

Annual Review of Environment and Resources Sustainability in Health Care

Howard Hu,¹ Gary Cohen,² Bhavna Sharma,³
Hao Yin,^{4,5} and Rob McConnell¹

¹Department of Population and Public Health Sciences, Keck School of Medicine, University of Southern California, Los Angeles, California, USA; email: howard.hu@med.usc.edu

²Health Care Without Harm, Boston, Massachusetts, USA

³School of Architecture, University of Southern California, Los Angeles, California, USA

⁴Department of Economics, Dana and David Dornsife College of Letters, Arts and Sciences, University of Southern California, Los Angeles, California, USA

⁵School of Population and Public Health, University of British Columbia, British Columbia, Canada

ANNUAL REVIEWS CONNECT

www.annualreviews.org

- Download figures
- Navigate cited references
- Keyword search
- Explore related articles
- Share via email or social media

Annu. Rev. Environ. Resour. 2022. 47:173–96

First published as a Review in Advance on
July 18, 2022

The *Annual Review of Environment and Resources* is
online at environ.annualreviews.org

<https://doi.org/10.1146/annurev-environ-112320-095157>

Copyright © 2022 by Annual Reviews. This work is licensed under a Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See credit lines of images or other third-party material in this article for license information

Publisher note: The authors have provided an updated and amended supplemental appendix for the section entitled “Organizations and Ongoing Initiatives” and provided an updated Disclosure Statement.



Keywords

sustainability, health care, healthcare, environment, decarbonizing, life cycle

Abstract

The academic public health and biomedical communities have a long history of researching and documenting the adverse impacts of pollution on human health. However, the healthcare industry itself is a major contributor to pollution as well as the greenhouse gas (GHG) emissions responsible for global warming. For example, the health sectors of the United States, Australia, England, and Canada are estimated to emit a combined 748 million metric tons of carbon dioxide equivalents annually, equivalent to a nation that would rank seventh in the world for GHG emissions. Moreover, the healthcare sector is a major consumer of natural resources, thereby contributing to the imbalances characteristic of what is increasingly being referred to as the Anthropocene and a threat to planetary health. In this article, we summarize current information on the healthcare industry’s environmental footprint and the potential for markedly reducing that footprint by applying the principles and tools of sustainability science. We discuss some of the industry’s special challenges, including those associated with new construction (which have undergone relatively little examination in relation to sustainability, despite predictions of accelerated growth). We examine current ideas and efforts to advance sustainability solutions in the healthcare industry, in high-, middle-, and low-income countries alike, where the healthcare industry can be expected to grow the fastest. Finally, we review case studies and discuss research needs.

Contents

INTRODUCTION 174

THE ENVIRONMENTAL FOOTPRINT OF THE HEALTHCARE

 INDUSTRY: OPERATIONS 175

 Examples of Healthcare-Specific Sources of Carbon Emissions 176

 Impacts on the Burden of Disease 177

THE ENVIRONMENTAL FOOTPRINT OF THE HEALTHCARE

 INDUSTRY: DESIGN AND CONSTRUCTION 177

 Manufacturing, Construction, and Decarbonization 178

 Well-Being 178

 Design and Operational Energy 179

 Embodied Carbon in Construction 179

GOING FORWARD: SOLUTIONS 180

 The Big Picture: Circular Economy Principles 180

 Organizations and Ongoing Initiatives 180

 Sustainability and the COVID-19 Pandemic 182

RESEARCH NEEDS 183

 Metrics and Reporting 183

 Cost of Carbon and Sustainable Healthcare Financing 185

SUMMARY AND CONCLUSIONS 188

INTRODUCTION

The academic health community has long researched and documented the adverse impacts of pollution on human health, including specific toxicants encountered by workers and communities such as asbestos, lead, mercury, and pesticides, as well as complex mixtures such as outdoor and indoor air pollutants. Partly on the basis of the World Health Organization’s and entities such as the Institute for Health Metrics’ global burden of disease estimates, researchers have been able to reveal, for example, that in 2015, pollution was likely responsible for 9 million premature deaths globally and 16% of all deaths (1). Given that these estimates focused on a relatively small set of pollutants, efforts are being made to expand them (2) and to estimate the current and likely future burden of disease from climate change (3).

What has been less acknowledged is that the healthcare industry itself is a major contributor to pollution as well as the greenhouse gas (GHG) emissions responsible for global warming. It has been recently pointed out that the health sectors of the United States, Australia, England, and Canada emit a combined 748 million metric tons of carbon dioxide equivalents annually (4). If these countries’ health sectors were an independent nation, they would rank seventh in the world for GHG emissions (4). Moreover, the healthcare sector is also a major consumer of natural resources, thereby contributing to the imbalances threatening ecosystems that are characteristic of the Anthropocene and that, in turn, threaten health in ways that have become the focus of an area known as planetary health (5).

In this article, we summarize current information on the healthcare industry’s environmental footprint and the potential for markedly reducing that footprint by applying the principles and tools of sustainability science. We discuss special challenges, such as the need for high-throughput ventilation systems in order to reduce in-hospital transmission of airborne infectious diseases, and the status of current inhaled anesthetic agents as potent GHG emissions. Given the inexorable

Healthcare:
the adjective used to describe something in relation to health care

Sustainability:
avoidance of the depletion of natural resources in order to maintain an ecological balance

demand for building new healthcare facilities and renovating existing ones to keep up with changing healthcare system demands and clinical practices, we also focus on the design aspects of healthcare facilities that pertain to energy, the carbon footprint of associated materials, and principles of design that address patient well-being. We also examine concerted efforts to advance sustainability solutions in the healthcare industry (6), including the work in the United States of nongovernmental organization coalitions such as Health Care Without Harm (HCWH) (7), the ideas generated by the Workshop on Environmental Sustainability in Clinical Care held at Yale University in 2018 (8), an initiative started in 2021 by the National Academy of Medicine to decarbonize the US health sector (9), and the World Bank, which recently funded a detailed examination of low-carbon and resilience strategies for the health sector with a major focus on middle- and low-income countries (10). The latter regions are where the healthcare industry can be expected to grow the fastest and thereby afford opportunities to leapfrog into healthcare industry designs that incorporate sustainability principles at the start.

Finally, we examine several case studies that illustrate potential best practices as well as some of the organizational, policy, political, and cultural obstacles to implementing sustainability-related changes to the healthcare industry. We consider the cost of carbon and sustainable healthcare financing. Finally, we draw some conclusions and provide a summary of research needs.

THE ENVIRONMENTAL FOOTPRINT OF THE HEALTHCARE INDUSTRY: OPERATIONS

Health care accounts for approximately 10% of global economic output, with large variability between countries (11). Like most service sectors, the corresponding global carbon footprint of health care is not as large proportionally as many manufacturing sectors. Nevertheless, health care has been estimated to account for 4.4% of global GHG emissions (11), with some countries contributing disproportionately greater emissions. Overall, health care represents an energy-intensive sector given the need for continuous operation, required mechanical services (e.g., lighting, heating, ventilation, and cooling), and a high-performance environment to support services (12). One of the few international comparisons using standardized methods is a study of healthcare GHG emissions associated with the 36 Organization for Economic Co-operation and Development (OECD) countries plus India and China, which account for 54% of world population and 78% of global production (13). Among these countries, the healthcare emissions per capita varied by almost 25-fold between the lowest (India) and highest (the United States). Health care is responsible for approximately 8.5% of emissions in the United States, where health care contributes more GHG than any other country, almost 25% of the world's healthcare emissions by one estimate (6). Moreover, GHG emissions in the United States have been increasing (6).

The health carbon footprint is commonly divided into three scopes (6) (**Table 1**): Scope 1 includes direct emissions by healthcare facilities, for example from vehicles for patient transport,

Carbon: the element that, with oxygen, forms carbon dioxide, the gaseous compound released into the atmosphere that is associated with climate change

Health care: the sector of society and industry that provides professional health services

Environment: the conditions in which people live and operate, including the composition of air, food, water, working environments, atmospheric conditions, green versus urban environments, etc.

Table 1 Greenhouse gas emissions from the healthcare industry, by scope

Emissions, by scope	Covered activities
Scope 1: Direct, by health industry	Fossil fuel combustion for health facility operations and associated vehicles (for patient transport, etc.); use of refrigerants, medical gases, etc.
Scope 2: Indirect, from energy associated with utilities purchased and used by health services	Electricity supply, heating and cooling, steam, chilled water
Scope 3: Indirect, related to buildings and other capital resources, equipment, devices, consumables, pharmacologics, etc.	Pharmaceuticals, uniforms, data centers, downstream applications (home-based care, waste management, etc.)

Life cycle: the “life” of a commercial product, process, or service (e.g., from raw material extraction through manufacturing, distribution, use, recycling, or disposal)

anesthetic gases, and burning of fuel for heating and other operations. These are emissions that health facilities can develop policy to reduce. Scope 2 emissions are indirect, for example those generated by production of electricity purchased for operating health facilities. Scope 3 emissions are also indirect, from purchase of pharmaceuticals, procurement of medical supplies, and downstream emissions from waste and home-based care. These emissions provide an opportunity for large healthcare consortia to exert pressure on vendors to increase the sustainability of operations by auditing and purchasing from more responsible companies.

