 4,803 patient lines contributed to the total waste stream, mainly composed of plastic and glass components.

Discussion: Most ICM waste derived from residual volumes in daily injection kits discarded at the end of each shift, rather than from patient administration. High variability in patient flow and fixed daily kit usage appear to be the determining factors of environmental impact. These findings indicate the need for operational adjustments, such as the use of ICM vials of different volumes to reduce waste at the end of the day and the implementation of containers for recycling ICMs, disposable devices and packaging.

Conclusion: Contrast media waste remains a relevant source of environmental impact in emergency CT operations. Reducing residual ICM and optimising injector use could significantly improve sustainability and resource efficiency. Radiographers could play an important role in monitoring injector usage, promoting awareness, and implementing waste reduction strategies within clinical workflows

RÉSUMÉ

Introduction/contexte: L'introduction des injecteurs automatiques multidoses a révolutionné la gestion des produits de contraste en imagerie TDM, affectant à la fois l'efficacité du flux de travail et la production de déchets. Cependant, les données disponibles concernant leur performance environnementale dans les services d'urgence à forte

Abbreviations: CECT, Contrast enhanced computed tomography; CT, Computed tomography; GHG, Greenhouse gas; ICM, Iodinated contrast media; IQR, Interquartile range; PACS, Picture archiving and communication system; SD, Standard deviation.

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activité sont limitées. Cette étude fournit une évaluation quantitative des déchets de produits de contraste et des matériaux associés à un injecteur multidoses dans un service de radiologie d'urgence.

Méthodologie: Toutes les administrations de produits de contraste iodés (PCI) pour les examens en TDM réalisés entre mai 2023 et avril 2024 ont été analysées rétrospectivement à partir des données extraites des rapports numériques de l'injecteur. Pour chaque examen, le volume administré, les PCI inutilisés, le nombre de flacons et les déchets de plastique, de verre et de papier associés ont été enregistrés et agrégés mensuellement.

Résultats: Au total, 4 418 tomogrammes avec produit de contraste ont été examinés. Au total, 1362 flacons de produit de contraste ont été utilisés, ce qui correspond à 600,9 litres chargés et 456,2 litres administrés. La dose moyenne injectée était de 103,3 ml par examen (médiane 110; EI 70-127), tandis que 144,7 L (31,7 %) de produit de contraste ont été gaspillés, soit l'équivalent de 290 flacons et 53,1 kg d'iode. De plus, 411 kits d'injection quotidiens et 4 803 lignes de patients ont contribué au flux total de déchets, principalement composé de composants en plastique et en verre.

Discussion: La plupart des déchets de produit de contraste provenaient des volumes résiduels des trousses d'injection quotidiennes jetées à la fin de chaque quart de travail, plutôt que de l'administration aux patients. La grande variabilité du flux de patients et l'utilisation quotidienne fixe des trousses semblent être les facteurs déterminants ayant une incidence sur l'environnement. Ces résultats indiquent la nécessité d'ajustements opérationnels, tels que l'utilisation de flacons de produit de contraste de différents volumes afin de réduire les déchets à la fin de la journée et la mise en place de conteneurs pour le recyclage des produits de contraste, des dispositifs jetables et des emballages.

Conclusion: Les déchets de produits de contraste restent une source importante d'impact environnemental dans les activités de TDM d'urgence. La réduction des résidus de produits de contraste et l'optimisation de l'utilisation des injecteurs pourraient améliorer considérablement la durabilité et l'efficacité des ressources. Les radiographes pourraient jouer un rôle important dans la surveillance de l'utilisation des injecteurs, la sensibilisation et la mise en œuvre de stratégies de réduction des déchets dans les flux de travail cliniques.

Keywords: Contrast media; Automatic injector; Computed tomography; Environmental sustainability; Emergency radiology

Introduction

Environmental awareness has become highly significant, and its importance is increasingly recognised in the healthcare sector. Nowadays, radiology departments have a considerable carbon footprint, consuming a large amount of energy [1–4] and generating a significant volume of waste [5–7]. Therefore, research on the environmental impact of radiology has increased over recent years [8,9]. Radiological activity is estimated to contribute approximately 1% of global greenhouse gas (GHG) emissions, mainly due to the extensive use of energy-intensive imaging equipment [10–13].

Another important aspect associated with the environmental impact of radiological activities is waste generation. Among waste generation factors, the use of iodinated contrast media (ICM) and their discharge into the environment represent an important sustainability issue [14–16]. High costs associated with the production of iodine, considered a scarce and limited resource, and a greater focus on saving resources, have increased the focus on iodine recycling [17–22]. The number of annual computed tomography (CT) examinations is increasing and leads to a higher demand, higher use of ICM and a significant amount of waste with considerable environmental and economic challenges. In fact, approximately 100 million contrast-enhanced computed tomography (CECT) examinations are performed worldwide each year, resulting in the consumption of more than 10 million litres of iodinated contrast media [17,23,24]. The use of ICM presents challenges, particularly related to their management, recycling and disposal. Indeed, recent studies show that ICM have been detected in wastewater and surface water worldwide and standard purification techniques are insufficient to remove these substances [23,25]. ICMs also contribute to significant contamination of drinking water systems due to patient urination after procedures, posing a threat to aquatic ecosystems and drinking water supplies [23]. To mitigate this impact, future measures should focus on minimising the use and waste of ICMs. The introduction of new automatic injectors, which has led to a change in ICM administration, workflow and waste production, can play a key role [26]. This study aims to analyse the waste production of an automatic injector in a radiology department and to hypothesise possible waste mitigation strategies.

