



Review Article

Society for Cardiovascular Magnetic Resonance recommendations toward environmentally sustainable cardiovascular magnetic resonance

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ABSTRACT

Delivery of health care, including medical imaging, generates substantial global greenhouse gas emissions. The cardiovascular magnetic resonance (CMR) community has an opportunity to decrease our carbon footprint, mitigate the effects of the climate crisis, and develop resiliency to current and future impacts of climate change. The goal of this document is to review and recommend actions and strategies to allow for CMR operation with improved sustainability, including efficient CMR protocols and CMR imaging workflow strategies for reducing greenhouse gas emissions, energy, and waste, and to decrease reliance on finite resources, including helium and waterbody contamination by gadolinium-based contrast agents. The article also highlights the potential of artificial intelligence and new hardware concepts, such as low-helium and low-field CMR, in achieving these aims. Specific actions include powering down magnetic resonance imaging scanners overnight and when not in use, reducing low-value CMR, and implementing efficient, non-contrast, and abbreviated CMR protocols when feasible. Data on estimated energy and greenhouse gas savings are provided where it is available, and areas of future research are highlighted.

Abbreviations: AI, artificial intelligence; CO₂, carbon dioxide; CO₂e, carbon dioxide equivalent; CMR, cardiovascular magnetic resonance; MRA, CMR angiography; CT, computed tomography; GBCA, gadolinium-based contrast agents; GHG, greenhouse gas; eIFU, electronic instructions for use; LGE, late gadolinium enhancement; MRI, magnetic resonance imaging; OS, oxygenation sensitive; SSFP, steady-state-free-precession; US, United States

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1. Introduction to planetary health, climate change, and environmental sustainability

The imperative for sustainability permeates every aspect of daily life and all economic sectors, including health care and cardiovascular magnetic resonance (CMR) imaging. Climate change is now considered the greatest global health threat of the 21st century [1]. The health care sector is responsible for approximately 5% of greenhouse gas (GHG) emissions worldwide, although estimates vary by country [2]. Climate change impacts cardiovascular health through heat stress, poor air quality, and other factors [3,4]. Downstream adverse health impacts of climate change include an increase in chronic cardiovascular diseases, from coronary artery disease and heart failure to acute conditions such as myocardial infarction and life-threatening arrhythmias [5].

Medical imaging generates approximately 1% of global GHG emissions due to its high energy demand and associated carbon dioxide (CO₂) emissions and waste [6]. Despite the diagnostic capability and important role of CMR in optimizing clinical workflow, the environmental impact is higher for CMR compared to computed tomography (CT), ultrasound, and radiography [7,8]. There is limited data on the environmental impact of other cardiovascular imaging modalities, although emissions for positron emission tomography and invasive angiography may be higher than for CMR [3,8,9]. There is growing recognition that health professionals, including radiologists, cardiologists, scientists, technologists, and industry partners, have an important role in reducing the environmental impact of the delivery of CMR services [10,11]. This recent shift toward environmental consciousness in medicine is reflected in the latest 2021 release of the ethical code by the World Medical Association, which states, “Physicians should always strive to practice medicine in ways that are environmentally sustainable to minimize environmental health risks to

current and future generations” [12]. The planetary health framework recognizes that the health of all living and non-living components on Earth are interconnected, Fig. 1. Damage to the planet ultimately translates to damage to human health. The CMR community has an opportunity and responsibility to decrease our carbon footprint, mitigate the effects of the climate crisis, and develop resiliency to current and future impacts of climate change [13,14]. CMR imagers need to closely work with the medical imaging industry and governments on collaborative actions to improve the sustainability of medical imaging. Adopting more sustainable practices with affordable and sustainable diagnostic strategies, optimized for efficiency and access, can result in economic advantages and cost savings and benefits all stakeholders, Table 1.

The goal of this document is to review and recommend actions to reduce the environmental impact of CMR, including efficient CMR protocols and CMR imaging workflow strategies for reducing GHG emissions, energy, and waste, decreased reliance on finite resources including helium and waterbody contamination. The article also highlights the potential of artificial intelligence (AI) and new hardware concepts in achieving these aims, including low-field, helium-free, and gadolinium-based contrast agent (GBCA)-free CMR, and recommends specific actions for improving CMR sustainability. Opportunities to collaborate between cardiologists, radiologists, technologists, scientists, and industry partners are emphasized.

2. Intersection of climate change and cardiovascular health

Cardiovascular disease is the leading global cause of death and is inextricably linked to climate change [3]. Although cardiovascular outcomes have improved due to diagnostic and therapeutic advances in recent decades, the concurrent increase in GHG emissions and waste

Fig. 1. Interconnectedness of cardiovascular magnetic resonance (CMR), planetary health, and cardiovascular health. CMR is used to optimize and improve cardiovascular health. At the same time, delivery of CMR has a large environmental impact, contributing to greenhouse gas emissions and waste, thereby negatively impacting planetary health and climate change. Climate change exacerbates and causes cardiovascular disease, leading to higher health care utilization and imaging. *MRI* magnetic resonance imaging

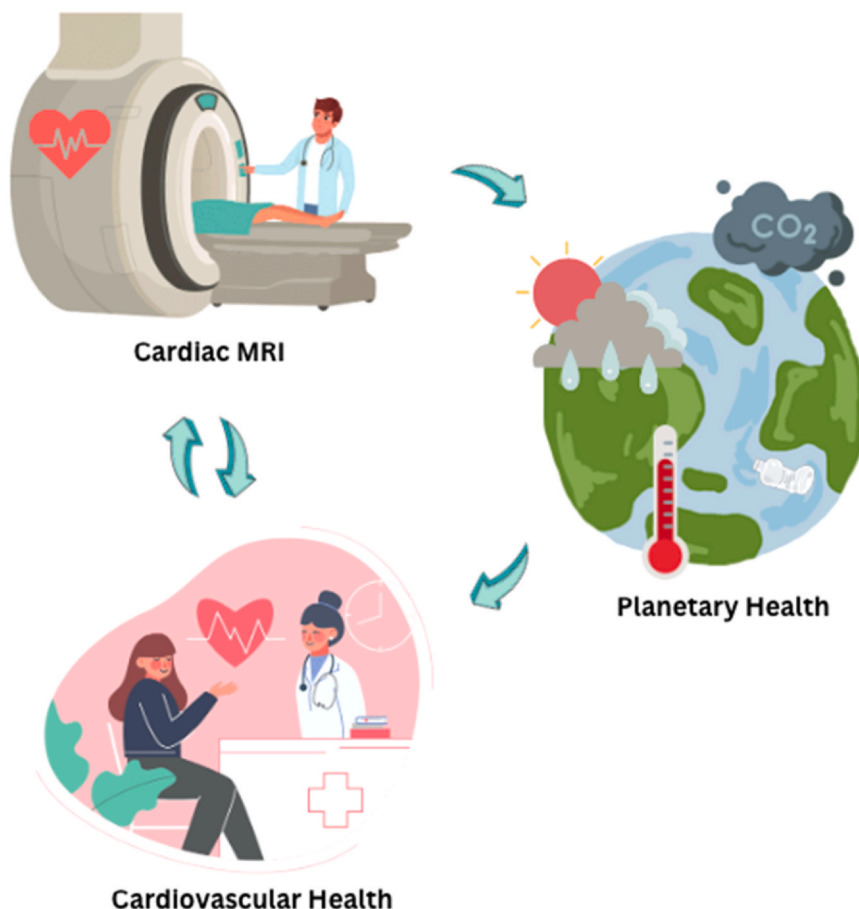


Table 1
Key stakeholders for sustainable CMR: patient, physician, payer, and planet.