A recent study of US healthcare emissions estimated that Scope 1 emissions accounted for 9% of the total, Scope 2 for 11%, and Scope 3 for approximately 80% (6). However, Scope 2 emissions depend heavily on whether renewables or fossil fuels power the utility grid for the area of operation. In addition, production of electricity is a major contributor to the impact of the health sector on Scope 3 emissions. Thus, total US healthcare emissions could be reduced by 39% if electric power for the entire sector came from renewable energy. Internationally, the study of OECD countries, India, and China estimated that during the 2000 to 2014 period there were a group of (largely European) countries that had declining healthcare carbon footprints in spite of increasing expenditures, which if accelerated could be a model for other countries to reduce emissions (13). This is largely attributable to what the authors describe as a “core insight” from the study that the carbon footprint of the national energy grid has an outsized impact on the healthcare carbon footprint, effectively delinking emissions from national health expenditures (13). Therefore, decarbonizing energy production across the economy can markedly reduce the healthcare carbon impact. Other countries, including the United States, Canada, Australia, and some Asian countries, had increased emissions, even if they did not increase proportionally as rapidly as the expenditures on health care. Healthcare emissions in China and Turkey increased more rapidly than expenditures.

Examples of Healthcare-Specific Sources of Carbon Emissions

Some clinical activities are particularly carbon intensive. Operating rooms with high heating, ventilation, and air conditioning (HVAC) energy consumption (due in part to the very high air exchange rates to reduce risk of infection) also use anesthetic gases such as desflurane, which results in tenfold increased emissions compared to other less polluting anesthesia (14). Operating rooms are 3–6 times more energy intensive than the rest of the hospital. The relative impact of anesthetic agents is an area of active research. A recent study of 20 injectable anesthetics reported that the associated carbon footprint ranged from 11 kg CO₂ equivalents (kgCO₂eq) for succinylcholine to 3,000 kgCO₂eq for dexmedetomidine (15). Conducting the study required creating life cycle inventories of GHG emissions for 130 other compounds used in the manufacture of these drugs, representing a major challenge for estimating the carbon footprint of pharmaceuticals, which, in turn, may account for 25%, 18%, and 10% of healthcare carbon footprints in Canada, Australia, and the United States, respectively (8). Much work remains to be done to provide inventories for healthcare organizations to be able to generate accurate data on carbon footprint. A recent review of 84 available studies examining the carbon footprint of healthcare facilities found only six covered all three scopes (16). Nevertheless, assessments have been made of the carbon and other environmental impacts of many supply chain products, including metered dose inhalers, equipment for anesthesia, central venous catheters, dental burs, disposable surgical kits and instruments, medical use of plastics, hospital gowns, radiology equipment, and incontinence products (8, 17, 18). Estimates have also been made for many procedures including births, hysterectomy, dialysis, plastic surgery, cataract extraction, various minimally invasive surgical services, intensive care and perioperative care, ambulance services, and telehealth services. GHG contributions of building

construction and of different building design, and strategies for reducing this impact, are another area of active research, which we consider below.

Impacts on the Burden of Disease

An irony of the healthcare sector carbon footprint is that climate change has direct health consequences from heat waves and as a result of hurricanes, flooding, drought, and wildfires caused or exacerbated by global heating from fossil fuel emissions. Thus, the sector's contribution to global warming is counter to the mission of improving health. What has been less studied is the contribution of health care more broadly to environmental degradation with substantial adverse health impact. This sustainability research has begun to identify opportunities for health and environmental co-benefits of efforts to decarbonize health care. A recent review identified priorities for developing sustainability metrics for health care beyond GHG emissions to include reduction of health-damaging pollutants such as pollution from pharmaceutical production and disposal, reduction of unneeded procedures, increased substitution of reusable for disposable single-use consumables, better and simplified methods for life cycle assessment, and development of composite measures encompassing GHG, air pollution, chemical pollution, and resource depletion (19). A global assessment estimated the environmental impact of health care, based on the direct and indirect effects of the supply chain (corresponding to much of the Scope 3 emissions) (20). The study found substantial impacts of demand generated by the health sector on (a) water scarcity, contributing to poor sanitation and hygiene; (b) deforestation resulting from the sector's supply chain, resulting in malaria; and (c) ambient air pollution from burning of fossil fuels. An estimated 2.8% of global ambient particulate matter, 3.4% of nitrogen oxides, and 3.6% of SO₂ were attributed to health care, largely as a consequence of Scope 1 activities such as patient transport and heating, and of the supply chain, with large variation across countries. Moreover, these effects are increasing as spending in the health sector grows. Although the health burden of exposure to these pollutants depends on the distribution of the population exposure attributable to the healthcare emissions (and this was not estimated), the global burden of disease of ambient air pollution includes 6.7 million deaths (21). A US study estimated that the healthcare sector was responsible for 470,000 disability adjusted life years, just due to air pollution effects. This burden of disease is roughly equivalent to that due to preventable medical errors (22). The burden of disease attributable to air pollution also likely substantially underestimates the impact of other pollutants created in the supply chain, such as the health effects of environmental contamination with pharmaceuticals, which have not been well studied (9). Thus, healthcare sector contributions to climate change scenarios with adverse impacts on health can markedly reduce the net population benefit of healthcare services. This consequently places an ethical burden on health care to decarbonize; moreover, there are substantial secondary health co-benefits of a sustainable approach. In the United States, in particular, where the cost of health care has escalated rapidly, accounting for close to 20% of gross domestic product, reducing waste and unnecessary medical procedures could reduce the cost of health care without compromising patient care, while generating substantial secondary sustainability health co-benefits (6). In addition, most healthcare systems make little investment in preventive services. Therefore, Pichler et al. (13) have suggested that the value returned of "carbon costs of health care" might be best evaluated based on health outcomes.

THE ENVIRONMENTAL FOOTPRINT OF THE HEALTHCARE INDUSTRY: DESIGN AND CONSTRUCTION

A dimension to the healthcare industry and sustainability issue that has received much less attention is the environmental footprint related to construction and associated building materials.

This is critical, given the continual pressure on hospitals to expand and/or renovate in relation to demand for services of, among other things, a growing population of seniors in most countries, and the constant need to upgrade to accommodate new technologies. In addition, the hospital construction industry is expected to surge in 2022 as construction markets rebound and hospitals invest in dedicated wards for COVID-19 (coronavirus disease 2019) and future pandemic patients (23).

Manufacturing, Construction, and Decarbonization

Manufacturing and construction of the built environment, directly and indirectly, contribute to 39% of energy-generated global CO₂ emissions (24). There is a need to address both operational and embodied carbon (i.e., the emissions associated with the construction materials within a building) across all scopes of health care to support decarbonization of the built environment. The complexity of healthcare facilities is often a challenge in implementing sustainable design strategies. One must consider multiple scales and needs to provide a holistic approach. This includes exploration of zones within a building for required HVAC and lighting requirements, as well as the physical envelope of the building, and finally the overall campus of buildings where applicable. Healthcare campuses represent a complex system, with management of the physical buildings, the operations, supply chain, and information and communication technology (25). As awareness of the need for sustainable design strategies grows, the methods to assess sustainability also have expanded. Examples of international certification methods include the US Green Building Council Leadership in Energy and Environmental Design (LEED), UK Building Research Establishment Environmental Assessment Methodology (BREEAM), Japan Comprehensive Assessment System for Built Environment Efficiency (CASBEE), and Australian Green Star, which draws from LEED and BREEAM (12, 26). In addition, certification rating systems exploring human health and well-being have emerged (e.g., FitWel, WELL). These certification systems serve as a general guide in the design process on how to incorporate sustainable design strategies into a project. Regenerative design methods, such as the Living Building Challenge, expand the assessment from the physical infrastructure to the surrounding community and ecosystem, a reflection of the goal for the facilities to be an integral part of community that they serve (27). Further consideration of the broader context provides opportunity for additional co-benefits through expansion of design performance metrics beyond the construction of the physical structure. Assessment of performance would then occur in multiple phases of the building: the design stage, post-occupancy stage, operations and management, and end-of-life stages. Evaluation criteria must also go beyond emissions and explore other metrics, such as well-being and productivity, to reflect the diverse impacts that the healthcare sector has on users (both staff and patients), as well as the potential benefits for surrounding communities.

Well-Being

Design of spaces for well-being was incorporated into designs in the late nineteenth and early twentieth centuries. Use of daylight, nature views, art, and other interventions aims to create positive benefits to staff performance and patient health outcomes (28). Increased attention to the intersection between the built environment, human well-being, performance, and productivity has led to the identification of design features for healthy spaces. These factors explore comfort (e.g., light, acoustics, temperature, air quality), function (e.g., safety, adaptability, and patient-centered care), and restorative atmosphere (e.g., visual displays, connection to nature, multisensory) (29). These design features have been shown to reduce stress and fatigue in patients and staff with improvement in overall health (30, 31); there are also suggestions that nature views can shorten the

hospital stays of intensive care unit (ICU) patients, thereby reducing costs (32). The influence of light on health and well-being has been explored (33). The promotion of natural daylight has the co-benefits of reduction in operational energy and positive benefits for well-being, especially in a healthcare setting. Similarly, use of natural ventilation has benefits for the users, as well as the reduction in need for HVAC systems.

Design and Operational Energy

In existing healthcare infrastructure, the focus is on reduction of energy consumption, achieved through energy efficiency measures (e.g., lighting, HVAC, automated controls), improved indoor environmental quality, and modifications to the building envelope. In new infrastructure, the baseline goal is net-zero energy or net negative emissions (34). Automated controls for operating rooms, which are energy intensive, have been shown to be successful at reducing energy demand by reducing consumption when not in use. Reduction in operational energy of healthcare facilities is challenging, as the energy requirements are strict to satisfy standards (e.g., hygiene control, ventilation, temperature, and relative humidity) (35, 36). Further research is needed to explore heating, ventilation, and cooling requirements (e.g., setpoints, air changes per hour, variable frequency drives) for healthcare facilities to identify areas for optimization and automation. Centralized systems provide efficiency; however, localized controls and measures for thermal comfort have been shown to be effective (35). Life cycle analysis of HVAC systems within healthcare facilities would provide further opportunities to identify areas for improvement (37).