Materials and methods

Study design

ICM usage was estimated retrospectively by reviewing all consecutive emergency CECT examinations performed in a Radiology Emergency Department between 1 May 2023 and 30 April 2024, with no additional exclusion criteria apart from missing injector data. All emergency CT examinations performed during the stated time frame were therefore considered. If a subject had undergone more than one CECT examination during the observation period, all the examinations were considered. Only studies conducted in the CT suite equipped with Centargo (Bayer AG, Leverkusen, North Rhine-Westphalia, Germany) injector were included in the analysis. Contrast-enhanced CT examinations performed with manual (hand) injection or using different injection systems were excluded from the study. The injector analysed in this study is a dual-head programmable automatic piston-based injector that uses the same ICM vial and saline bag across multiple patients, requiring only the replacement of the patient line between examinations. The

CECT examinations included in the study involved the brain, head and neck, chest, abdomen and pelvis, as well as the upper and lower limb regions.

The volume of ICM administered is automatically recorded on the data report available in the hospital's Picture Archiving and Communication System (PACS) (Enterprise Imaging Platform, Agfa Healthcare, Mortsel, Belgium) by the automatic injector and was used to calculate the average mL of ICM administered per study. Individual contrast volumes were recorded to the nearest millilitre, whereas cumulative volumes are presented in litres for reporting clarity. ICM injected into each patient was subtracted from the total ICM loaded into the automatic injector to calculate the average mL of ICM wasted per study. ICM waste was defined as the difference between the volume of ICM loaded into the injector and the volume administered to the patient. ICM waste also included residual ICM remaining in the vials and in the automatic injector's syringe before changing the daily kit. Any unused ICM is typically discarded as waste. Two-hundred- and 500-mL vials of ICM with different concentrations (320 mg/mL, 350 mg/mL, 370 mg/mL and 400 mg/mL) were emptied of contrast and weighed. The weight of each item, including glass, paper, plastic, syringes, and patient lines, was obtained through direct measurements using a digital weighing scale with a resolution of 1 g to calculate the total annual weight of disposable materials. Waste weight measurements were obtained through a single set of measurements performed independently by two researchers; this methodological aspect is acknowledged as a limitation of the study.

Ethics statement

Ethical approval was not required for this study, as it was a retrospective analysis of anonymised data and focused exclusively on the assessment of waste production, without involving patient-related data or interventions, in accordance with institutional policies.

Statistical analysis

All data were collected and organised using Microsoft Excel (Microsoft Cork, Redmond, WA) and subsequently analysed descriptively using IBM SPSS V3 (IBM Inc, Armonk, NY). Descriptive statistics were computed to summarize the characteristics of the dataset, including the number of CECT examinations, ICM volumes administered, ICM wasted and the distribution of disposable materials. Continuous variables were assessed for normality and are reported as mean ± standard deviation (SD) when normally distributed, or as median and interquartile range (IQR) when non-normally distributed. Categorical variables, including the ICM's concentrations and vials' size, were presented as absolute frequencies and percentages.

Results

Data from all CECT examinations were retrieved from the hospital's PACS from May 2023 to April 2024. The dataset consisted of 4,441 consecutive CECT acquisitions, of which 4,418 were included in the analysis; 23 examinations (0.5%) were excluded due to missing information on injected ICM volumes. The mean number of CECT examinations performed was 12 per day and 368 per month. A total of 600.9 L of ICM were loaded into the injector, of these, 456.2 L were injected, with an average dose per examination of 103.3 mL (median 110 mL, IQR 70-127). The distribution of ICM loaded and ICM wasted monthly is shown in Fig. 1.

Table 1
Type of ICM used in the radiology department, their relative concentrations and the quantity of ICM wasted.

ICM concentration (mg/mL)	ICM waste (L)	ICM waste %
320	4.7	3.2
350	9.8	6.8
370	130.1	89.9
400	0.1	0.1

ICM wasted amounted to 144.7 L (32.7 mL per exam), corresponding to n=290 500 mL vials (a total of 76.9 kg of glass and 14.2 kg of paper) and 31.7% of the total ICM loaded into the automatic injector. The specific quantities of ICM wasted are illustrated in Table 1.

ICM volume administered for the examination ranged from 25 to 155 mL, as shown in Fig. 2.

Waste production of disposal materials was categorised into three streams: recyclable plastic, recyclable paper and recyclable glass. In one year, 1,362 ICM vials are used, more precisely 267 200-ml glass vials and 1,095 500-ml vials, of which 1,075 are glass and 20 are plastic. We also used 411 daily kits, for a total of 34 per month, and 4,803 patient lines, for a total of 13 per day. All individual weights of disposable materials are analysed in Table 2.

The total weight of the waste generated from these 4,418 CECT examinations is outlined in Fig. 3. In particular, the total waste amount was 736.2 kg divided as follows: 81.1 kg (11 %) of recyclable paper, 342.5 kg (46.5 %) of recyclable plastic and 312.6 kg (42.5 %) of glass.