	What we have	What we need
Patient		
Informed consent	Health risks	Clear reporting of carbon and other environmental costs
Physician		
Guidelines	Diagnostic efficacy	Integration of environmental cost of cardiovascular imaging Clear identification of low-value cardiovascular imaging
Payer		
Cost-benefit analysis	Financial direct and indirect costs	Social cost, financial incentives to avoid low-value cardiovascular imaging
Planet		
Carbon cost reduction	An ethical responsibility	An economic opportunity

threatens to undo this progress. The worsening climate crisis is already impacting our health by exacerbating individual risks, access to care, and burdens on already taxed health care systems [1].

Vulnerable populations are disproportionately affected by climate change, particularly at the extremes of age and in resource-limited environments where already fragmented care can become further limited [1,15,16]. Climate-associated environmental exposures and extreme weather events, including exposure to wildfire smoke, extreme temperatures, and air pollution, adversely impact cardiovascular morbidity and mortality [17–20]. These environmental exposures also increase health system utilization including higher emergency department visits and hospital admissions, taxing an already over-burdened system [21,22]. Increased utilization of the health system could lead to higher CMR utilization and volumes, further exacerbating the environmental impact of delivery of CMR and other health care services [22–24].

Climate change also results in secondary adverse cardiovascular health impacts. Higher global ambient temperatures and more frequent extreme heat exposure days are associated with less physical activity [25]. Biodiversity loss impacts the agriculture and food industry which may limit patient’s ability to follow a heart-healthy diet [26]. On the other hand, medical imaging can be leveraged as a non-invasive tool to advance our understanding of the mechanisms underlying climate-related cardiovascular disease and outcomes. Future-oriented solutions are critical to prepare health systems to improve cardiovascular health while minimizing the environmental impact of delivering that care.

3. Sustainability units, metrics, and measurements

Environmental impact is measured using a variety of metrics and methodologies that assess how human activities or systems affect the environment. These metrics focus on specific areas such as resource and energy use, GHG emissions, pollution, and waste, Table 2. For CMR, the most relevant metrics include:

- **Greenhouse gas emissions:** Refers to the total amount of GHGs emitted directly or indirectly across the entire CMR value chain, including raw material extraction, manufacture, production, shipping, installation, use, and end-of-life. The most prevalent GHG is CO₂ although there are many others, including methane and fluorinated gases, which have different global warming potentials. Carbon dioxide equivalent (CO₂e) is useful to describe the cumulative effect of different GHGs as a common unit and signifies the amount of CO₂, which would have the equivalent global warming impact. GHG emissions per CMR scan are approximately 6–20 kg CO₂e, dependent on the technique, protocol, and equipment used [3,27].
- **Energy:** Refers to the amount of energy or electricity consumed by a CMR unit and related electronic equipment, such as computer workstations or imaging data archives. Energy is typically expressed as kWh of electricity. The environmental impact of energy depends on the geographic location and time of use due to various energy sources. Overall, higher energy consumption is associated with greater environmental impact due to the reliance on fossil fuels for

energy production in most jurisdictions. Energy consumed per CMR scan is approximately 14–17 kWh, dependent on the technique, protocol, and equipment used [7,27].

- **Waste:** Refers to the quantity of solid, liquid, or hazardous waste produced by assembling, shipping, installing, and operating a CMR system, typically assessed in kilograms of waste. The environmental impact of waste management depends on the type of waste and is higher for medical compared to non-medical waste.

These metrics help quantify the environmental impact of CMR and guide decision-making for improving sustainable operations. By converting these measurements into relatable equivalents (Table 2), stakeholders, CMR practitioners, and patients can better grasp the significance of their sustainability efforts in medical imaging. There are various methods that can be used to quantify and evaluate these environmental impacts including power meters to directly measure electricity use, waste audits to assess waste, and life cycle analysis to estimate GHG emissions and other environmental impacts. Life cycle analysis is a comprehensive method for evaluating the environmental impact of a product, process, or service throughout its entire life cycle [28]. Electricity and GHG emissions per scan can also be estimated by modeling scanner-specific power consumption for idle and active states and use of readily available online GHG emission calculators [27,29].

4. CMR power and energy

While CMR offers comprehensive assessment of structure, function, tissue characteristics, and superior diagnostic capabilities, it also has higher demand for electricity compared to CT and echocardiography, potential for contamination of water bodies with anthropogenic gadolinium related to contrast administration, and reliance on finite resources, including helium and rare earth metals [7].

4.1. Environmental impact of CMR compared to other modalities

On one hand, magnetic resonance imaging (MRI) contributes to optimizing clinical workflow, reducing the overall costs in patient treatment, management, and health care [30,31]. On the other hand, CMR consumes higher electricity and energy compared to other imaging modalities, such as CT and ultrasound, with the exception of positron emission tomography which has similar or higher energy consumption compared to CMR [11]. For example, the annual energy consumption of various imaging devices is estimated at 111,000 kWh/year for all MRI (including CMR), 41,000 kWh/year for CT, 9500 kWh/year for radiography, and 760 kWh/year for ultrasound/echocardiography [32]. In a cross-sectional analysis of annual GHG emissions by modality, MRI was the largest cumulative contributor to GHG emissions (41%) despite only accounting for 12% of medical imaging tests [8].

Energy usage can also be measured during the entire life cycle of an MRI system, approximately 10–15 years, through its various phases of the supply chain, including raw material extraction, manufacturing, production, transport, installation, use phase, and end of life. It is

Table 2
Metrics and units for sustainable CMR.

Metric	Unit	Description	Easy-to-understand equivalents	Quantitative examples
Carbon footprint	Metric tons of CO ₂ equivalent	Total GHGs emitted directly or indirectly by an activity, process, or product.	- Driving a gasoline car for 10,000 miles emits ~4.6 metric tons of CO ₂ . - One transatlantic flight emits ~1 metric ton CO ₂ per passenger. - 1 kWh is enough to power a 100 W light bulb for 10 h. - An average US household uses ~900 kWh of electricity per month.	A typical household in the United States emits ~36 metric tons of CO ₂ annually.
Energy consumption	Kilowatt-hours (kWh)	The amount of electrical energy consumed by MRI machines and related systems during operation.		An MRI machine left running 24/7 consumes energy equivalent to powering over 20 homes for a year.
Waste generation	Kilograms (kg) or tons	Total amount of waste produced by MRI operations, including electronic waste, disposable supplies, and contrast agents.	- The average person generates ~2 kg (4.4 lbs) of waste per day.	The United States generated ~292.4 million tons of municipal solid waste in 2018, or about 0.8 metric tons per person annually.