Passive design strategies provide reduction of operational energy consumption. There are examples in developed, as well as developing, countries that have successfully employed this strategy in design to support healthcare services and well-being of the communities they serve. The design of low-carbon healthcare infrastructure has been achieved through sourcing of local materials, passive design strategies, and use of technology to address the need for sterilization of spaces (10). As previously discussed, decarbonization of energy supplies will also support the reduction in emissions (6). Decreased energy consumption and the transition to a clean power grid will reduce air pollution from energy production, providing positive health benefits to the surrounding community. The focus on operational carbon is an important aspect of addressing the impacts from the healthcare sector. The physical infrastructure of the healthcare sector is another area in need of further exploration.

Embodied Carbon in Construction

Reduction of the embodied carbon of building materials is a major focus to decarbonize the built environment. Architecture and engineering practitioners globally have recognized and committed to reducing impacts from design and engineering practice [e.g., Architecture 2030 (<https://architecture2030.org>)]. These efforts include the reduction of the need to build, through modular design for future expansion, adaptive reuse and retrofit of existing buildings. As described above, an increased need for healthcare infrastructure is predicted to occur globally. Increasing the longevity and life span of the healthcare facilities would reduce the need for future construction. Exploration of structural systems and materials also provides a pathway to optimize the design, while minimizing the associated CO₂ emissions from the materials selected. Healthcare facilities provide an interesting challenge, as they often include specific design constraints that are highly regulated and materially intensive (38). Early studies exploring the embodied carbon of structural systems indicated that optimization of the structure can result in reduction of the overall impacts of the design of a healthcare facility (39). Assessment of the embodied carbon of buildings is increasingly used in the design process of other building types and should be included

in the design of healthcare facilities (40). The technology is available to support net-zero infrastructure (34) and, through a collaborative design approach, design challenges can be overcome to ensure decarbonization of the healthcare sector infrastructure.

GOING FORWARD: SOLUTIONS

The Big Picture: Circular Economy Principles

The Scope 3 emissions represent approximately 80% of the healthcare sector emissions. Categorization and assessment of the emissions from the various supply chains and services outside of Scopes 1 and 2 is challenging, but not impossible. Circular economy principles have emerged as methodology to assess and reduce impacts from materials, through a life cycle design approach. The method is applicable on a product scale, with the ability to assess the materials within a product and identify opportunities for new business models, increased product life span, disassembly, reuse, and recycling. This approach aims to shift society from a linear take-make waste model to a circular approach to reduce the need for extraction of further resources as well as to create new value chains. Commercial healthcare and technology companies are exploring the method as way in which to reduce impacts, but also provide new business opportunities (41). A major area of focus is waste generated from healthcare services, in particular single-use plastics. A shift from conventional plastics (e.g., polyvinyl chloride), to bio-based plastics would further reduce the impacts associated with healthcare services.

Organizations and Ongoing Initiatives

A complementary strategy for healthcare sustainability is medical society campaigns, such as the American Society of Anesthesiologists' Inhaled Anesthetic 2020 Challenge (42) to help practitioners reduce their centers' anesthetic carbon emissions by 50%. Simple measures, such as using low fresh gas flows, phasing out or reducing desflurane and nitrous oxide in favor of intravenous and regional procedures, and investment in waste anesthetic gas-trapping or gas-destroying technology for the anesthesia machine, can markedly reduce the anesthesia footprint. A facility carbon calculator, based on anesthetic gas use, provides feedback to practitioners and management. The simple data collection procedure is a template for standardized data collection that could be widely implemented as part of healthcare carbon reporting requirements. Marked reductions in GHG emissions are possible using these approaches (43, 44). Another quality-linked initiative is the American Board of Internal Medicine's Choosing Wisely campaign to reduce unnecessary tests and procedures for which there is little evidence of efficacy, directed especially to vulnerable and marginalized populations. This is an opportunity to link quality in health care with co-benefits across health outcomes and carbon emission reductions. In India, cataract surgery accounts for 6 kg of CO₂ emissions per operation, compared with 20 times the carbon emissions and 10 times the cost for the same operation in the United Kingdom, where clinical outcomes are similar (8, 10). These reports have resulted in recommendations by organizations representing clinicians and specialists for healthcare quality criteria to include carbon emission metrics.

More broadly, detailed recommendations on a broad range of measures have been developed for reducing GHG emissions in healthcare facilities. In the United Kingdom's National Health Service (NHS), a detailed list of options for CO₂ reductions, costs of doing so, and financial savings has been developed for everything from unnecessary packaging of medical equipment, drug wastage, and travel that could be replaced with digital conferencing, to lowering the thermostat 1°C and improving lighting controls. In medical laboratories and research facilities, equipment and reagents have been shared efficiently to reduce duplication and waste (45). Cooling freezers to −70°C instead of −80°C, which may be appropriate for storage of many samples, can markedly

reduce the carbon footprint of freezer operation. My Green Lab (<https://www.mygreenlab.org/>) provides guidance and performance certification for laboratories.

Health Care Without Harm (HCWH), an international nonprofit organization, is one of several organizations providing leadership on sustainability to the health care sector. For updated and amended information, please see the **Supplemental Addendum**. Its climate strategy is built on three pillars:

Supplemental Material >

- **Mitigation:** The healthcare sector radically reduces its own carbon footprint and implements low-carbon healthcare delivery, using its supply chain leverage to drive the market to low-carbon, healthy products and services.
- **Resilience:** The healthcare sector prepares its facilities for climate impacts and helps to build community health and climate resilience.
- **Leadership (advocacy and communication):** Healthcare institutions and professionals use their trusted voices to define climate change as a public health threat and become powerful advocates for climate-smart policies at all levels of government and in healthcare oversight organizations.

Using this framework, HCWH has built out the scaffolding and resources for effective and collective climate action in the healthcare sector, developing key strategic vehicles, resources, and tools to engage and support the sector in this work.

In 2014, HCWH convened the US Health Care Climate Council, a leadership body of health systems that implement innovative climate solutions, inspire and support others to act, and use their trusted voice and purchasing power to move policy and markets to drive the transformation to climate-smart health care. The Council currently has 18 leading health systems representing 600 hospitals in 41 states, 50 million patients served annually, a total annual operating revenue of more than \$200 billion, and a million employees. These leaders have set ambitious GHG reduction goals and purchase or generate more than two million megawatt hours of renewable energy annually.

In 2015, HCWH launched the Health Care Climate Challenge to mobilize healthcare institutions around the world to protect public health from climate change. The Challenge has engaged more than 300 institutions to date, representing the interests of more than 22,000 hospitals and health centers in 36 countries. Participating health systems commit to meaningful action in alignment with the three pillars of the framework, including a commitment to set a GHG reduction goal within a year. Through this challenge, HCWH collects annual data and tracks the global healthcare sector's climate action.

HCWH also has produced resources to support sector climate action. The following are examples:

- HCWH's Global Road Map for Health Care Decarbonization, produced in collaboration with Arup, charts a course for zero-emissions health care by 2050 (46). The paper identifies seven high-impact actions as key to healthcare decarbonization and policy recommendations to drive change. This paper follows on the 2019 Health Care's Climate Footprint report that found that the global healthcare sector is responsible for 4.4% of net global emissions and the US healthcare sector makes up 27% of those emissions (<http://www.healthclimateaction.org>).
- The Energy and Health Impact Calculator enables hospitals, organizations, and policymakers to estimate the impact of energy use on their communities (47). Using data from the US Environmental Protection Agency and US Department of Energy, the Calculator provides the number of health incidents, medical treatment costs, and societal costs related to energy choices, supporting the case for a transition to clean energy.

- The Safe Haven in the Storm report, written with PricewaterhouseCoopers Advisory Services, LLC, examines the financial impacts of being ill-prepared for extreme weather and the benefits of investing in resilience measures (48). It features concise case studies and clear infographics to make the business case for climate resilience.

In October of 2021, the US National Academy of Medicine launched an Action Collaborative on Decarbonizing the U.S. Health Sector (49). Envisioned as a neutral platform for the public, private, and nonprofit sectors, the Collaborative is setting shared sustainability goals that focus on four workstreams related to healthcare supply chain and infrastructure; healthcare delivery; health professional education and communication; and policy, financing, and metrics. The focus on the 80% of health sector emissions in the supply chain is paramount, with pharmaceuticals and chemicals being the largest contributor (6). Among the actions the Collaborative aims at advancing are incentivizing innovation in products and services, obtaining commitments from industry to reduce unnecessary waste and move toward reusable and recyclable packaging, and facilitating the development of shared sustainability metrics. Examples of other strategies to be pursued include creating linkages between performance on sustainability metrics with value-based payments and reimbursement for healthcare services, and expanding remote care and telehealth services, thereby reducing hospital visits and increasing prevention-oriented primary care that will, in turn, reduce hospitalizations.

Sustainability and the COVID-19 Pandemic

The COVID-19 pandemic has generated both new challenges and new opportunities with respect to the healthcare sustainability agenda. A big challenge has been the enormous worldwide spike in hospitalizations, particularly in ICUs, that has been required to manage the acutely ill. Surveys in the United States have demonstrated that ICUs were at or over capacity in many hospitals at various times during the pandemic (50); for example, among 13 geographically dispersed academic medical centers, COVID-19 patients accounted for 44% of ICU patients in the month of April of 2020, with 6 hospitals reporting being at 100% or over capacity (51). Given the ongoing nature of the pandemic, the evolution of viral variants, and the specter of future pandemics, there is anticipation that many hospitals will be expanding their ICU capacities. In addition, the need for social distancing and minimizing the risk of airborne infection is stimulating the redesign of waiting spaces to allow for social distancing, more room between chairs, low height walls with glass separation panels, more compartmentalization, and minimal wait times (52). Designs are incorporating sections or pods that have independent infrastructure so that multiple beds can be switched to more negative or positive pressure. There is also clear pressure to increase the number of airborne infection isolation rooms, which require dedicated exhaust, anterooms, specific air exchanges, and pressure differential monitoring. To contain airborne pathogens, there is heightened attention to installing UV lighting in HVAC systems, and healthcare systems now require larger, more robust high efficiency particle air (HEPA) filtration systems with minimum efficiency reporting values (MERV) 16-level protection. All of these changes will involve new construction and new demands on energy.