Discussion

This study analysed the amount of waste produced in a radiology department, focusing on ICM and its disposable materials. The results show that CECTs represent a significant source of waste production and resource consumption. In fact, the total quantity of iodine wasted corresponds to 53.1 kg. This waste is not negligible, both economically and environmentally, considering the number of CECTs performed (n = 4,418) during the period under consideration, the cost of producing iodine, a scarce natural resource and the implications in terms of waste generated, particularly glass, paper and plastic. Due to excretion via the patients' urine, ICM enter surface waters and groundwater systems, and in recent years concerns have grown re-

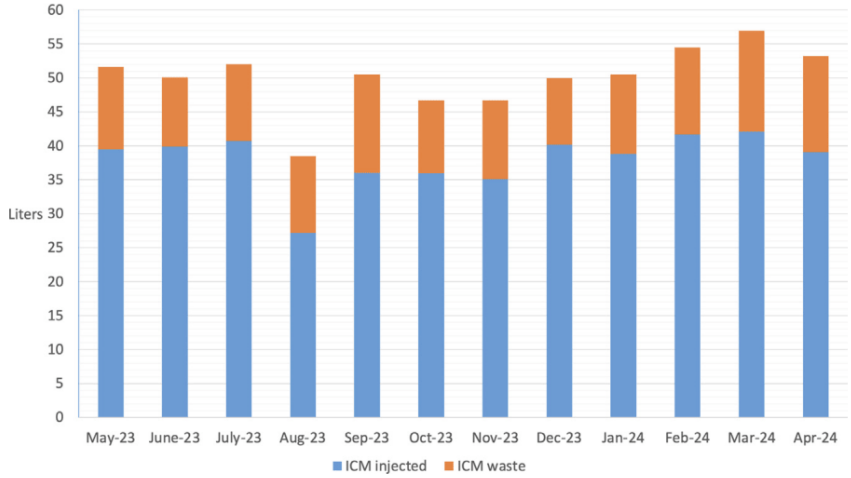


Fig. 1. Monthly volumes of iodinated contrast media (ICM) used in the Emergency Radiology Department over the 12-month study period. Blue bars represent ICM administered to patients, while orange bars indicate ICM wasted, including residual volumes remaining in vials and in the automatic injector syringe. Volumes are expressed in litres.

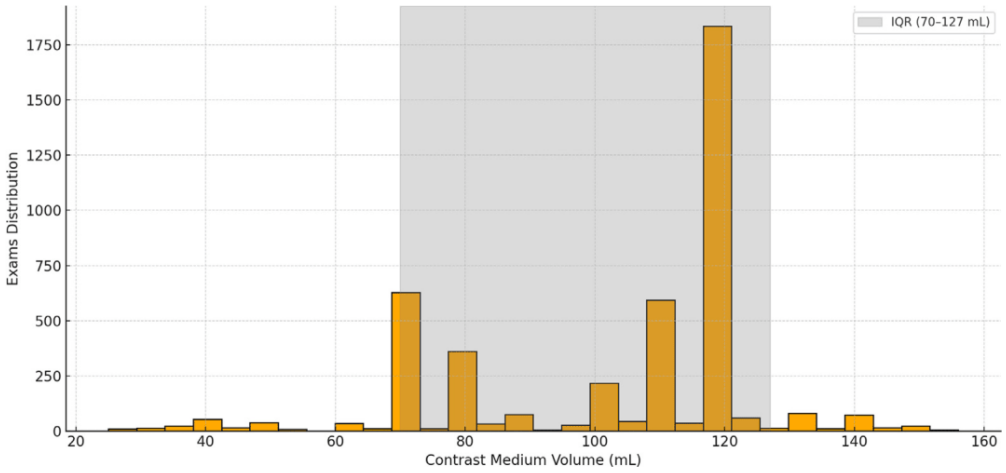


Fig. 2. Distribution of ICM injected with the relative frequencies. The average dose for examination amount of 103.3 mL with an interquartile range between 70 mL and 127 mL.

Table 2
Weights (g) of the single disposable materials used for one CECT examination.

	Plastic (g)	Glass (g)	Paper packaging (g)	Plastic packaging (g)	Total waste (g)
Daily kit	414	-	7	190	**611**
Patient line kit	30	-	3	3	**36**
500-mL glass ICM vial	-	256	49	-	**305**
500-mL plastic ICM vial	300	-	38	-	**338**
200-mL glass ICM vial	-	104	35	-	**139**

garding the impact of these substances on the aquatic environment and the water cycle. Consequently, an increasing amount of evidence highlights the environmental problem caused by the breakdown of ICM degradation products [27]. High concentrations of ICM were found in rivers and lakes in many regions of the world, such as the Sydney estuary (Australia), Madrid (Spain), the Danube and Rhine (Germany), Taihu Lake (China), Adriatic Sea (Italy), Aegean Sea and Dardanelles (Greece & Turkey) and San Francisco Bay (USA) [16,28–31]. Although ICMs are inherently low in toxicity, the by-products resulting from their transformation in wastewater treatment plants and in the environment can pose a threat to aquatic ecosystems and the safety of drinking water [16,32]. Therefore, this environmental impact can be reduced only through strategies and measures concerning optimised management of ICM use and disposal. With the increase in CECT examinations,