Metrics and units to measure environmental impact and comparisons with everyday activities or products to make the data more relatable. Quantitative examples illustrate the magnitude of these impacts
CMR cardiovascular magnetic resonance, CO₂ carbon dioxide, GHG greenhouse gas, MRI magnetic resonance imaging

estimated that the production phase, incorporating raw materials through to delivery, consumes 2.73 million MJ (753,000 kWh) of fossil fuel [7]. The use phase, incorporating installation through to decommission, has an estimated emission of 17–20 kg CO₂e per exam [3].

4.2. Impact of energy and electricity source

The source of energy and electricity has a significant impact on the sustainable operation of MRI equipment. In regions where most electricity is generated from fossil fuels, the carbon footprint of operating an MRI machine is higher, compared with countries that derive a larger proportion of energy from renewable energy sources (e.g., over 60% in Canada) and have much lower emissions [33]. The country-specific contribution of the health care sector to total national GHG emissions is lower in Canada (4.6%) compared to the United States (9–10%) [34,35]. This underscores the importance of transitioning to clean energy sources as an overarching strategy to reduce the environmental impact of CMR globally.

4.3. Energy and power in various MRI scanner states

Energy consumption for MRI depends on use, with a substantial amount wasted during unproductive states, such as idle time between patient scans and overnight if scanners are left in a ready-to-scan state when not in use [36,37]. One study reported that standby mode accounted for 60% of machine time and 40% of energy consumption, active mode accounted for 20% of machine time and 40% of energy consumption, and idle mode for 20% of machine time and 20% of consumption [38]. Another study reported “low power” states have 7–10 kW of energy consumption in comparison to 29–48 kW in “scan” mode, 17–26 kW in “prepare-to-scan” (standby) mode, and 10–15 kW in “idle” mode [37]. Further data are needed on the impact of MRI chiller systems with respect to energy use in various systems.

4.4. Impact of CMR operations and protocol parameters

There are several actions that can be taken to improve CMR energy consumption by adjusting imaging protocols and scanner power management, including switching to lower power mode during non-productive hours such as overnight and on the weekend [3,23]. Powering down MRI machines when not in use for several hours (e.g., overnight) can reduce energy consumption by 25–33% and using “power save” modes can achieve additional 22–28% in energy savings. In the United States, adopting such strategies across all outpatient MRIs could save enough energy to power over 6600 homes annually [37]. Powering off computer workstations when not in use for several hours (e.g., overnight) and during non-productive hours can also save substantial electricity and GHG emissions [39]. Idle time can be reduced through improved scheduling and staffing to reduce gaps between scans, improving efficiency and emissions per patient [6]. Further, improving scanning efficiency by implementing the Society for Cardiovascular Magnetic Resonance (SCMR) recommended 30-minute CMR protocol [40] for the most common clinical indications can improve CMR operations and reduce energy consumption.

4.5. Energy and power use of CMR—recommendations

1. Switch MRI units, workstations, and other electronics to the lowest available power mode overnight and on weekends if not in use.
2. Implement SCMR-recommended 30-minute CMR protocol to reduce active acquisition time and GHG emissions per patient.
3. Optimize scanner scheduling to minimize idle time between scheduled patients and in the evenings.

5. CMR contrast and waste

Gadolinium ions, when bound as a chelate in commonly used CMR contrast agents, render the gadolinium ions as mostly non-toxic, but

free gadolinium ions are toxic. GBCAs, commonly used in CMR, contribute to environmental sustainability concerns due to their persistence in water systems and the environmental impact of production [7]. Although used in small quantities on a per-patient basis, the acquisition of contrast-enhanced MRI worldwide results in the use of thousands of liters of GBCAs per year [41].

Approximately 95% of injected GBCAs, which include gadolinium ions bound as a chelate, are excreted unchanged via urine, entering wastewater. Traditional treatment plants are often unable to fully remove GBCAs. GBCAs and related degradation products have been detected with increased concentrations in environmental waterbodies and in sources of drinking water [7,42]. Studies have detected gadolinium concentrations in rivers near urban areas at levels up to 1.5 µg/L, raising concerns about long-term ecological effects on aquatic environments [43]. The environmental and health impacts of GBCA oral ingestion are still being evaluated but the presence of GBCA in the rivers, lakes, and seas creates cause for concern. What remains uncertain is how environmental factors might affect GBCAs and whether this could result in the breakdown and release of gadolinium ions into the environment.

5.1. Opportunities to reduce the environmental impact of GBCAs

To tackle the issues of GBCA's impact on environment, strategies such as low-dose or non-contrast techniques (mapping, virtual late gadolinium enhancement [LGE], non-contrast CMR angiography [MRA]) can be employed. CMR fingerprinting is a newer approach to quantitative MRI that allows simultaneous measurement of multiple tissue properties in a single acquisition [44]. The ability to acquire information on multiple myocardial tissue properties in a single breath hold would facilitate faster CMR imaging, in addition to more objective tissue diagnoses and more precise comparisons of serial studies. Contrast-free CMR, such as cine and T1/T2 parametric mapping and oxygenation sensitive (OS-CMR), can unveil important changes due to pathology, similar to current clinical-standard methods, contrast-enhanced CMR with LGE and extra-cellular volume assessment [31,45,46]. In the future, the combination of novel AI models with contrast-free MRI may improve non-contrast CMR tissue characterization by producing virtual contrast images [47]. For example, deep learning virtual native enhancement models have been used to delineate ischemic and non-ischemic fibrosis and scarring closely matching LGE [48–50]. AI can also be used to suppress image noise and augment CMR image quality allowing for lower GBCA doses, with reductions of up to 80% in magnetic resonance (MR) angiography of congenital heart disease [51].

5.2. Opportunities to reduce waste

To reduce the impact of the packaging of contrast agents, there has been interest in utilizing electronic instructions for use (eIFUs) for any contrast media, contrast media giving sets, and medications in general. Thereby removing the need for paper instructions in all GBCA packaging. There are multiple benefits to changing to eIFU, including the reduction in paper waste, and the costs of printing, distribution, and shipping. Updates and corrections can be readily implemented.

Reducing the use of GBCAs also has a co-beneficial impact of reducing associated plastic and packaging waste. When GBCAs are needed, sustainability can be optimized. For example, the plastic tubing and the contrast bottle should be appropriately disposed of in the clinical waste and glass recycling waste streams as appropriate [52].

Other strategies to reduce environmental impact from GBCA have been proposed, including a switch from single-dose to multi-patient dose contrast delivery systems to reduce plastic and contrast waste, recycling of unused GBCA, and the use of other contrast agents that do not contain gadolinium such as ferumoxytol [41]. One of the benefits of using a blood pool agent, such as ferumoxytol, is that it can facilitate a comprehensive cardiovascular flow and function examination with one four-dimensional (4D) flow MRI acquisition, potentially decreasing the

overall CMR duration to the 8–15-minute 4D flow MRI exam time [53]. Patient collection of urine after CMR for first void or up to 24 h has also been proposed but not clinically implemented [54]. When a GBCA administration for a CMR is truly necessary, then the ideal agent should have excellent relativity to ensure the lowest possible administered dose and be extremely stable. Gadopiclenol is an example of a new commercially available high relaxivity nonionic macrocyclic GBCA ($R_1 = 12.8$) which can be administered at half or less the dose of other GBCA agents (0.05 mmol/kg or less) [55]. Other similar compounds are currently being developed and tested.