Another dimension to COVID-19's impacts has been the substantially increased associated demand for single-use medical devices (personal protection equipment, test kits, etc.) which, in turn, has worsened waste management problems in the healthcare sector. As of August 2021, pandemic-related preventive equipment and medical treatments generated more than 8 million tons of waste (53), which not only polluted the soil and ocean environment but also generated massive carbon emissions during the process of waste management (54, 55). This is on top of the 5% contribution of waste to the total carbon emissions of the healthcare sector that was estimated, for example, in

relation to the NHS in prepandemic England in 2019 (56). In response to COVID-19, a growing literature has emphasized two major streams of strategies to reduce healthcare waste and its related carbon emissions. First, the healthcare waste management system should shift to a circular economy. Hospitals and healthcare centers should encourage reusable medical devices, biodegradable alternatives, extending equipment lifetime, products with eco-friendly packaging, and investment in nonburn waste treatment technologies (57–59). Second, the healthcare sector needs to integrate waste treatment systems with the energy sector. By deploying waste-to-energy management strategies, such as photo-biological and ethanol fermentation, unrecycled medical waste can be treated as a potential carbon-neutral energy source (60, 61). Third, local government, specialized companies, and community should actively consolidate medical waste management practices (62). Research is needed to improve medical waste management capacity, assess best available sustainable technologies, develop new guidelines, and provide financial support in order to advance toward a net-zero emission target in the healthcare sector.

However, an impact of the COVID-19 pandemic that has been net positive for sustainability has been the associated hyperacceleration of the development of telemedicine, with one recent analysis using claims data indicating that telehealth use increased rapidly from a mean (standard deviation) of 773 (155) weekly visits in prepandemic 2020 to 45,632 (19,937) weekly visits in the pandemic period, a 59-fold increase (63). Such shifts have been made possible by the increased willingness of both consumers and providers to use telehealth, and regulatory changes that allowed for greater access and reimbursement. In so doing, telehealth dramatically decreased the healthcare environmental footprint related to transportation. For example, a review of outpatient care at a health system serving more than 600,000 members in the US Pacific Northwest demonstrated that the shift to telehealth was associated with a 46.2% decline in in-person visits, which was estimated to result in a decline in transportation-related GHG emission from 19.6 to 10.5 kiloton CO₂ equivalents (64). It is possible that further advances in telehealth will also improve primary care in ways that can improve preventive medical services and, as a result, the need for hospitalization for acute illnesses in general (and the associated high environmental footprint).

RESEARCH NEEDS

Metrics and Reporting

Global estimates of the impact of health care on GHG emissions are uncertain, because the metrics used are limited and are not standardized across countries. Estimation of other impacts on environmental degradation and of the direct and indirect adverse health impacts of the healthcare sector due to these effects are even more uncertain. Development of standardized and accurate ways of reporting data that can be used to develop better estimates is critically needed to design effective plans to reduce current unfavorable emission trends. In the medical supply chain that contributes disproportionately to GHG emissions, frameworks such as the Environmental Product Declaration (ISO 14025) could be used to design procedures for reporting the carbon footprint of medical products that could result in pressure on suppliers to develop more sustainable products. In the United States, the Energy Star program provides accounting tools for estimating energy use of individual healthcare facilities. However, there is no international standard for estimating emissions of specific clinical activities, such as HVAC energy consumption in operating rooms. Several recent reviews have recommended procedures for mandatory reporting of emissions at the facility level that would allow or require mitigation and performance monitoring also at the local level, and would make bottom-up estimates of national emissions more accurate (6, 65).

There is widespread use of the Global Reporting Initiative (<https://www.globalreporting.org/standards/>) and the Carbon Disclosure Project (<https://www.cdp.net/en>) that are potential

CASE STUDY: THE NATIONAL HEALTH SERVICE AND PUBLIC HEALTH ENGLAND

The National Health Service (NHS) and Public Health England lead the world in sustainable health care (67). In 2007, a national Sustainable Development Unit was established to develop metrics to monitor progress in decarbonizing the healthcare system. Local staff and management in medical centers across the country developed bottom-up examples of best practices that were shared widely. Reducing meat in food service, sourcing locally, reducing energy consumption through building management, travel planning, and in procurement can markedly reduce a hospital's carbon footprint. The 2008 Climate Change Act and 2012 Public Services Act have promoted sustainability in NHS operations and planning. Facilities were required to provide information on metrics that were used to develop the Sustainable Health Dashboard. The Dashboard provides performance information for every provider, clinical unit, and region in the NHS on indicators of carbon emissions, water and waste, air pollution, and plastics use, among other mandated indicators (19).

Almost 5% of all road trips in the United Kingdom are related to health services (44). A 25% reduction in air pollution produced by the sector could be achieved through measures promoting car sharing, installing chargers for electric vehicles, and providing bicycling infrastructure. NHS purchasing requirements are reducing the procurement, including pharmaceutical, carbon footprint. Engaged local practitioners and management, supported by regulation, are institutionalizing a culture of sustainability supporting local decision makers implementing best practices. Consistent standards for mandatory data collection are essential for planning and developing policy and guidelines. In England, there was an 18.5% reduction in greenhouse gases between 2007 and 2017 (as health services increased substantially) (19, 44). By 2017, the return on investment was 90 million pounds annually.

models for reporting healthcare corporations' sustainability record. Alternatively, existing corporate responsibility schemes for reporting GHG emissions could be potential models for reporting. However, even in providing basic sustainability reports, large healthcare organizations have lagged behind the rest of the corporate sector (66). For example, 78% of all Fortune 500 and 82% of S&P 500 companies provided sustainability reports between 2015 and 2016, compared with just 12% of large healthcare corporations. The one country that has made substantial progress in developing good estimates of GHG emissions is the United Kingdom, where across the NHS the Sustainable Development Unit has published estimates since 2009 (6) (see the sidebar titled Case Study: The National Health Service and Public Health England). Other proposals, specific to the United States, include the development of procedures to make comparisons across facilities with different energy requirements, in the same way that clinical performance metrics have been developed and are used to create incentives for clinical care that could be adapted to carbon emissions (46).

A *Lancet* commission in 2009 described the health effects of climate change as the biggest global health threat of this century (68). Although there had been only modest progress in reducing GHG emissions, it was recharacterized in 2015 as the greatest opportunity to improve global health (67, 69, 70). In particular, framing climate change as a public health challenge may offer promise for uniting people across the world that a focus on carbon emissions has not, and the health sector could lead the transformation by example. The development of metrics for both emissions and corresponding reductions in burden of disease associated with air pollution and other co-benefits of sustainable development in the health sector could influence the political calculus that currently impedes progress in reducing emissions within countries and globally (71, 72). Opportunities for a bottom-up emissions reporting system that would allow individual healthcare facilities and clinicians to consider the emissions impact of clinical decisions could help reduce the healthcare carbon footprint; incentives to do so would accelerate progress. Models such as the UK's NHS show that marked reductions are feasible.

Cost of Carbon and Sustainable Healthcare Financing

Another challenge to reducing carbon emissions in the healthcare sector is the lack of information on the cost of carbon emissions (or the benefits of decarbonization) and the cost of decarbonization interventions. Such science-based knowledge is critical input in cost-benefit analyses in designing decarbonization strategies.

According to the World Health Organization, the costs of direct damages to public health induced by climate change will be \$2–\$4 billion per year by 2030 (73). Costs associated with the social cost of carbon are even larger. Dynamic impacts of temperature on biological, ecological, and geological processes might reduce global average income by 23% by 2100 (74). A large body of literature documented the social cost of carbon with values ranging from \$1 to more than \$1,000 per ton CO₂ (75). By including the impacts of climate change on social economic development, human life, and the environment, the Stern Review showed that the global economic damages of climate change can be as large as \$5.5 trillion (76).

Although studies on the social cost and benchmark estimates of climate change impacts have been widely discussed and reviewed, the social cost of carbon is largely uncertain given climate model, utility function, discounting, and the damage functions in use (74, 75, 77). The social cost of carbon is commonly estimated using integrated assessment models (IAMs). US economist William Nordhaus developed a dynamic integrated climate economy (DICE) model in the early 1990s (78), followed by a range of different IAMs (79). Although these IAMs are helpful for developing climate policies, the simplification of human-climate interactions can bias the economic estimates of climate change impacts, leading to suboptimal decision making. Among all the uncertainties embedded in the IAMs, damage function is one of the most concerning components. Specifically, damage function is defined as a function that links the economic cost in lives, health, environment, and ecosystem with climate variables, such as temperature, sea level rise, and CO₂ concentration (80, 81). The shape of damage function is either quadratic, linear, or cubic correlation, with aggregated estimates at global or regional levels (64), while tipping point of temperature increase was still unclear and often ignored in economic models (82). In addition, many of these damage functions were determined in studies published years to decades ago (63, 64, 83–85). Some recent epidemiological studies showed millions of deaths were attributable to extreme temperatures each year globally (86, 87), which is comparable to the health damage attributable to ambient air pollution (21). Such health damages might cause trillions of dollars per year (88). This updated evidence from public health should be considered in the estimates of the social cost of carbon.