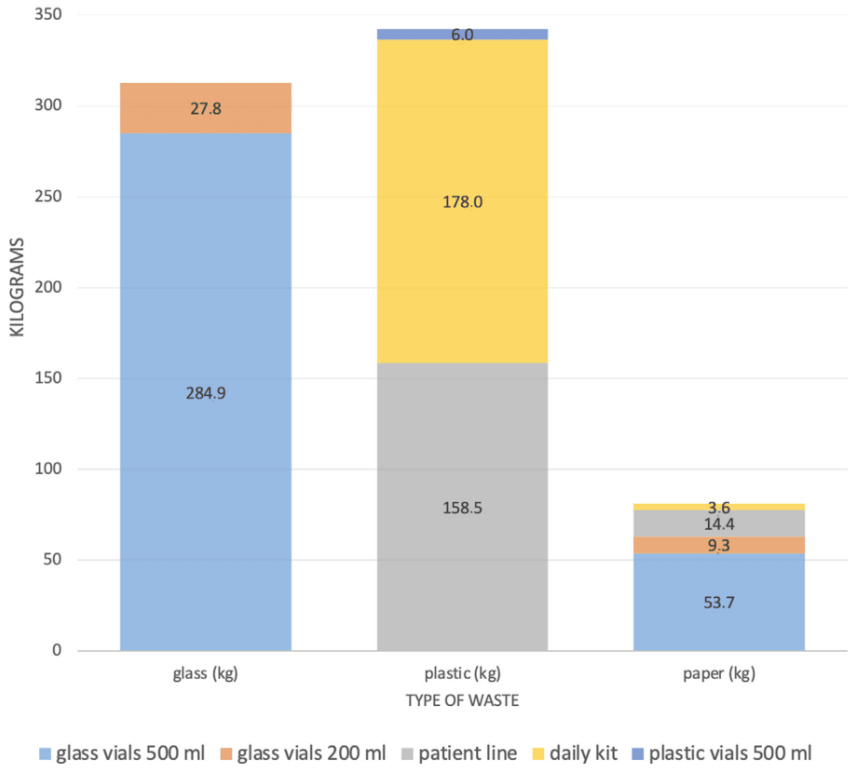


Fig. 3. Total weight (kg) of glass, plastic, and paper waste generated by contrast-enhanced CT (CECT) examinations during the study period. Stacked bars illustrate the contribution of individual disposable components, colour coded as follows: glass vials 500 m L (light blue), glass vials 200 mL (orange), patient lines (grey), daily injector kits (yellow), and plastic vials 500 mL (blue).

the use of single-dose vials has become a major contributor to pharmaceutical waste, carrying both environmental and economic consequences [33]. An alternative to single-dose ICM bottles is representing by multi-dose packaging options, which have larger volumes and can deliver repeat ICM doses. Several studies in the literature have also investigated multi-dose ICM packaging, recognising the significant waste associated with using single-dose bottles, demonstrating the feasibility of reducing ICM waste when switching to multi-dose packaging [33–36]. The introduction of automatic injectors has been a step forward in workflow management and waste reduction, improving administration efficiency and reducing human error. Studies in the literature have demonstrated the superior efficacy and efficiency of automatic multi-use injector compared to single-use syringe-based injectors [36,37], and their use has been associated with a reduction in ICM volumes [38] optimising ICM waste and preparation time, allowing radiographers to focus more on patient management and care [26]. Based on the data analysed, we can state that there is good diversification of ICM in our radiology department during the period under review, but the amount of wasted ICM remains high compared to other studies that considered automatic injectors and multi-dose vials. For example, Lindsey et al. [33] reported that, using 100 mL single-dose ICM bottles, the average waste was 19.7 mL per CT scan and that the adoption of a multi-dose ICM system may reduce both pharmaceutical and plastic waste. Therefore, waste reduction strategies must be implemented to decrease the amount of waste produced, including through smarter inventory management. The use of vials of different volumes would allow for a more flexible approach, optimising the use of ICM and reducing surpluses. Similar findings were also highlighted by Pepin et al., [35] who highlighted an average waste of 26 mL per CECT examination, using only 100 ml vials. Diversifying vial sizes and combining this strategy with multi-dose injectors can therefore reduce ICM waste by up to 50% and result in cost savings [35]. Another sustainable strategy could be the recycling of ICM. Some ICM manufacturers have started providing recycling containers. This means that instead of being disposed of, unused ICMs are poured into these containers and returned to the manufacturer, who recovers the iodine, treats it and reuses it in the production of new ICMs [25]. However, the adoption of such programs remains limited and inconsistent across institutions [11]. A European survey on radiographer perceptions of environmental sustainability issues reveals that although 60% of respondents identify contrast media as a major source of waste, only 13% indicated that these agents are recycled. Furthermore, many participants were unaware of the existence of contrast media recovery programmes in some radiology departments. This highlights the fundamental need to inform radiology staff about new opportunities to improve environmental sustainability [11]. Educational programmes focused on best practices, such as the correct use of

the automatic injector, weight-based adaptive dosing protocols, and recognition of opportunities for contrast medium reuse, could significantly improve ICM efficiency. For example, radiographers should be trained to adjust the volume of contrast medium loaded into the injector based on expected demand, avoiding the use of 500 ml vials during low patient traffic hours. Ultimately, integrating green radiology practices into radiographers' training and daily routines is essential to provide an understanding of the reasons behind sustainable strategies[17,39]. Environmental sustainability in radiology cannot rely solely on technology, it requires cultural change, interdisciplinary collaboration, and institutional commitment.

Limitations

This study is subject to several limitations that need consideration. Firstly, ICM volumes are analysed in a continuously functioning 24-hour emergency department, where patients are treated as needed rather than by scheduled appointments and this unscheduled workflow leads to fluctuations in ICM waste depending on patients' volume. Secondly, neither the type of CECT examinations performed nor the use of fixed or weight-based injection protocols in the radiology department were considered and consequently analysed. In addition, waste weight measurements were obtained through a single set of measurements, and although these were performed independently by two researchers using the same digital scale, potential measurement errors and operator-related biases associated with manual weighing cannot be entirely excluded. Another limitation is that the study was carried out in a single university hospital. This limits the generalizability of our findings and may not reflect practices in non-academic or non-emergency radiology settings. Future research should expand the sample size and include multiple institutions with different organisational models to provide more robust and generalizable results and should also investigate contrast media management strategies and operational practices adopted by other hospitals. Although we did not perform a complete life cycle assessment [40], the production and disposal of more than 53 kg of iodine and over 76 kg of glass represent a non-negligible environmental footprint, particularly in terms of energy use and carbon emissions. Despite these challenges, we believe our study offers meaningful insights into the environmental impact of a novel automatic contrast media injection system in an emergency radiology department. Our findings serve as a foundation for further exploration of sustainable practices in contrast media usage and waste reduction.