5.3. CMR contrast and waste—recommendations

1. Use non-contrast or low-dose contrast protocols when feasible.
2. Reduce use of single-use disposable supplies, waste, and packaging.
3. Switch from single dose to multi-patient dose contrast delivery systems.

6. CMR efficiency

The power consumption during active MRI scanning is about four times higher than in idle mode, when the scanner is on but is not actively being used to acquire images [23]. This highlights the critical need for optimizing scan protocols and sequences to reduce power use during active scanning period. As total scan time is directly linked to MRI energy use, eliminating unnecessary sequences and tailoring protocols to specific clinical needs can be highly effective. As global demand for MRI continues to rise, it becomes increasingly important to reduce the energy consumption of CMR protocols to balance this demand with the goal of minimizing the overall energy footprint.

SCMR has developed an efficient 30-minute CMR protocol which is feasible for the most common clinical indications [40]. This has multiple benefits, including improved patient experience and access, affordability and sustainability [40]. Efforts are also underway to develop a 10-minute CMR protocol. CMR imagers should aim to abbreviate protocols tailored to the specific clinical question and can easily be performed on most scanners and in most clinical practice settings. There is a growing body of literature on options for shortened, comprehensive, contrast-free CMR protocols eliminating repeated breath-holds; these are based on recent developments, including compressed sensing and parallel imaging to reduce scan time, OS-CMR, conventional two-dimensional (2D) cine replaced by optimized three-dimensional (3D)-cine, multiple phase-contrast sequences substituted by 4D-flow, conventional myocardial tagging replaced by fast strain-encoding imaging, and native T1 and T2 mapping sequences for GBCA-free myocardial tissue characterization [56,57]. Idle time during CMR protocols that include LGE imaging can be reduced by moving cine steady-state-free-precession (SSFP) acquisitions from before to after contrast administration, making use of the requisite wait period before beginning LGE sequences [27]. This single protocol change could save 13,200 kWh of energy and prevent 5600 kg CO₂e emissions annually [27].

6.1. CMR efficiency—recommendations

1. Utilize abbreviated and focused CMR protocols where feasible.
2. Reduce idle time during CMR protocols that include LGE imaging by moving cine SSFP acquisitions after contrast administration.
3. Integrate appropriate accelerated CMR sequences to reduce CMR scan time.

7. Sustainable and appropriate use of CMR

7.1. Education and awareness in the CMR community

The CMR community must be aware of the environmental cost associated with CMR and other diagnostic procedures. This knowledge should be an integral part of shared decision-making. While thresholds

for acceptable environmental and carbon costs are challenging to establish due to variability, acknowledging and recording GHG emissions is crucial. Departments and physicians should regularly compare actual environmental costs to reference values to promote responsible usage and continual improvement. The implementation strategy of these principles will lead to a remodeling of several key aspects of education and training, policy development, technology, and innovation. GHG emissions and environmental awareness should be incorporated into medical education and training programs for health care providers [58]. Importantly, no diagnostic test should be withheld from a patient due to high costs, radiation dose, or carbon footprint if it is clinically indicated and necessary for patient care. When multiple diagnostic techniques provide similar value, preference should be given to the method with the lowest cost, minimal or no radiation, and the least environmental impact [6,59].

Applying the principles of justification, optimization, and responsibility from radiology dose management to carbon cost management can lead to more sustainable and equitable health care. By integrating carbon cost considerations into medical imaging practices, the health care sector can contribute to environmental sustainability while maintaining high standards of patient care. This approach not only benefits individual patients but also supports broader global health and environmental goals [5,59].

7.2. Environmental cost and the triple bottom line

The triple bottom line framework can be applied to CMR to address financial, population, and environmental costs [3]. A high-value imaging study is one where the expected clinical benefit outweighs potential negative consequences. These negative consequences encompass the risks of the procedure itself (e.g., radiation or contrast exposure), negative outcomes for the patient of not doing the procedure, and also the financial and environmental costs [60]. Essentially, the balance lies between the benefit for the patient and the cost, which includes the direct financial cost, social and health cost, and environmental cost [60].

The first step in improving cost-benefit analysis is to consider not only the direct costs but also the long-term, downstream costs, including environmental damage. This should also include consideration of the potential value of CMR for limiting additional downstream testing [31]. For carbon emissions, the social cost of carbon is a widely used metric to estimate the economic damage from CO₂ emissions [61]. This metric represents the total damage an additional ton of CO₂ inflicts, expressed in monetary terms. It includes impacts on human health, agricultural productivity, property damage from increased flood risks, and changes in energy system costs, such as reduced heating and improved air conditioning.

The environmental cost is not automatically reflected in market prices and varies across different countries and over time within the same country [62]. For instance, estimations of the social cost of carbon ranged between \$5 and \$185 per ton of CO₂ between 2014 and 2023 [63]. This variability is crucial from an economic perspective, particularly when indirect, downstream costs are included in the cost-benefit analysis of medical imaging. The cost-benefit evaluation must encompass more than direct financial costs; it should account for the environmental damage caused by medical imaging and its repercussions on the health care system. When the social cost of carbon is included in the evaluation, mitigating carbon costs in medical imaging becomes more beneficial, offering significant health, economic, and social co-benefits.

7.3. Appropriate use and low-value imaging

Reducing low-value imaging, defined as imaging that has little or no impact on the management of the individual patient or imaging that provides little to no clinical benefit to a patient, is essential to improve

equitable access and decrease the environmental cost of CMR [64]. Up to 20–40% of medical imaging is considered inappropriate or low-value, increasing cost and risk without commensurate benefit [6,65,66]. To avoid unnecessary testing, multi-society and multi-modality appropriate use criteria for CMR and other cardiac imaging modalities should be followed [67–72]. In addition, there is a need for dedicated decision support tools that include an obligatory report of cost, radiation, and environmental impact for each order or imaging test [6,60]. For example, a recent study has shown that a point-of-care clinical decision support tool helped to reduce not needed multi-modality ordering, manifesting in reduced imaging volume per patient and reduced estimated carbon emissions [73].

7.4. Patient engagement

Patient engagement is a critical component in the implementation strategy of a sustainability program. The use of clear and transparent informed consent forms for disseminating radiological information has led to an increased awareness of radiological practices among patients and doctors, subsequently reducing inappropriate examinations [74]. Although the significance of this variable is widely recognized, the environmental impact of common diagnostic tests remains poorly understood. Furthermore, efforts to educate patients and health care providers about the environmental impact of these procedures are insufficient. Raising awareness about the environmental impact of these investigations can help establish a clear rationale for choosing examinations that are both clinically appropriate and environmentally sustainable [75]. To facilitate this, carbon costs should be communicated in simple, concrete terms that are easily understood, such as the annual emissions from cars, households, or power plants (Table 2). This increased awareness of the direct connection between environmental hazards and patient well-being will help to align health care practices with evolving societal values, recognizing the informed consent form as a vital bridge to patient engagement [60,76].