Tracking the cost of decarbonization techniques is a prerequisite for allocating limited healthcare resources, evaluating decarbonizing strategies, and advocating sustainable decarbonization policy. At the macro level, the cost of decarbonization is estimated by the benefit-cost IAMs, such as DICE and the Climate Framework for Uncertainty, Negotiation and Distribution model (62). However, these estimates are highly aggregated at global or country levels, which makes it difficult to use the estimates for specific decision making within the healthcare sector. To achieve affordable and sustainable health care, it is essential to understand the cost of specific actions to decarbonize the system and the return on investment of the avoided carbon emissions. By calculating the benefit-cost ratios of each action, healthcare sectors can prioritize and customize their own decarbonizing strategies. However, there is still no available comprehensive database for doing so. In the absence of a comprehensive benefit-cost support system, policymakers have limited information to decide which components of the health system should be prioritized, how much can be spent, and what can be planned for future spending.

CASE STUDIES: LOW- AND MIDDLE-INCOME COUNTRIES

There is great potential for developing countries to reduce the healthcare carbon footprint by retrofitting or building new systems right, although there are fewer documented examples than in the developed world. A series of case studies has been reported by the World Bank (8). Examples include the installation of solar panels for lighting that substituted previous use of highly polluting kerosene lamps. In South Africa, the Western Cape's 53 public hospitals eliminated almost all coal- and oil-fired boilers. The region's Lentegeur Hospital's campaign for efficiency in laundry facilities saved more than 19 million liters of water and reduced CO₂ emissions by more than 550 metric tons, resulting in savings of \$62,000 annually, which would translate into \$3.3 million in savings if implemented across the entire region.

Between 1995 and 2015, healthcare spending in middle- and low-income countries increased continuously with an annual growth rate of more than 5% compared with 3% in high-income countries (89) (see the sidebar titled Case Studies: Low- and Middle-Income Countries). Global health spending will reach \$20 trillion in 2040 (90). Such a rapid rise in healthcare spending exceeds the growth rate of the average wage income (91). In addition, the COVID-19 pandemic has revealed the fragilities and inequalities in the healthcare systems (92). Together with the demographic shift to an aging population, pandemic shocks, and economic downturns, the healthcare systems need to improve their resilience by enacting healthcare financing strategies that respond to climate change. Beyond growing healthcare expenditures, demand and supply of healthcare services play a key role that is further affected by factors such as demographic change, technology progress, and resource availability.

Leveraging green financing to support and design sustainable health care has the potential to reduce its carbon footprint. Sustainable health care is viewed as healthcare services of better quality, more affordable and with less impact on the planet, and that can be accessed by people equally and efficiently (93). Green finance is an important channel that links climate policy and climate targets. Studies showed that green finance has positive effects on environmental quality and decarbonization (94, 95). Shifting money from carbon-intensive health care to low-carbon health care can ignite the expansion of sustainable health care.

There are two key principles that should be considered in redesigning healthcare systems. First, reduce the demand of healthcare services. The most cost-effective way to achieve sustainable health care is to keep people healthy (96, 97). The healthcare sector should promote health literacy, encourage healthy lifestyles, and facilitate an affordable health check-up system. Collaborating with other sectors to reduce environmental, behavioral, and occupational risks has the potential to avoid millions of deaths and billions of life years lost annually. The sector should balance the demand and supply of healthcare services (98). A sustainable healthcare system should be able to avoid unnecessary treatment and inadequate use of resources. Studies showed that the US healthcare system wasted approximately 20–25% of the total healthcare expenditure (99, 100). This high level of healthcare expenditure waste undermines sustainability goals in healthcare systems. High-income countries are dealing with waste and rising healthcare spending, while low-income countries are facing insufficient spending on health care (101). Sustainable healthcare financing should focus on balancing supply and demand to achieve universal healthcare coverage and at the same time on identifying solutions to underlying factors that distort this balance.

So far, the focus of measurements and reporting for healthcare institutions has been on corporate social responsibility and disclosures of the carbon footprints of hospitals and hospital services

(16) and specific associated processes and materials, such as anesthetic gases (102), devices, and consumables (17, 18). Reporting related to corporate responsibility has at its source the demands of key investors and shareholders for disclosure based on corporate ethics as well as the vulnerability of corporate business models to climate change risks. Many large healthcare providers and industries engaged in the production of pharmaceuticals, devices, and other products participate in the Carbon Disclosure Project (103). Such information and other creative approaches to estimate downstream impacts have recently been used to generate a global environmental healthcare footprint estimate (20). However, the information collected and accessed is heavily skewed toward GHG emissions, reflecting the availability of technical measures rather than a true full accounting of impacts on environment.

An exception can be found internationally with the development by the UK's NHS of its Sustainable Health Dashboard (<https://www.england.nhs.uk/greenernhs/whats-already-happening/sustainable-development-unit-archive/>). Having a centralized, publicly funded system allows the NHS to collect data and report performance for every NHS provider and associated healthcare units on carbon, resources, water, and waste; air pollution; plastics; and adaptation.

Recommendations have been made for developing and advancing sustainability metrics that better capture the full environmental footprint of the healthcare industry. For example, leveraging experiences in Australia and the United Kingdom, Hensher & McGain (19) proposed a range of directions and priorities that attempt to align a comprehensive set of sustainability metrics reporting with the methods currently being used by healthcare institutions to report on quality and performance (see **Table 2**).

Table 2 Future directions and priorities for developing healthcare sustainability metrics^a

Target areas	Areas to prioritize
Greenhouse gas emissions	Clearer framing of strategic purpose and goals for reporting at national, state, health system, and organizational levels and of healthcare system contributions to overall emissions reduction targets; assessment of highest-priority areas for advancing Scope 3 emissions measurement for both reporting and improvement purposes
Health-damaging pollutants	Identification and quantification of those healthcare environmental impacts that have the most severe impacts on human health to guide prioritized development of measures of harm reduction
Reducing overuse	Double-duty measures that capture the improvements to patient outcomes and environmental impacts from reducing healthcare overuse
Simplified Life Cycle Assessment methods	Invest in the development of simplified, low-cost Life Cycle Assessment methods and capabilities, allowing rapid and economical expansion of Life Cycle Assessment to support healthcare environmental impact measurement at all levels
Pharmaceutical pollution and waste	Development of system- and local-level measurement techniques to capture the scale and impacts of pharmaceutical pollution, including manufacturing, distribution, use, and wastage
Composite measures	Investigate the feasibility and design of composite measures or indices to capture multiple dimensions of healthcare environmental impact (for example, greenhouse gases, air pollution, chemical pollution, resource depletion)
Absolute versus relative measures	Balanced metric sets that support improved efficiency (relative measures) while also reducing overall environmental impacts (absolute measures) to support “absolute decoupling” of health care from environmental degradation
Single-use versus reusable consumables	Rigorous and comprehensive measures of environmental impacts of single-use versus reusable consumables, drawing on experiences from COVID-19

^aTable adapted from Hensher & McGain (19, exhibit 2) (CC BY 4.0).

Others have focused on specific steps in the supply chain, such as the cradle-to-grave GHG emissions life cycle analysis associated with anesthesia drugs conducted by Parvatker et al. (15); however, few evaluations of the carbon footprint of the healthcare sector could be deemed comprehensive. In terms of practices specific to hospitals, Alshqaqeeq et al. (16) reviewed a series of studies from the US Environmental Protection Agency (104) on hospitals to identify carbon emissions based on 12 subdivisions of typical services: “diagnostic,” “surgical services,” “inpatient care,” “critical care,” “emergency care,” “dialysis,” “physical therapy,” “outpatient care,” “clinical research,” “oncology, respiratory care, and laboratory services,” “hospital general,” and “support services.” Following this rubric, the authors conducted a systematic search of the literature and found 48 peer-reviewed articles that generated carbon footprint metrics for one or more of the service subdivisions, of which only 6 used life cycle analyses to make estimates related to all 3 environmental scopes (travel-related energy, direct energy, and the procured goods and equipment embodied energy). However, few evaluations of the healthcare sector’s carbon footprint could be deemed comprehensive.

To address these deficiencies, a Working Group for Environmental Sustainability in Clinical Care was formed, which, following a 2018 workshop, developed a set of “Key Research Gaps and Priorities for Environmental Sustainability in Clinical Care.” Observations and recommendations were made pertaining to four areas (8): safety, quality, and value in health care; healthcare emissions research; implementation, benchmarking, and accountability; and research funding for sustainable clinical care (see **Table 3**). Based on the discussion above, strong arguments could be made to add to the priorities attention to construction in the healthcare industry and greater attention to economic analyses and leveraging green financing. Among the conclusions of the Working Group was the recommendation to form a Commission on Environmental Sustainability in Healthcare that could advance the research and implementation science necessary to address the gaps and priorities. As of 2022—as the dominant focus of the healthcare world remains on addressing the COVID-19 pandemic—this has not yet occurred.

SUMMARY AND CONCLUSIONS

The healthcare industry has been identified as a major contributor to GHGs that are responsible for climate change as well as other pollutants and unsustainable practices that ultimately have negative impacts on human health and well-being. Given the mission of the healthcare industry, it has an inherent responsibility to reduce its environmental footprint, and recent initiatives have started to address the healthcare sustainability agenda by tackling aspects of each of the three scopes of GHG emissions. Although it is understood that Scope 3 emissions (indirect, related to buildings and other capital resources, equipment, devices, consumables, pharmacologics, etc.) make up approximately 80% of the total GHG emissions generated by health care, there are clear opportunities to make progress on all three types of emissions—an agenda that is ambitious, given, in part, the countervailing pressures that are specific to health care, such as the energy and material intensity that are typically needed for infection control.