Conclusion

Over one year, ICM waste amounted to 144.7 L and iodine waste corresponded to 53.1 kg, derived mainly from residual ICM in expired kits at the end of the working day. Waste production of glass, plastic and paper is associated with disposable materials such as vials, daily kits and patient lines used. A key finding of this study is that the majority of iodinated contrast media waste was driven by organisational and workflow-related factors rather than by patient-specific administration, particularly in the context of a high-throughput emergency radiology setting characterised by unpredictable patient volumes and fixed daily injector kit usage. These results highlight that, even when advanced multi-dose injection systems are adopted, contrast media waste remains substantial and largely dependent on operational practices. This underscores the importance of optimising contrast media management strategies alongside technological solutions to effectively reduce the environmental footprint of emergency CT imaging. Therefore, it becomes increasingly important to implement waste mitigation strategies where radiographers will play a crucial role to improve environmental sustainability of the radiology departments, such as:

- Use ICM vials of different volumes to reduce waste at the end of the day.
- Use containers for recycling ICM, disposable devices and packaging.
- Improve training for radiographers on sustainability and environmental awareness.

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PAPER VI

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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.

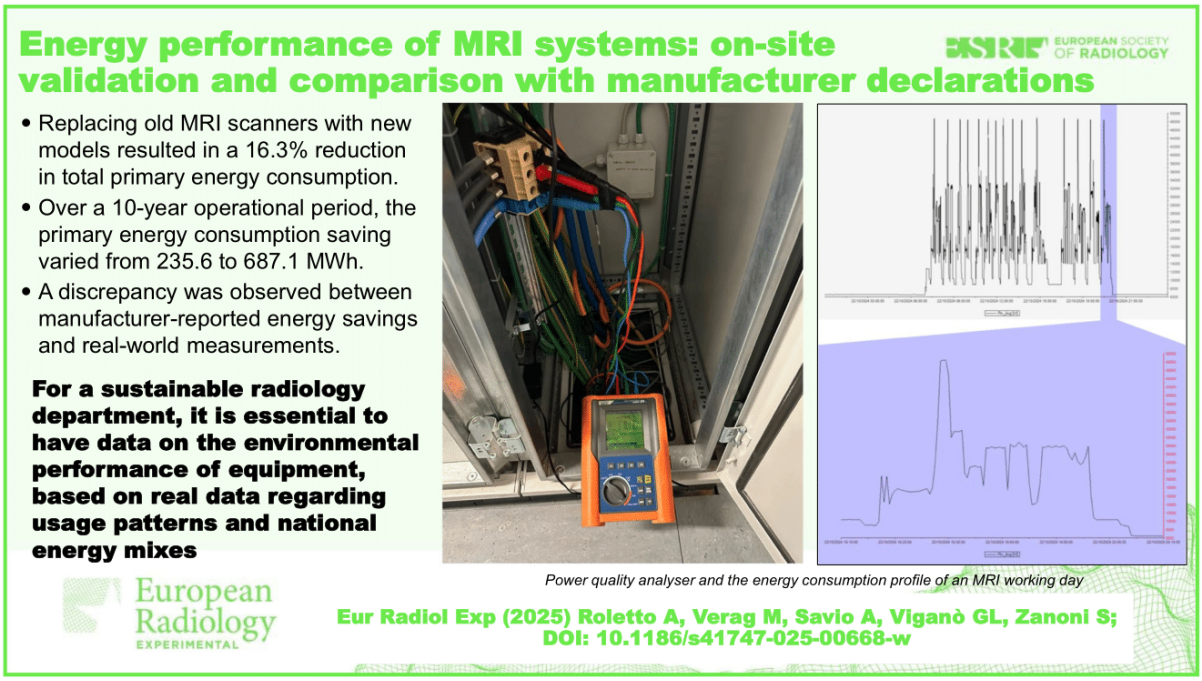
Keywords Carbon footprint, Conservation of natural resources, Electricity, Magnetic resonance imaging, Radiology

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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

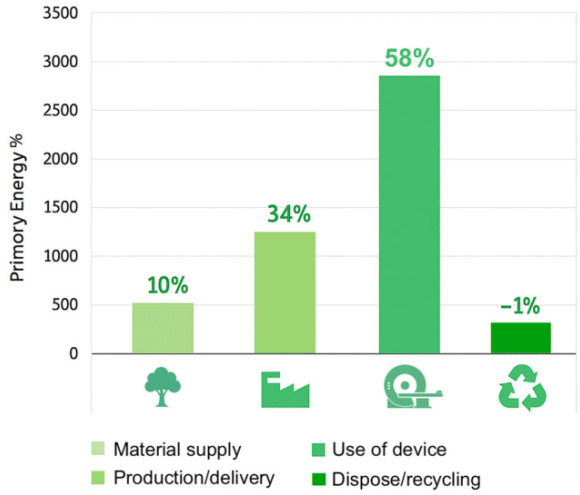


Fig. 1 Distribution of primary energy demand across the life cycle stages of an MRI system. The clinical use represents the largest share of total energy consumption (58%), followed by production and delivery (34%), material supply (10%), and end-of-life disposal/recycling, which provides an energy recovery 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),

