Sustainable and Resilient Health Care in the Face of a Changing Climate

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Abstract
Climate change is a threat multiplier, exacerbating underlying vulnerabilities, worsening human health, and disrupting health systems’ abilities to deliver high-quality continuous care. This review synthesizes the evidence of what the health care sector can do to adapt to a changing climate while reducing its own climate impact, identifies barriers to change, and makes recommendations to achieve sustainable, resilient health care systems.
1. INTRODUCTION
Climate change is already worsening human health and inequities and disrupting physical infrastructure and supply chains that are essential to high-quality continuous care. Changing health needs, surges in demand, and interruption of service delivery are expected to continue to increase over the coming years, leading to calls from the international community to halve anthropogenic greenhouse gas (GHG) emissions by 2030 and to achieve net zero emissions by 2050 (39). Ironi-

cally, the health care industry is also a major source of the GHGs that drive climate change and other emissions (notably, fossil fuel–related air pollution) that harm health.

2. CLIMATE IS CHANGING HEALTH AND CARE NEEDS
There is growing recognition in the health community of the ways in which the extraction and combustion of fossil fuels are threatening the fundamental mission of health care—to improve health and well-being—by creating and exacerbating illness, disrupting infrastructure, increasing costs, and threatening the delivery of high-quality health care (34, 81, 82, 87). Fossil fuel combustion is a primary driver of both air pollution and climate change and is thus an upstream contributor to illness (see Figure 1). Sustainability efforts must be integrated with resilience and adaptation efforts to break the vicious cycle stemming from fossil fuels used throughout health care system operations and value chains, which harm the health of the very patients and communities they serve (90).

2.1. Fossil Fuel Combustion, Public Health, and Health Care
Fossil fuel combustion generates a wide variety of air pollutants, some also short-lived greenhouse gases themselves (102), including fine particulate matter (e.g., PM$_{2.5}$), nitrogen oxides, sulfur dioxide, black carbon, and ozone, which are known to cause significant health harms (45). For example, exposure to PM$_{2.5}$ is a significant cause of cardiovascular morbidity and mortality (8), and long-term exposure to traffic-related air pollution is causally linked to the development of asthma in children (110). Air pollution is associated with a range of health conditions, including cerebrovascular disease, cognitive decline, autism, diabetes mellitus type 2, and adverse pregnancy outcomes (e.g., preterm birth, low birthweight) (45).

A significant portion of the global GHGs driving climate change arises from burning fossil fuels. Climate change serves as a threat multiplier, exacerbating existing conditions and health risks. The diversity of pathways through which climate change alters disease burdens spans nearly every organ system. These pathways include heat stress, poor air quality (e.g., from wildfire smoke, higher pollen counts), threatened food supply and safety (e.g., due to floods and droughts), impaired water quality and quantity (e.g., from Vibrio growth, harmful algae blooms), intensification of extreme weather and climate events (e.g., tropical cyclones, floods, droughts), alterations in vector ecology for infectious diseases, and social factors (e.g., short-term displacement or long-term migration of populations) (91). A recent landmark study found that 37% of heat-related deaths worldwide are due to climate change (116).

In addition, climate change is disrupting the delivery of health care by impeding access (e.g., climate-intensified weather events leading to facility damage, impaired transportation, power outages), increasing costs (e.g., due to altered and increased disease burdens, system damages), and reducing quality (e.g., from supply chain disruptions and infrastructure damage) (108). In a global survey of nearly 800 health care leaders, 75% reported that climate change is already impacting health care delivery today (86). These impacts are anticipated to accelerate in frequency and intensity in the coming years and decades.
2.2. Education and Data-Driven Solutions

While health impacts are experienced by everyone to some degree, certain populations are disproportionately harmed. Economic injustice and systemic and structural racism have led to long-standing health disparities, which air pollution and climate change exacerbate, even as they create new disparities. This heightened vulnerability arises from three main factors: increased exposure (e.g., from outdoor occupation), increased susceptibility (e.g., from extremes of age),
or an impaired ability to adapt (e.g., due to lack of financial means for household cooling, or insufficient health insurance coverage) (81, 82, 89). It is critical for clinicians to better identify the still often-missed, climate-sensitive diagnoses and vulnerabilities in their patients. Once these factors are identified, medicine and public health professionals, administrators, and policy makers can work together to implement targeted health protections, or adaptations, at both the individual and community levels. For example, for extreme heat exposure, clinicians can screen for—and intervene on—heat-related risk factors (85), whereas public health systems can implement neighborhood-level cooling mechanisms such as the expansion of tree cover, cool roofs and pavement, and widespread availability of health-protective cooling (e.g., heat pumps) (43).