7.5. Sustainable and appropriate use of CMR—recommendations

1. Incorporate environmental sustainability into medical education and CMR training programs.
2. Consider decision support tools to ensure that the optimal and most sustainable imaging test is selected for a given patient.

8. CMR access and transportation

Global disparities in access to cardiovascular imaging persist [77,78]. In the United States, there is 10-fold geographic variation in availability of CMR centers [79]. Sustainable CMR should focus on increasing patient access while reducing the environmental impact of our imaging services. Considerations include location of service delivery, transportation, remote reporting, and remote scanning.

8.1. Centralized vs community CMR

Centralized CMR services, typically located in larger medical centers, concentrate expertise and resources. This approach necessitates some patients to travel longer distances, resulting in increased GHG emissions. Striking a balance between centralized expertise and patient convenience is crucial to improve access while simultaneously decreasing the environmental impact related to patient travel [6]. A hybrid hub-spoke model could be explored, where complex cases are referred to centralized centers while routine CMR remains accessible locally to minimize patient travel. Additionally, mobile CMR units could be used to reach remote and rural communities [10,78]. Further studies are needed to systematically evaluate the overall net sustainability benefits (e.g., reduced travel times vs need for new CMR systems at remote locations) of these health care settings.

8.2. Patient and workforce transportation

Transportation and travel of both patients and the workforce to CMR centers contribute to GHG emissions [6]. Several solutions could be considered, including the deployment of mobile CMR units to underserved areas to enhance patient access while reducing travel-related emissions, encouraging patients to use public transport or shared rides for appointments, and incentivizing health care workers to use sustainable transportation.

8.3. Remote reporting for cardiac imagers

Remote reporting reduces the need for staff transportation. A hybrid model could be adopted, where the option of remote reporting is made available, so that the reporting physician does not necessarily need to travel to report a CMR scan. Established and secure telemedicine platforms enable remote reporting without compromising quality and safety.

8.4. Remote scanning

Remote scanning occurs when highly skilled CMR technologists control one or more MRI scanners from afar. This new solution can increase access to CMR services in underserved areas and lower emissions by reducing patient and staff travel, and increase CMR availability and cost effectiveness [78,80,81]. While vendors are increasingly developing remote command centers, this approach is still early in the adoption cycle. Concerns about quality, technology, cybersecurity, and cost remain fruitful areas of study.

8.5. CMR access and transportation—recommendations

1. Minimize need for patient travel to undergo CMR if feasible.
2. Encourage sustainable transportation options for patients and the CMR workforce including cycling, public transportation, or shared rides.
3. Establish mechanisms to allow for remote CMR reporting and remote scanning.
4. Schedule multiple clinical and imaging visits for patients on the same day rather than over multiple days.

9. Environmental impact of data storage

A largely unexplored area of sustainability in medical imaging is related to storage of imaging data. The burden of image data storage is anticipated to rise, and this is likely to be exponential in view of the growing use of diagnostic medical imaging. In addition to the number of studies performed, there is also an increase in complexity and post-processing of data. In Ireland, the national radiologic data storage system has an annual growth of 23%. CT studies accounted for 53% of the entire data storage, and the size of CT study files had increased from an average of 66 megabytes in 2011 to 160 megabytes in 2020 [82].

Imaging should only be undertaken when appropriate. Once imaging data are acquired, only essential image data should be stored long-term, limiting the storage of secondary reformats to those that cannot be reproduced. A further important mitigation strategy includes appropriate data retention policies following patient death, which needs societal discussion. The need for large data sets for AI model training is

a further contributor to data storage and longer-term “low carbon” archiving is an urgent need.

9.1. Data storage—recommendations

1. Minimize the number of CMR images archived for long-term storage by removing repeat or non-essential images before storage and abbreviating protocols so that only essential images are acquired.

10. Low-field and low-helium CMR

Sustainable low-field CMR is another opportunity to reduce the environmental impact of CMR, Fig. 2 [83]. Recently, there has been growing interest in low-field CMR to improve global access to CMR by virtue of the reduced system costs and easier siting, in addition to offering new clinical imaging opportunities [84,85]. To date, most low-field CMR has been performed using superconducting mid-field (0.35T and 0.55T) systems, and a commercial 0.55T system is available but not currently United States Food and Drug Administration-cleared for cardiac applications. Low-field CMR has been optimized using efficient acquisitions and modern reconstruction algorithms [86–88], and low-field CMR has been demonstrated to generate high-quality images that provide consistent clinical interpretation to 1.5T [89,90]. Example 0.55T CMR images are provided in Fig. 3. In this section, we describe the potential advantages of low-field CMR from the lens of improved sustainability.

10.1. Energy consumption and material usage

Some scanner manufacturers have recently launched 1.5T MRI scanners with minimal helium (as little as 0.7 L) which are now commercially available, including CMR applications. These systems help to meet both financial and environmental goals by saving 30–45% energy per year compared with previous generation scanners. This new technology also allows easier installation of MRI systems in elevated flooring due to the reduction in scanner weight and no requirement for a vent pipe.

Energy consumption and lifecycle CO₂ emissions are reduced for lower field systems during both their manufacturing and operational phases, which include reduced energy needed for cooling, powering the magnet and gradient system amplifiers, and maintaining the system. For example, previous studies have compared power consumption from 30-minute protocols at 0.55T, 1.5T, and 3T using optimized parameters for each field strength and found a 3-fold difference in energy consumption [7] (Table 3). Energy is consumed even in MRI scanner “off” mode because of cooling requirements, and this baseline power usage varies with field strength due to difference in cooling requirements. Additionally, the incremental increase in power consumption during scanning also increases with field strength and power requirement for inter-system differences in gradient amplifiers specifications (maximum gradient strength, minimum ramp times), resulting in a notable difference in energy usage. However, if scan times are extended at 0.55T, the advantages are diminished, encouraging the use of efficient imaging at 0.55T.