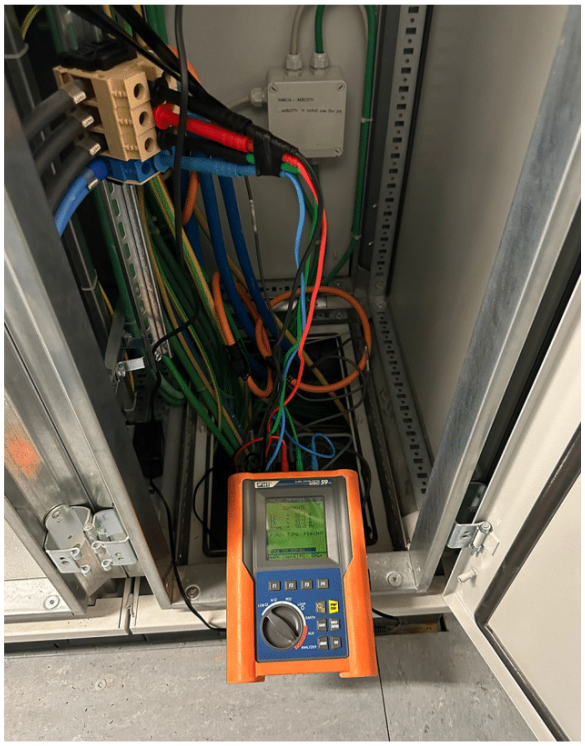


Fig. 2 Measurement setup for on-site energy monitoring. Power consumption was measured noninvasively with a power quality analyzer (GSC59, HT Instruments) connected to the incoming power line of the MRI electrical cabinet. The analyzer continuously measured voltage, current and power parameters during 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.

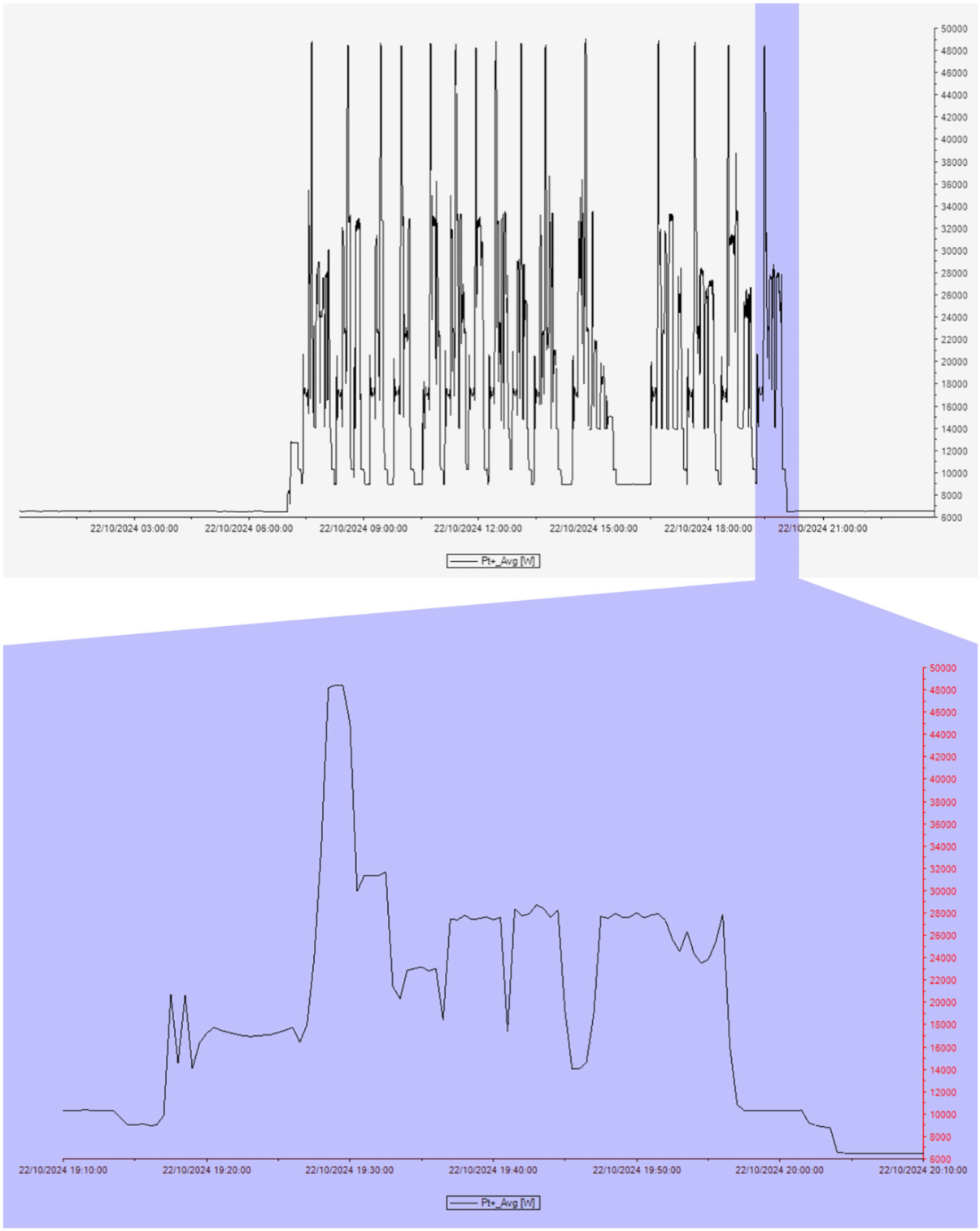


Fig. 3 The graphs show the consumption profile (in W) of an MRI unit working day recorded by the power quality analyzer, in which an MRI scan is zoomed in to show the footprint of energy consumption in the active state

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.