In response, numerous initiatives are being advanced by academic researchers, higher education institutions, selected health systems such as Kaiser Permanente (see the sidebar titled Case Study: Kaiser Permanente), selected industries involved in producing healthcare products, non-governmental organizations such as HCWH, and most recently, governmental bodies, such as the US National Academy of Medicine’s Action Collaborative on Decarbonizing the U.S. Health Sector and Public Health England’s national Sustainable Development Unit. Research gaps and priorities have been identified, and we advocate for expansion to include a focus on healthcare construction and a greater focus on environmental economics.

Table 3 Key research gaps and priorities for environmental sustainability in clinical care^a

Safety, quality, and value in health care	Pollution and climate change are contributing to a global health crisis.
	Pollution itself is a patient safety issue, and pollution prevention should be included in efforts to improve healthcare quality.
	Clinical activities are the major driver of resource utilization and waste in health care and provide a fundamental opportunity for engaging health professionals in pollution prevention efforts.
Healthcare emissions research	Strategic areas of investigation include basic materials management, pharmaceuticals and medical device design, environmentally preferable clinical care pathways, hospital/health systems, and provider-level performance metrics with international benchmarks.
	A new life cycle inventory database containing whole medical products (pharmaceuticals and medical devices) is needed to facilitate research and development of best practices. It should be integrated into electronic health records and procurement information management systems to support environmentally preferable practices and performance benchmarking.
	Translational science must include application of existing metrics that measure environmental performance. Such metrics should then be embedded into existing quality and safety reporting frameworks, including remuneration models.
	The study of clinical best practices should be expanded to include optimization of resource efficiency and pollution prevention, in addition to patient outcomes.
	Reporting guidelines for healthcare sustainability research also need to be developed. This can be achieved through the Enhancing the Quality and Transparency Of health Research (EQUATOR) network for other types of translational research (https://www.equator-network.org/reporting-guidelines/cheers/).
Implementation, benchmarking, and accountability	Partnership is needed between healthcare sustainability experts and patient safety experts. Safety and quality organizations such as the Institute for Healthcare Improvement, the National Patient Safety Foundation, and the Anesthesia Patient Safety Foundation should work to advance the synergistic agenda around resource stewardship.
	Excessive infection control standards and practices without sufficient evidence are viewed as a major driver of avoidable pollution and waste generation in health care. Engagement of accrediting agencies and regulatory bodies is essential to minimize unintended adverse environmental effects as a result of care that offers no proven patient benefit.
	The evidence-based, best practices identified by initiatives like Choosing Wisely, Getting It Right First Time, and the Wise List must include environmentally preferable, in addition to waste-sparing, practices. Partnerships with these organizations are recommended to mainstream environmental stewardship into the healthcare quality discourse.
	Integrating environmental sustainability into value-based healthcare reform, and communicating with clinicians and policymakers in the language of these paradigms, can help to achieve rapid uptake and success of healthcare sustainability initiatives.
Research funding for sustainable clinical care	Government funding agencies, e.g., the National Science Foundation, the National Institutes of Health, and the Agency for Healthcare Research and Quality as well as philanthropic foundations, should create funding mechanisms that bridge environmental sustainability science with health services research to translate knowledge into sustainable clinical practices.
	Formation of a Global Commission on the Advancement of Environmental Sustainability in Healthcare, e.g., through the National Academies of Science, Engineering and Medicine, is needed to further research efforts that inform policy and practice and urgently focus leadership on the pollution public health crisis.

^aTable adapted with permission from Sherman et al. (8, table 1).

CASE STUDY: KAISER PERMANENTE

Kaiser Permanente is the largest integrated health system in the United States and the country's leader in health-care sustainability. It achieved net-zero carbon emissions in 2020 through a decade of sustained investment in solar and other renewable energy, construction of US Green Building Council Leadership in Energy and Environmental Design (LEED) buildings, including the first LEED Platinum hospital in California, and funding of carbon offset projects (105). It developed solar energy hospital microgrids that store energy for local use. In 2016, the organization committed to recycling, composting, or reusing all nonhazardous waste; sourcing food from local farms; and sending no waste to landfills. In 2019, some Kaiser Permanente regions committed to reducing or phasing out potent greenhouse anesthetic gases (which account for 3% of the organization's greenhouse gas emissions). Large savings accrued to some of these initiatives, including \$19.6 million annually in energy efficiency (compared with 2013) and \$2.8 million annually from decreased water use. Kaiser Permanente has ambitious goals to become carbon net negative, through further investments in renewable energy, sustainable food, waste reduction policies, and water conservation (106). Information required from suppliers on toxic chemical use and recycling policies has helped to identify and reduce the carbon footprint in procurement and to promote markets for environmentally less hazardous products, such as vascular catheters and breast pump equipment free of endocrine disrupting chemicals. In California, Kaiser Permanente was a cofounder of the California Healthcare Climate Alliance to help support state policy for reducing carbon emissions in health care.

Overall, these are daunting challenges, even if the world had not been recently plunged into the vast difficulties and associated demands of responding to the current global COVID-19 pandemic. However, the pandemic crisis may bear some silver linings that have implications for the healthcare sustainability agenda, even if modest. An example is the hyperacceleration of healthcare delivery to telemedicine, which carries the promise of not only markedly reducing the carbon footprint of healthcare transportation but also increasing preventive medicine services and reducing the need for medicines and hospitalization.

Given what is now clear—that society needs to be able to simultaneously respond to the climate crisis and (the current and) future pandemics—taking an approach that involves collaborations across a wide swath of disciplines and takes every opportunity to coordinate and leverage collateral benefits of solutions will be critical.

SUMMARY POINTS

1. The healthcare industry is a major contributor to pollution as well as the greenhouse gas (GHG) emissions that are responsible for global warming.
2. The GHG emissions include those that are direct, such as those associated with patient transport, fuel consumption, and anesthetic gases (Scope 1); indirect related to energy, such as the purchase of electricity (Scope 2); and indirect related to products used, such as pharmaceuticals and medical supplies, as well as downstream emissions from waste and home-based care (Scope 3).
3. Some clinical activities, such as the operations of surgical operating rooms, are particularly energy/carbon intensive.
4. Most of the GHG emissions (approximately 80%) stem from Scope 3 emissions, particularly the manufacture of pharmaceuticals and materials.

5. If one applies a global assessment of the environmental impact of health care on the burden of disease, just limiting the assessment to the particulate air pollution associated with the healthcare sector in the United States yields an estimated 470,000 disability-adjusted life years lost—an impact roughly equivalent to that due to preventable medical errors.
6. Several initiatives have been launched by academics, hospital systems, industry partners, nongovernmental organizations, and governmental bodies to address the sustainability in the healthcare agenda.
7. As the healthcare construction industry begins to resume (from its relative pause during the COVID-19 pandemic), there is also a need—and opportunity—to apply green design principles that could help significantly reduce the healthcare footprint.
8. Generating and applying the results of implementation research, leveraging the hyper-acceleration of healthcare delivery by telemedicine (brought on by the pandemic), advancing a broadly transdisciplinary approach, and incorporating a greater focus on environmental economics are among the recommendations that will hopefully lead to meaningful gains in meeting the sustainability in healthcare agenda.

FUTURE ISSUES

1. Life cycle analyses and the construction of a database are needed in relation to pharmaceuticals, medical devices, materials used for medical facility construction, and other aspects of healthcare facilities and operations.
2. The planning of healthcare facilities needs more attention to balancing healthcare-specific needs (such as infection control, sterilization of equipment) with energy-efficient designs.
3. The shift to telemedicine needs to be shaped to not only reduce the need for patient transportation but also increase attention to primary care and preventive medicine that can reduce the need for hospitalization, procedures, pharmacologics, etc.
4. Greater integration of environmental economics into value-based healthcare reform needs to be injected into healthcare operations and planning.
5. Funding is needed to bridge environmental sustainability with health services research.

DISCLOSURE STATEMENT

Gary Cohen is co-founder and president of Health Care Without Harm and Practice Greenhealth. Health Care Without Harm is a non-profit organization that seeks to transform health care worldwide so the sector reduces its environmental footprint and becomes a leader in the global movement for environmental health and justice. Practice Greenhealth is the innovation hub scaling the work of Health Care Without Harm and delivering environmental solutions to more than 1,500 hospitals and health systems in the United States and Canada.

The other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

Erratum >

ACKNOWLEDGMENTS

The authors would like to acknowledge the research and editorial assistance of Marisol Macedo. This work has been supported, in part, by National Institutes of Health grant P30ES007048.