Another advantage of lower field systems is reduced material usage and depletion of finite resources. A 1.5T MRI system requires approximately 1000 L helium, 4000 kg copper, 210 kg niobium, and 240 kg titanium for a 10-year clinical lifespan [91]. These materials are

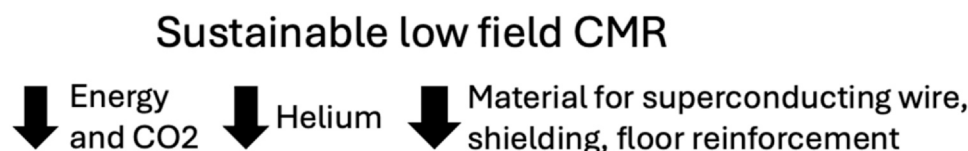


Fig. 2. Potential advantages of low-field CMR for more sustainable CMR. CMR cardiovascular magnetic resonance, CO₂ carbon dioxide

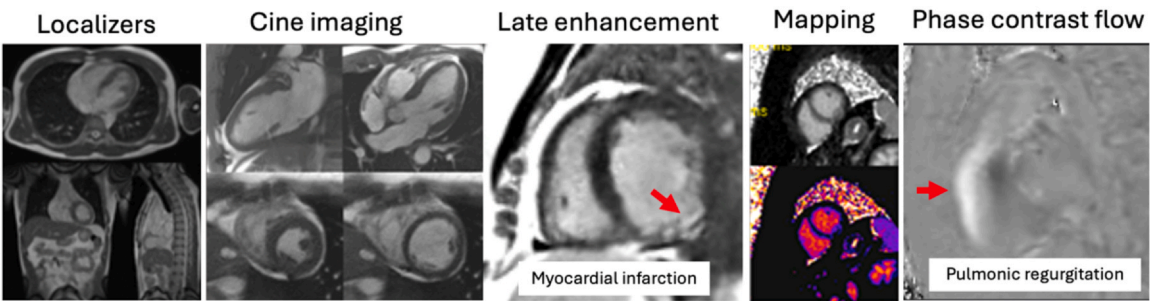


Fig. 3. Example 0.55T CMR images. Lower power gradients were used, for example, localizer, cine, and mapping images. *CMR* cardiovascular magnetic resonance

Table 3
Energy consumption and greenhouse gas emissions across MRI field strengths and MRI system specifications (e.g., magnetic field gradient system strengths and switching rates).

Energy consumption		0.55T and standard gradients	1.5T and standard gradients	3T and high-performance gradients	Average US household
Example 30 min ankle protocol					
Baseline power, scanner idle		10 kW	13 kW	20 kW	
Peak power		20 kW	31 kW	55 kW	
Total energy		6.5 kWh/exam	10 kWh/exam	20 kWh/exam	30 kWh/day
CO ₂ emissions		0.064T portable ultra-low-field brain MRI and low gradients	1.5T and standard gradients	3T and high-performance gradients	Average US household
Example neuro scan					
Mean CO ₂ emissions		~0.105 kg/exam @ 0.6 KVA	~10 kg/exam @ 50 KVA	~17.5 kg/exam @ 80–100 KVA	~100 kg/day

Data based on previous literature [7]. For comparison, average household in the United States consumes 30 kWh/day of energy and emits 100 kg/day of CO₂ CO₂ carbon dioxide, KVA kilovolt-amperes

rare or have high economic vulnerability and may have associated risks, such as supply chain disruptions [92]. Low-field systems require less helium (e.g., 0.7 L for a commercial 0.55T system), niobium-titanium superconducting wire, shielding material, and floor reinforcement. Composite metals used in superconductors are energy-intensive to produce and hard to recycle, especially niobium alloys, making this an important consideration [7]. Additionally, the lower-weight systems may reduce emissions associated with shipping. An exciting future opportunity is the transition to high-temperature superconductors for lower-field magnet design, permitting the use of different metal alloys, helium-free designs, and lighter-weight systems, and the decrease in energy and GHG emissions.

10.2. Future ultra-low-field systems

Portable ultra-low-field MRI systems are now available for neuroimaging applications and extremity imaging [93,94]. To date, a single example of cardiac imaging has been demonstrated on a portable whole-body ultra-low-field (0.05T) MRI system [95]. These systems further reduce power consumption since they can be plugged into a standard outlet, or even powered by cleaner battery, solar, or diesel power. These systems are also cryogen-free thereby requiring no power consumption for cooling, require no shielding, and have simplified service requirements. There is a promise that using deep learning and generative AI approaches, higher resolution and higher signal-to-noise ratio images that provide comparable clinical value can be synthesized from ultra-low-field MRI [96].

10.3. Other considerations for low-field CMR

There are some other important considerations in the role of low-field and ultra-low-field MR in clinical care more broadly. A unique advantage of low-field CMR systems is the improved pulmonary image quality [85,97], which may offer value for imaging populations and regions most affected by climate crises, including by combined cardiopulmonary assessment. There is interest in using low-field systems also

for “screening” exams, which can result in incidental findings that need follow-up resulting in more energy consumption and emissions. These considerations should be carefully balanced with medical care needs. To date, standard doses of GBCA have been used, meaning that there is no additional reduction in the environmental impact of GBCA. However, ferumoxytol offers higher relaxivity at lower field and the impact of ferumoxytol waste is not well characterized [85]. Furthermore, with deep learning and generative AI methods, lower doses or even zero dose/virtual gadolinium may provide equivalent information compared to contrast-enhanced CMR images [98].

10.4. Low-field CMR—recommendations

- 1. Consider installation of clinically available low-helium MRI systems.
- 2. Use lower field strength and low power gradient modes for CMR sequences if feasible with comparable diagnostic quality.

11. AI and CMR

11.1. Sustainability benefits of AI in CMR

Long scan times are a key obstacle for clinical use of CMR, which not only limits patient throughputs but also increases per-scan cost and energy consumption. AI brings in new perspectives and approaches to significantly improve the efficiency and sustainability of CMR [99]. A comprehensive 5-year review was recently conducted, which unveiled a growing number of AI developments for CMR with impact on almost all imaging sequences and workflows [100]. These include accelerating the reconstruction, automated CMR planning, quality control, image post-processing, reporting, and diagnosis [47,100].

A notable machine learning approach is generative AI which can learn the pattern of large datasets and produce realistic new content. For example, generative AI can perform fast image reconstruction, image registration, enhance pathological signals in contrast-free CMR, and synthesize large volume of medical images to support AI training [48,101–103]. Beyond imaging, large language models such as

Generative Pre-trained Transformer (GPT) with transfer-learning on biomedical tasks may lead to automated CMR reporting and diagnosis, further improving CMR efficiency and consistency [104,105]. These AI techniques have demonstrated high promise to advance CMR toward faster and less expensive imaging, increase CMR throughput with low-field MRI or similar scanner facilities, therefore, potentially significantly improving its environmental sustainability in this respect.

11.2. AI environmental cost and concerns

It is important to note that the benefit of AI also comes with significant environmental impact in its development and deployment, and ethical concerns specific to AI in health care [47]. Developing large AI models consumes considerable amount of energy [47,106]. This includes costs in AI-specific infrastructure and model training. For example, using graphics processing units and high-performance computing to create a single large language model, GPT-3 is reported to consume 1300 MWh of electricity and generates over 500 tons of CO₂e [107]. Inference, the process of using a trained model to make predictions, classify data, or perform other tasks based on new input data, requires substantially less energy but occurs in many more instances than model training; therefore, the overall environmental impact varies [47]. With the growth of data volume—requiring storage, larger model size, and training infrastructure—the development, validation, and deployment of AI models will have ever-growing energy and environmental footprint consequences. In addition, the environmental impact of water consumption should also be considered. AI also consumes substantial water for cooling systems, electricity generation, and equipment manufacturing [108]. It was estimated that the global AI demand may be accountable for 4.2–6.6 billion cubic meters of water consumption in 2027, which is more than half of the total annual water consumption in the United Kingdom [108].