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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.

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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.

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

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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,

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Abbreviations

CO_2 eq	Carbon dioxide equivalent
EoL	End-of-Life
[^{18}F]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, [^{18}F]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 [^{18}F]FDG PET/CT exams remain limited and underdeveloped.

This study aims to provide an LCA-based estimation of the environmental impact of [^{18}F]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 [^{18}F]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 [^{18}F]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 [^{18}F]FDG with a radiopharmaceutical injector, (4) 60-min uptake period, (5) execution of [^{18}F]FDG PET/CT VMT scan, (6) image reconstruction, interpretation, 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).

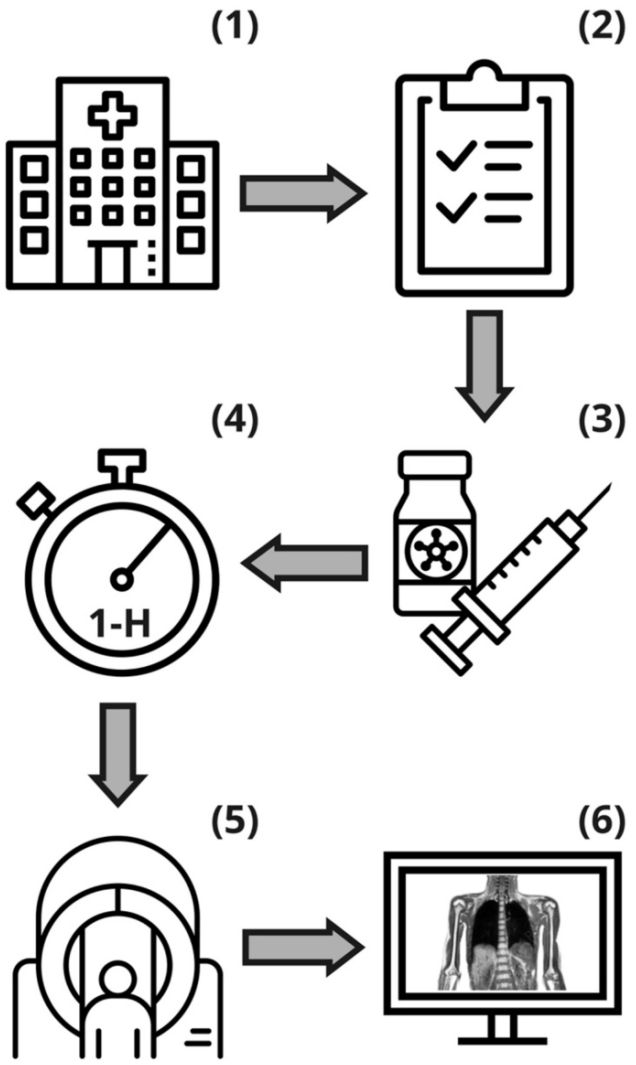


Fig. 1. Patient pathway for a [^{18}F]FDG PET/CT VMT Scan. (1) patient arrival at the hospital, (2) patient reception and registration, (3) intravenous injection of [^{18}F]FDG with a radiopharmaceutical injector, (4) 60-min uptake period, (5) execution of [^{18}F]FDG PET/CT VMT scan, (6) image reconstruction,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

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

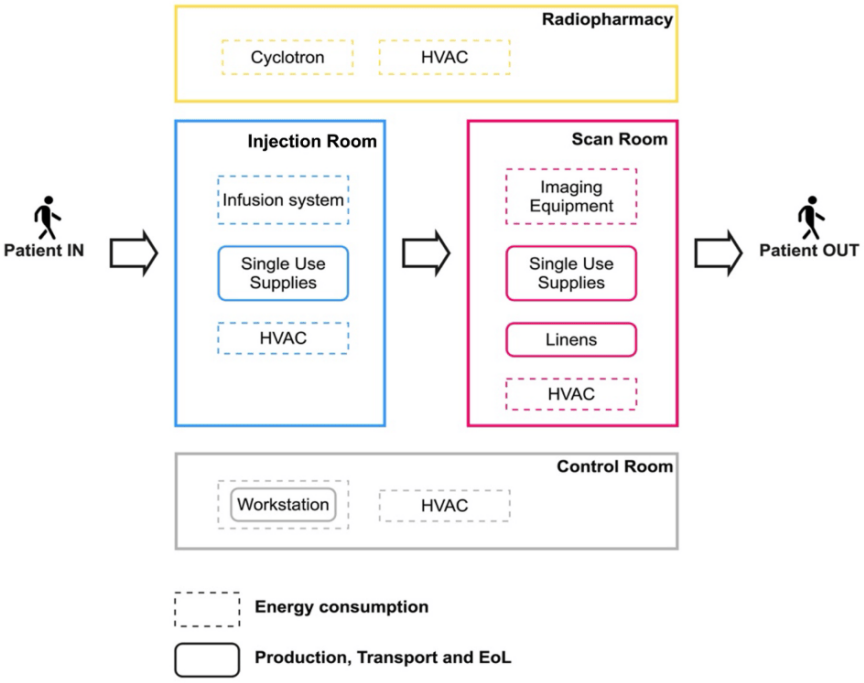


Fig. 2. System Boundaries and Functional Areas for [^{18}F]FDG PET/CT Life Cycle Assessment. Diagram showing the main functional spaces involved in a [^{18}F]FDG PET/CT scan: Radiopharmacy, Injection Room, Scan Room, and Control Room. The elements contributing to the life cycle environmental impacts 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