LITERATURE CITED

1. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, et al. 2018. The *Lancet* Commission on pollution and health. *Lancet* 391(10119):462–512
2. Shaffer RM, Sellers SP, Baker MG, de Buen Kalman R, Frostad J, et al. 2019. Improving and expanding estimates of the global burden of disease due to environmental health risk factors. *Environ. Health Perspect.* 127(10):105001
3. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Beagley J, et al. 2021. The 2020 report of The *Lancet* Countdown on health and climate change: responding to converging crises. *Lancet* 397(10269):129–70
4. Sherman JD, MacNeill A, Thiel C. 2019. Reducing pollution from the health care industry. *JAMA* 322(11):1043–44
5. Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, et al. 2015. Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–*Lancet* Commission on planetary health. *Lancet* 386(10007):1973–2028
6. Eckelman MJ, Huang K, Lagasse R, Senay E, Dubrow R, Sherman JD. 2020. Health care pollution and public health damage in the United States: an update. *Health Aff.* 39(12):2071–79
7. Health Care Without Harm. 2021. Leading the global movement for environmentally responsible health care. <https://noharm.org/>; accessed April 23, 2021
8. Sherman JD, Thiel C, MacNeill A, Eckelman MJ, Dubrow R, et al. 2020. The green print: advancement of environmental sustainability in healthcare. *Resour. Conserv. Recycl.* 161:104882
9. National Academy of Medicine. 2021. National Academy of Medicine launches Action Collaborative on Decarbonizing the U.S. Health Sector. *National Academy of Medicine*, Sept. 27. <https://nam.edu/national-academy-of-medicine-launches-action-collaborative-on-decarbonizing-the-u-s-health-sector/>
10. The World Bank. 2021. *Climate-smart health care: low-carbon and resilience strategies for the health sector*. Rep., World Bank, Washington, DC
11. Karliner J, Slotterback S, Boyd R, Ashby B, Steele K. 2019. *Health care's climate footprint: how the health sector contributes to the global climate crisis and opportunities for action*. Rep., Health Care Without Harm, Reston, VA
12. Castro MDF, Mateus R, Bragança L. 2014. A critical analysis of building sustainability assessment methods for healthcare buildings. *Environ. Dev. Sustain.* 17(6):1381–1412
13. Pichler PP, Jaccard IS, Weisz U, Weisz H. 2019. International comparison of health care carbon footprints. *Environ. Res. Lett.* 14(6):064004
14. MacNeill AJ, Lillywhite R, Brown CJ. 2017. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *Lancet Planet Health* 1(9):e381–88
15. Parvatker AG, Tunceroglu H, Sherman JD, Coish P, Anastas P, et al. 2019. Cradle-to-gate greenhouse gas emissions for twenty anesthetic active pharmaceutical ingredients based on process scale-up and process design calculations. *ACS Sustain. Chem. Eng.* 7(7):6580–91
16. Alshaqeeq F, Amin Esmaili M, Overcash M, Twomey J. 2020. Quantifying hospital services by carbon footprint: a systematic literature review of patient care alternatives. *Resour. Conserv. Recycl.* 154:104560
17. Jeswani HK, Azapagic A. 2019. Life cycle environmental impacts of inhalers. *J. Clean. Prod.* 237:117733
18. Willskytt S, Tillman A-M. 2019. Resource efficiency of consumables—life cycle assessment of incontinence products. *Resour. Conserv. Recycl.* 144:13–23
19. Hensher M, McGain F. 2020. Health care sustainability metrics: building a safer, low-carbon health system. *Health Aff.* 39(12):2080–87
20. Lenzen M, Malik A, Li M, Fry J, Weisz H, et al. 2020. The environmental footprint of health care: a global assessment. *Lancet Planet Health* 4(7):e271–79

21. GBD 2019 Risk Factors Collaborators. 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet* 396(10258):1223–49
22. Eckelman MJ, Sherman J. 2016. Environmental impacts of the U.S. health care system and effects on public health. *PLOS ONE* 11(6):e0157014
23. Avis E. 2021. Designing the post-pandemic hospital: Health care facilities planners are thinking ahead to prepare for future challenges. *ASHE Health Facilities Management*, Oct. 31. <https://www.hfmmagazine.com/articles/4329-designing-the-post-pandemic-hospital>
24. IEA. 2019. *Global Status Report for Buildings and Construction 2019: towards a zero-emissions, efficient and resilient buildings and construction sector*. Rep., IEA, Paris
25. Shohet IG, Lavy S. 2010. Hard facilities and performance management in hospitals. In *Improving Healthcare Through Built Environment Infrastructure*, ed. M Kagioglou, P Tzortzopoulos, pp. 229–48. Hoboken, NJ: Blackwell Publ.
26. Kim S, Osmond P. 2014. Analyzing green building rating tools for healthcare buildings from the building user's perspective. *Indoor Built Environ.* 25(5):757–66
27. Li Y, Pan X, Han Y, Taylor JE. 2021. Sustainable healthcare facilities: a scoping review. *ASCE J. Constr. Eng. Manag.* 147(12):03121007
28. Francis S. 2010. Plan for uncertainty: design for change. In *Improving Healthcare Through Built Environment Infrastructure*, ed. M Kagioglou, P Tzortzopoulos, pp. 40–52. Hoboken, NJ: Blackwell Publ.
29. Zhang Y, Tzortzopoulos P, Kagioglou M. 2019. Healing built environment effects on health outcomes: environment–occupant–health framework. *Build. Res. Inf.* 47(6):747–66
30. Younger M, Morrow-Almeida HR, Vindigni SM, Dannenberg AL. 2008. The built environment, climate change, and health: opportunities for co-benefits. *Am. J. Prev. Med.* 35(5):517–26
31. Verderber S, Gray S, Suresh-Kumar S, Kercz D, Parshuram C. 2021. Intensive care unit built environments: a comprehensive literature review (2005–2020). *HERD* 14(4):368–415
32. Kohn R, Harhay MO, Cooney E, Small DS, Halpern SD. 2013. Do windows or natural views affect outcomes or costs among patients in ICUs? *Crit. Care Med.* 41(7):1645–55
33. Figueiro M. 2008. Sustainable lighting for healthcare facilities: more than just lumens per watt. *J. Green Build.* 3(1):74–89
34. Salas RN, Maibach E, Pencheon D, Watts N, Frumkin H. 2020. A pathway to net zero emissions for healthcare. *BMJ* 371:m3785
35. Yuan F, Yao R, Sadrizadeh S, Li B, Cao G, et al. 2022. Thermal comfort in hospital buildings—a literature review. *J. Build. Eng.* 45:103463
36. Dovjak M, Shukuya M, Krainer A. 2018. User-centred healing-oriented conditions in the design of hospital environments. *Int. J. Environ. Res. Public Health* 15(10):2140
37. Garcia-Sanz-Calcedo J, de Sousa Neves N, Almeida Fernandes JP. 2021. Measurement of embodied carbon and energy of HVAC facilities in healthcare centers. *J. Clean. Prod.* 289:125151
38. De Wolf C, Yang F, Cox D, Charlson A, Hattan AS, Ochsendorf J. 2016. Material quantities and embodied carbon dioxide in structures. *Eng. Sustain.* 169(4):150–61
39. Kaethner SC, Burridge JA. 2012. Embodied CO₂ of structural frames. *Struct. Eng.* 90(5):33–40
40. De Wolf C, Pomponi F, Moncaster A. 2017. Measuring embodied carbon dioxide equivalent of buildings: a review and critique of current industry practice. *Energy Build.* 140:68–80
41. MacNeill AJ, Hopf H, Khanuja A, Alizamir S, Bilec M, et al. 2020. Transforming the medical device industry: road map to a circular economy. *Health Aff.* 39(12):2088–97
42. Gaya da Costa M, Kalmar AF, Struys MMRF. 2021. Inhaled anesthetics: environmental role, occupational risk, and clinical use. *J. Clin. Med.* 10(6):1306
43. Alexander R, Poznikoff A, Malherbe S. 2018. Greenhouse gases: the choice of volatile anesthetic does matter. *Can. J. Anaesth.* 65(2):221–22
44. Choosing Wisely®. 2021. Promoting conversations between patients and clinicians. <https://www.choosingwisely.org/>; accessed November 11, 2021
45. Budd K. 2019. Hospitals race to save patients—and the planet. *AAMC News*, Oct. 15. <https://www.aamc.org/news-insights/hospitals-race-save-patients-and-planet>