Given the amount of resources required, most of the recent large AI models have been developed in commercial industry labs rather than diverse academic centers [109]. This poses a concern about diversity, generalizability, and equality of AI research and models (e.g., it is often challenging for academic institutions to match computational resources available in industry and retain highly experienced AI researchers). Further, AI models trained on homogenous and unrepresentative data may have bias and consequently result in misdiagnosis for demographic minorities [110]. AI development should therefore ensure diversity and equality in data, model training, and deployment. There are also ethical concerns in the use of patient medical data to train and develop AI models, and the consent of the patients should be in place before these models are commercialized and licensed.

11.3. Solution

With the clear benefits and associated costs of AI models, the development of sustainable CMR with AI should have a holistic mindset of

cost-benefit balance, by considering both the savings and benefit that it brings to MRI, and the resultant medical and environmental costs of AI development and inference, Fig. 4.

12. AI and CMR—recommendations

1. Incorporate commercially available AI-accelerated imaging techniques in CMR protocols if available.
2. Use commercially available AI-based GBCA-free imaging techniques in CMR protocols if comparable diagnostic quality and clinical value are achievable.
3. Integrate commercially available AI-driven CMR analysis and reporting tools to reduce workstation use and increase patient throughput.

13. Sustainable pediatric CMR

13.1. Environmental considerations in pediatric CMR

CMR can be a daunting experience for pediatric patients. The large noisy machines, long exam times, need for lying still, and potential need for breath holding combine to make it challenging for a child to complete a successful CMR scan. As a result, there is an increased requirement for sedation and anesthesia in pediatric CMR, which increases the environmental impact. Thus, an initial step in improving sustainability in pediatric CMR should be ensuring that the clinical indications meet the relevant clinical appropriateness criteria to ensure that the result cannot be achieved by more sustainable modalities and that the timing of the CMR exam is appropriate with regard to the child's age and potential co-operation level [111]. When CMR is indicated, the likelihood of a successful non-sedated CMR study can be assessed by a few simple questions to the parent/caregiver before the procedure, along with helpful preparatory material in the pre-exam timeline [112,113].

Inhalational anesthetics are potent GHGs that contribute to GHG emissions in health care [3]. Among these agents, desflurane and nitrous oxide have the highest global warming potentials, with desflurane being the most harmful. The clinical use of desflurane results in nearly 50 times more GHG emissions than other anesthetics [113]. Nitrous oxide is also a major environmental concern due to its 114-year atmospheric lifetime and its role in direct ozone depletion. In response to these concerns, some hospitals have removed desflurane vaporizers, adopted low-flow gas anesthesia techniques with decision support, limited nitrous oxide use, and monitored emissions. As a result, one facility achieved an 86% reduction in GHG emissions from inhalational agents over 5 years [114]. For pediatric CMR requiring anesthesia, it is typically recommended to use sevoflurane for mask induction and maintenance, with or without propofol infusion as needed. Reducing or eliminating desflurane and nitrous oxide is strongly encouraged to minimize the environmental impact of anesthesia in CMR practices.

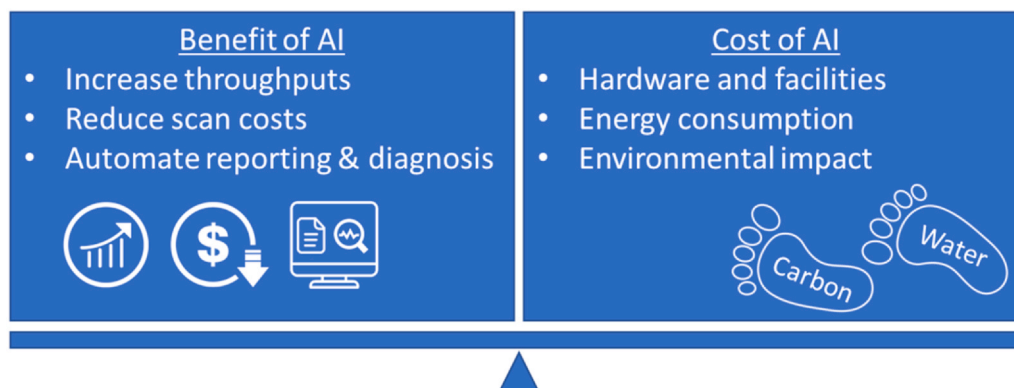


Fig. 4. AI development for sustainable CMR with a mindset of cost-benefit balance. AI artificial intelligence, CMR cardiovascular magnetic resonance

13.2. Child-friendly CMR environment

For children who are deemed suitable for an awake CMR study, creating a child-friendly environment is important for success, and this can include engaging child life specialists, a mock MRI scanner where the child can practice lying still and holding their breath, and selecting MR compatible distraction devices [115]. Use of pediatric-specific MRI coils and tailored CMR protocols can improve image quality, minimize the number of sequences needed, and reduce exam times. Reducing/eliminating breath-holding can increase the success of an awake pediatric CMR study. Shorter breath holds can be achieved on all scanners by reducing the spatial resolution or increasing the parallel imaging factor [115,116].

Performing breath holding during inspiration, rather than expiration, can improve compliance with breath holding instructions. Alternatively, motion compensation techniques with use of multiple signal averages, respiratory triggering, or respiratory navigation can facilitate a free-breathing study in children who are unable to comply with breath holding. Newer techniques for highly accelerated CMR, such as compressed sensing or AI, significantly reduce the number and length of breath holds, although these techniques may be susceptible to under sampling artifacts in smaller children [115,116]. In neonates (aged 3 months and less), feed and wrap studies can be very successful for certain indications where minor respiratory motion is tolerable [117].

13.3. Pediatric contrast considerations

GBCA-enhanced CMR protocols are utilized frequently for evaluation of congenital heart disease. However, non-contrast pediatric CMRs can decrease both the need for sedation and the excretion of GBCAs. In addition to concerns regarding urinary GBCA excretion, gadolinium deposition disease remains a concern in the pediatric CMR community and among parents. There are now a variety of non-contrast MRA techniques that can work as a reasonable alternative to GBCA-enhanced MRA. These include respiratory gated non-contrast 3D mDixon Relaxation Enhanced Acquisition Technique, electrocardiogram (ECG) and respiratory-navigated 3D SSFP, or 2D ECG gated black blood spin echo double inversion recovery sequences [118,119]. In settings where it is approved for use, ferumoxytol is a potential alternative when a contrast-enhanced MRA is necessary, although some special use precautions to administration are advised. Ferumoxytol also facilitates comprehensive ultrafast 3D and 4D cine techniques that can dramatically reduce exam times and eliminate both breath holding and

multiplanar acquisitions [53,120–123]. When GBCA is required, such as for tissue characterization, newer gadolinium agents such as gadopichol, which use half the dose of other agents and have a higher stability, can be considered where possible [124]. GBCA-free myocardial tissue characterization methods, such as parametric mapping and AI-based virtual LGE techniques, are also being actively developed, and validation in pediatric populations would be important [48–50].