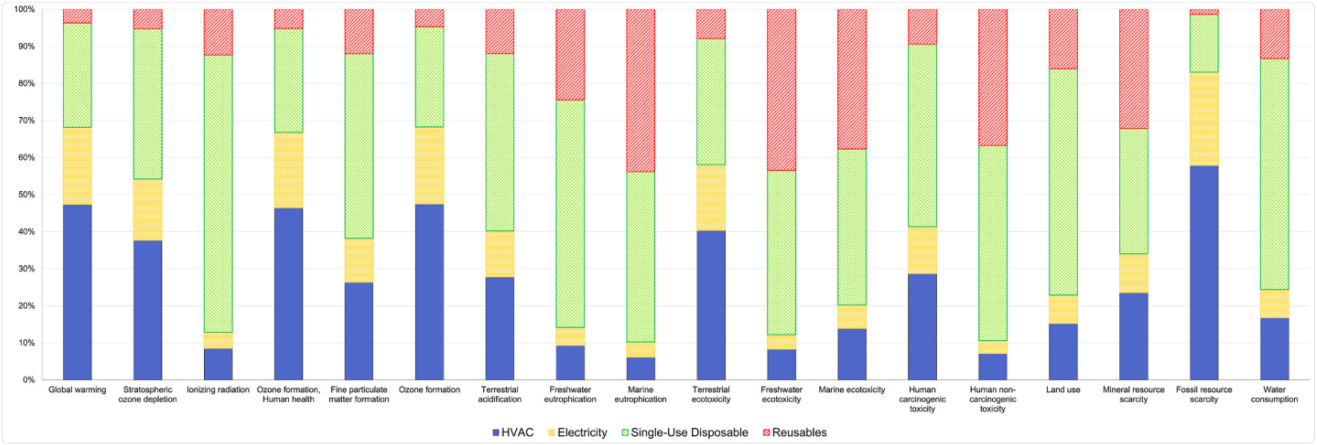


Fig. 3. Life cycle impact category contributions by major component for a single [^{18}F]FDG PET/CT scan. Stacked bar chart showing the percentage contribution of four main components: HVAC (plain blue), Electricity (yellow horizontal lines), Single-Use Disposables (green grid), and Reusables (red diagonal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

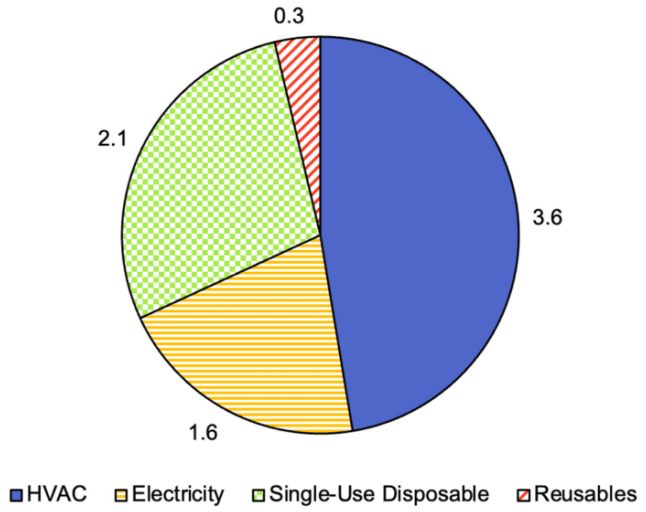


Fig. 4. Breakdown of life cycle GHG emissions, expressed in kg CO_2-equivalent, per [^{18}F]FDG PET/CT scan. The chart shows the relative contributions of major system components: HVAC (plain blue), Electricity (yellow horizontal lines), Single-Use Disposables (green grid), and Reusables (red diagonal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

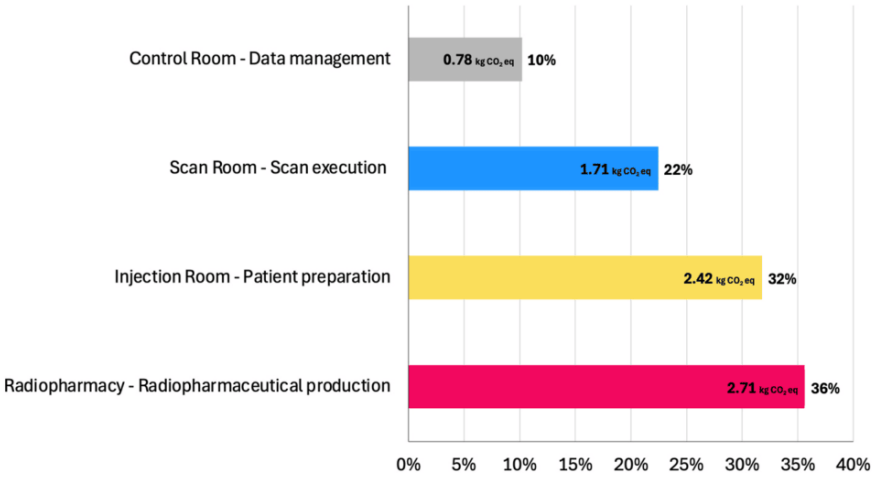


Fig. 5. Process-Level Contribution to Life Cycle GHG Emissions per PET/CT scan. Relative contribution (values and percent contribution) of each functional phase to the total GWP per [^{18}F]FDG PET/CT scan.

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.

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