46. Health Care Without Harm. 2021. Leading the way for a health climate. <https://healthcareclimateaction.org>; accessed December 28, 2021
47. Health Care Without Harm. 2021. Energy and Health Impact Calculator. <https://calculatehealthimpact.org>; accessed December 28, 2021
48. Health Care Without Harm. 2021. *Safe haven in the storm: protecting lives and margins with climate-smart health care*. Rep., Health Care Without Harm, Reston, VA
49. National Academy of Medicine. 2021. *Action Collaborative on Decarbonizing the U.S. Health Sector: Public Launch & Members Meeting*. Brief: Grand Challenge on Human Health & Climate Change. NASEM Commissioned Paper 2030: Next Steps to Healthcare Climate Leadership. September, 2021
50. Grimm CA. 2021. *Hospitals reported that the COVID-19 pandemic has significantly strained health care delivery. Results of a National Pulse Survey February 22–26, 2021*. Rep. OEI-09-21-00140, Off. Insp. Gen., U.S. Dep. Health Hum. Serv., Washington, DC
51. Douin DJ, Ward MJ, Lindsell CJ, Howell MP, Hough CL, et al. 2021. ICU bed utilization during the coronavirus disease 2019 pandemic in a multistate analysis—March to June 2020. *Crit. Care Explor.* 3(3):e0361
52. Simone R. 2021. 4 post-pandemic healthcare construction trends: rethinking hospital design to make spaces safer. *Healthcare Facilities Today*, July 8. <https://www.healthcarefacilitiestoday.com/posts/4-Post-Pandemic-Healthcare-Construction-Trends-26434>
53. Peng Y, Wu P, Schartup AT, Zhang Y. 2021. Plastic waste release caused by COVID-19 and its fate in the global ocean. *PNAS* 118(47):e2111530118
54. Das AK, Islam MN, Billah MM, Sarker A. 2021. COVID-19 pandemic and healthcare solid waste management strategy—a mini-review. *Sci. Total Environ.* 778:146220
55. Shekhar AR, Kumar A, Syamsai R, Cai X, Pol VG. 2022. Is the plastic pandemic a greater threat to humankind than COVID-19? *ACS Sustain. Chem. Eng.* 10(10):3150–54
56. Tennison I, Roschnik S, Ashby B, Boyd R, Hamilton I, et al. 2021. Health care's response to climate change: a carbon footprint assessment of the NHS in England. *Lancet Planet Health* 5:e84–92
57. Patrício Silva AL, Prata JC, Walker TR, Duarte AC, Ouyang W, et al. 2021. Increased plastic pollution due to COVID-19 pandemic: challenges and recommendations. *Chem. Eng. J.* 405:126683
58. Zarocostas J. 2022. WHO concerned over COVID-19 health-care waste. *Lancet* 399:507
59. van Straten B, Dankelman J, van der Eijk A, Horeman T. 2021. A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste. *Sustain. Prod. Consum.* 27:169–75
60. Rasheed T, Anwar MT, Ahmad N, Sher F, Khan SU-D, et al. 2021. Valorisation and emerging perspective of biomass based waste-to-energy technologies and their socio-environmental impact: a review. *J. Environ. Manag.* 287:112257
61. Nordahl SL, Devkota JP, Amirebrahimi J, Smith SJ, Breunig HM, et al. 2020. Life-cycle greenhouse gas emissions and human health trade-offs of organic waste management strategies. *Environ. Sci. Technol.* 54:9200–9
62. Hantoko D, Li X, Pariatamby A, Yoshikawa K, Horttanainen M, et al. 2021. Challenges and practices on waste management and disposal during COVID-19 pandemic. *J. Environ. Manag.* 286:112140
63. Friedman AB, Gervasi S, Song H, Bond AM, Chen AT, et al. 2022. Telemedicine catches on: changes in the utilization of telemedicine services during the COVID-19 pandemic. *Am. J. Manag. Care* 28(1):e1–6
64. Dacones I, Cave C, Furie GL, Ogden CA, Slutzman JE. 2021. Patient transport greenhouse gas emissions from outpatient care at an integrated health care system in the Northwestern United States, 2015–2020. *J. Clim. Change Health* 3:100024
65. Sherman JD, Lagasse R. 2018. How healthy is health care? *JAMA Netw. Open.* 1(4):e181000
66. Senay E, Landrigan PJ. 2018. Assessment of environmental sustainability and corporate social responsibility reporting by large health care organizations. *JAMA Netw. Open.* 1(4):e180975
67. Pencheon D. 2018. Developing a sustainable health care system: the United Kingdom experience. *Med. J. Aust.* 208(7):284–85
68. Costello A, Abbas M, Allen A, Ball S, Bell S, et al. 2009. Managing the health effects of climate change: *Lancet* and University College London Institute for Global Health Commission. *Lancet* 373(9676):1693–733. Erratum. 2009. *Lancet* 373(9682):2200

69. Watts N, Adger WN, Agnolucci P, Blackstock J, Byass P, et al. 2015. Health and climate change: policy responses to protect public health. *Lancet* 386(10006):1861–914
70. Wang H, Horton R. 2015. Tackling climate change: the greatest opportunity for global health. *Lancet* 386(10006):1798–99
71. Gamble JF. 1998. PM_{2.5} and mortality in long-term prospective cohort studies: cause-effect or statistical associations? *Environ. Health Perspect.* 106(9):535–49
72. Eckelman MJ, Sherman JD, MacNeill AJ. 2018. Life cycle environmental emissions and health damages from the Canadian healthcare system: an economic-environmental-epidemiological analysis. *PLOS Med.* 15(7):e1002623
73. WHO (World Health Organ.). 2021. Climate change and health. <https://www.who.int/en/news-room/fact-sheets/detail/climate-change-and-health>; accessed November 15, 2021
74. Burke M, Hsiang SM, Miguel E. 2015. Global non-linear effect of temperature on economic production. *Nature* 527(7577):235–39
75. Nordhaus WD. 2017. Revisiting the social cost of carbon. *PNAS* 114(7):1518–23
76. Stern N. 2007. *Stern Review: The Economics of Climate Change*. Cambridge, UK: Cambridge Univ. Press
77. Wagner G. 2021. Recalculate the social cost of carbon. *Nat. Clim. Change* 11(4):293–94
78. Nordhaus WD. 1992. An optimal transition path for controlling greenhouse gases. *Science* 258(5086):1315–19
79. Weyant J. 2020. Some contributions of integrated assessment models of global climate change. *Rev. Environ. Econ. Policy* 11(1):115–37
80. Diaz D, Moore F. 2017. Quantifying the economic risks of climate change. *Nat. Clim. Change* 7(11):774–82
81. Warren R, Hope C, Mastrandrea M, Tol R, Adger N, Lorenzoni I. 2006. *Spotlighting impacts functions in integrated assessment. Research report prepared for the Stern Review on the Economics of Climate Change*. Work. Pap. 91, Tyndall Cent. Clim. Change Res., Sch. Econ. Sci., Univ. E. Anglia, UK
82. Dietz S, Rising J, Stoerk T, Wagner G. 2021. Economic impacts of tipping points in the climate system. *PNAS* 118(34):e2103081118
83. Drouet L, Bosetti V, Padoan SA, Aleluia Reis L, Bertram C, et al. 2021. Net zero-emission pathways reduce the physical and economic risks of climate change. *Nat. Clim. Change* 11(12):1070–76
84. Guivarch C, Pottier A. 2018. Climate damage on production or on growth: What impact on the social cost of carbon? *Environ. Model. Assess.* 23(2):117–30
85. Tol RSJ. 2002. Estimates of the damage costs of climate change. Part 1: Benchmark estimates. *Environ. Resour. Econ.* 21(1):47–73
86. Burkart KG, Brauer M, Aravkin AY, Godwin WW, Hay SI, et al. 2021. Estimating the cause-specific relative risks of non-optimal temperature on daily mortality: a two-part modelling approach applied to the Global Burden of Disease Study. *Lancet* 398(10301):685–97
87. Zhao Q, Guo Y, Ye T, Gasparrini A, Tong S, et al. 2021. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *Lancet Planet Health* 5(7):e415–25
88. Yin H, Brauer M, Zhang J, Cai W, Navrud S, et al. 2021. Population ageing and deaths attributable to ambient PM_{2.5} pollution: a global analysis of economic cost. *Lancet Planet Health* 5(6):e356–67
89. Dieleman J, Campbell M, Chapin A, Eldrenkamp E, Fan VY, et al. 2017. Evolution and patterns of global health financing 1995–2014: development assistance for health, and government, prepaid private, and out-of-pocket health spending in 184 countries. *Lancet* 389(10083):1981–2004
90. Dieleman JL, Sadat N, Chang AY, Fullman N, Abbafati C, et al. 2018. Trends in future health financing and coverage: future health spending and universal health coverage in 188 countries, 2016–40. *Lancet* 391(10132):1783–98
91. Liapopoulos L, Goranitis I. 2015. Health care financing and the sustainability of health systems. *Int. J. Equity Health* 14:80
92. Kwon S, Kim E. 2022. Sustainable health financing for COVID-19 preparedness and response in Asia and the Pacific. *Asian Econ. Policy Rev.* 117(1):140–56
93. Fineberg HV. 2012. A successful and sustainable health system—how to get there from here. *New Engl. J. Med.* 366(11):1020–27

94. Zhou X, Tang X, Zhang R. 2020. Impact of green finance on economic development and environmental quality: a study based on provincial panel data from China. *Environ. Sci. Pollut. Res. Int.* 27(16):19915–32
95. Zhou G, Zhu J, Luo S. 2022. The impact of fintech innovation on green growth in China: mediating effect of green finance. *Ecol. Econ.* 193:107308
96. Healthier Societies for Healthy Populations Group. 2020. Healthier societies for healthy populations. *Lancet* 395(10239):1747–49
97. Pencheon D, Wight J. 2020. Making healthcare and health systems net zero. *BMJ* 368:M970
98. MacNeill AJ, McGain F, Sherman JD. 2021. Planetary health care: a framework for sustainable health systems. *Lancet Planet Health* 5(2):e66–68
99. Berwick DM, Hackbarth AD. 2012. Eliminating waste in US health care. *JAMA* 307(14):1513–16
100. Shrank WH, Rogstad TL, Parekh N. 2019. Waste in the US health care system: estimated costs and potential for savings. *JAMA* 322(15):1501–9
101. Chang AY, Cowling K, Micah AE, Chapin A, Chen CS, et al. 2019. Past, present, and future of global health financing: a review of development assistance, government, out-of-pocket, and other private spending on health for 195 countries, 1995–2050. *Lancet* 393(10187):2233–60
102. Parvatker AG, Tunceroglu H, Sherman JD, Coish P, Anastas P, et al. 2019. Cradle-to-gate greenhouse gas emissions for twenty anesthetic active pharmaceutical ingredients based on process scale-up and process design calculations. *ACS Sustain. Chem. Eng.* 7(7):6580–91
103. Belkhir L, Elmeligi A. 2019. Carbon footprint of the global pharmaceutical industry and relative impact of its major players. *J. Clean. Prod.* 214:185–94
104. EPA (Environ. Prot. Agency). 2005. *Profile of the Healthcare Industry, Healthcare Industry Sector Notebook Project* (EPA/310-R-05-002). Washington, DC: EPA Off. Compliance
105. Kaiser Permanente. 2021. The road to carbon neutral. <https://about.kaiserpermanente.org/community-health/improving-community-conditions/environmental-stewardship/the-road-to-carbon-neutral>; accessed November 1, 2021
106. Kaiser Permanente Institute for Health Policy. 2019. *Kaiser Permanente's 2025 Environmental Stewardship Goals*. Pap., Kaiser Perm. Inst. Health Policy, Oakland, CA. <https://www.kpihp.org/blog/kaiser-permanentes-2025-environmental-stewardship-goals-progress-in-northern-california/>