14. Pediatric CMR—recommendations

- 1. Perform non-sedated CMR studies creating a child-friendly environment when feasible.
- 2. Reduce or eliminate desflurane and nitrous oxide to minimize the environmental impact of anesthesia.

15. Opportunities to reduce the environmental impact of CMR

There are multiple opportunities to reduce the environmental impact of CMR, Table 4 and Fig. 5 [23]. Key strategies include powering down MRI units overnight when not in use, improving operational efficiencies with respect to patient flow and CMR table time, refurbishing and reusing CMR systems to emphasize a move from linear to circular economy, and reducing the use of GBCAs [13]. Abbreviating imaging protocols, considering low-helium and low-field MRI scanners, and ensuring that imaging is appropriately indicated can further minimize the need for follow-up CMR scans and additional testing [27]. Further studies are thus needed to quantify the actual impact of implementing these interventions and actions on reduced GHG emissions. The highest impact actions that require lowest effort and up-front financial cost should be prioritized, including switching MRI units to lower power modes during non-productive hours such as overnight and on the weekend, implementing the SCMR 30-minute CMR protocol to reduce active acquisition time and GHG emissions per patient, and use non-contrast or low-dose contrast protocols when feasible.

Opportunities to collaborate between cardiologists, radiologists, technologists, scientists, and industry partners should be emphasized. In this context, partnership and collaboration with the medical imaging industry and vendor partners is essential to develop joint recommendations and guidelines for approaches to circular economy, sustainable shipments and re-use of equipment, energy labels and real-time monitoring of energy consumption during CMR operations.

Reductions in GHG emissions not only improve the environmental sustainability of CMR but also have economic benefits, including costs

Table 4
Areas, actions, and economic benefits of sustainable CMR.

Area	Action	Economic benefit/cost savings
Energy and electricity	Powering down MRI machines overnight or while not in use	Reduces electricity consumption by 25–33% annually, translating to a potential annual savings of 12.3–21.0 MWh [37]
	Use low power or “power save” modes for imaging equipment	Additional 22–28% reduction in energy use, further decreasing electricity costs
CMR protocol efficiency	Adopt the SCMR 30-min CMR protocols, abbreviate other imaging protocols, use AI and deep learning for accelerated imaging	Reduces energy use and costs per patient exam
Operational efficiency	Optimize patient flow, reduce CMR table time, reduce idle time	Reduces total machine runtime, lowering both energy use and overall operating costs
Contrast agents	Reduce the use of GBCA doses, apply non-GBCA CMR techniques	Reduces costs for the purchase and disposal of GBCAs
Finite and limited resources	Reduce the use of finite resources by implementing low-helium CMR and developing low-field CMR applications	Reduce costs associated with scarce materials
Appropriate use of CMR	Using decision support tools to ensure appropriate ordering of tests, minimizing unnecessary scans	Lowens the volume of electronic and hazardous waste, reducing waste disposal costs
Circular economy in collaboration with the industry	Develop sustainable practices such as circular economy approaches, refurbishing and reusing equipment, sustainable shipments, energy labeling, and monitoring energy use	Reduces the need for expensive helium, conserving a finite resource, lowering the production and operational costs

The right column lists direct and indirect financial and cost benefits associated with reductions in CMR energy use, greenhouse gas emissions, and resource conservation strategies

CMR cardiovascular magnetic resonance, GBCA gadolinium-based contrast agents, MRI magnetic resonance imaging, MWh megawatt-hour

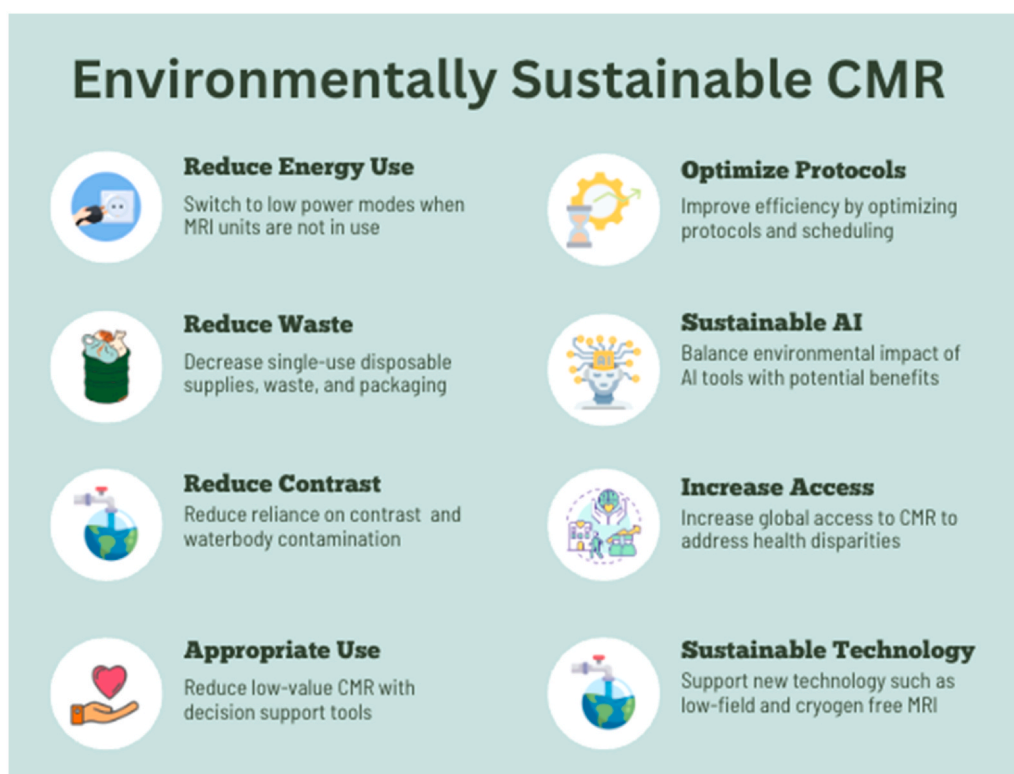


Fig. 5. Opportunities and actions to improve environmental sustainability of CMR. *AI* artificial intelligence, *CMR* cardiovascular magnetic resonance, *MRI* magnetic resonance imaging

for electricity, waste management, contrast agents, and scarce resources such as helium, [Table 4](#).

16. Conclusion

As clinical CMR volumes continue to rise globally, the environmental impact of CMR is expected to grow, demanding significant consideration to reduce its carbon footprint. In the future, technical developments and innovations should lead to MRI systems and CMR protocols with lower energy requirements and automated protocols for very low energy-off states and more cost-effective operations. AI tools will play an important role in addressing sustainability in MRI from various aspects, including techniques to automate and accelerate image reconstruction, enhance image clarity, models for identifying protocols best fit for a given patient from reviewing the electronic health record and environmental considerations [7]. Professional societies, including the SCMR, will play an increasingly important role in promoting education, research, and advocacy efforts related to sustainability in imaging.

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Consent for publication

Consent for publication.

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