The systematic incorporation of climate change into all levels of clinical education can lead to increased recognition and diagnosis of vulnerabilities and conditions. Pairing better-trained clinicians with the creation and application of climate-relevant codes [e.g., an International Classification of Diseases code for air-pollution exposure (Z77.110) already exists] can allow climate-relevant disease to be better identified in clinical practice, which could accelerate the generation of data that enables better quantification and understanding of climate-relevant exposures, mechanisms, and disease burdens. This type of data can guide evidence-based interventions, such as climate-sensitive adaptations of clinical practice that target vulnerabilities and the implementation of early warning and real-time notification systems (e.g., notification of climate-sensitive infectious disease in novel geographic locations) (16, 78, 105, 120).

3. HEALTH SYSTEM EMERGENCY PREPAREDNESS IN A CHANGING CLIMATE

While the health sector is faced with the expectation of caring for a rising burden of climate-related illness, its essential infrastructure is also directly threatened by climate change. These threats include, among others, growing flood zones and flood severity, increasing heat and wind stress on buildings, and interruptions of transportation, supply chain, and utility services needed by hospitals (see Figure 2). For example, in Harris County, Texas (which includes Houston), 770 hospitals, utilities, and water treatment plants are currently at risk of flooding at levels that threaten their ability to maintain operations (29, 41).

Climate-crippled health care infrastructure compromises access to and delivery of care through facility damage or closure, hospital evacuations, power outages, or disrupted transportation systems for patients, vendors, and staff. Following Hurricane Maria, nearly one-third of households surveyed in Puerto Rico reported disruptions to health care services (41). This lack of access to medical care poses an acute health threat. Research examining power outages following winter storms and hurricanes showed an association with worse health and higher mortality (50, 100). Over time, the mechanisms by which care is compromised after climate-related disasters evolve, such as through hospital overcrowding, supply chain disruptions, and population displacement for both patients and workers (7, 87). Excess mortality has been observed up to 3–6 months after hurricanes (19, 41, 75, 93). Patients with locally advanced non-small cell lung cancer were shown to have decreased survival rates after hurricanes, possibly owing to disrupted access to treatment (72). In Florida, following Hurricane Irma, nursing home residents experienced increased emergency department visits, hospitalizations, and mortality (19, 36, 100). In the month following the landfall of Hurricane Harvey, hospital emergency departments in Dallas–Fort Worth experienced patient surges of 600% due to visits from Houston-area evacuees (17). These events also create major financial burdens shifting between health systems, payers, and patients. Following Hurricane Sandy, New York University Langone Medical Center experienced $1.4 billion in losses, including from damaged infrastructure and displaced services. Coastal hospitals lost an estimated $9.5 million prior to hurricane landfall because of factors such as revenue lost through avoided health services.
3.1. Need for Improved Risk Assessments

Health system vulnerabilities due to climate change are wide-ranging. Health care facilities are facing increasing risks from flooding, dangerous wind speeds, extreme temperatures, and other climate-related effects that increase the likelihood of failure of structural elements such as foundations, walls, and roofs; the inability to maintain temperature control due to heating, ventilation, and air conditioning (HVAC) system failures, loss of adequate electricity supply from municipal or internal power outages, or brownouts; disruptions to facility communications, electronic health record, or other service systems; and loss of other municipal utility services, including potable water supply or wastewater drainage. Roadways, rail lines, and airports can also be disrupted by flooding, severe storm debris, or even the fact that their construction materials were not selected with a consideration for increasing temperature extremes (88). These transit system disruptions can make health care facilities inaccessible both to patients and to the staff needed to maintain operations and can disrupt accessibility to the already fragile medical supply chain. These potential disturbances impact the health system beyond acute care facilities, including through disruptions to home health services (e.g., oxygen therapy), community nursing care, telemedicine, and the use of electrically powered medical equipment. Despite these risks, only 21% of US health care
organizations are reported to have assessed their climate risks, and only 14% are using climate-resilient building codes for new construction (86).

The US Centers for Medicare and Medicaid Services (CMS) require that hospitals complete a hazard vulnerability analysis (HVA) annually to thoroughly assess the potential threats that they may face (112). The HVA is supposed to specifically consider the probabilities, consequences, and existing readiness of health care facilities for each potential hazard they may face; however, one of the limitations of this process is the increasing recognition that past experiences do not predict future events. Learning from the experiences of hospitals in New Orleans, Louisiana, during Hurricane Katrina in 2005, some New York hospitals built flood barriers around their electrical equipment. However, these proved inadequate when the flooding from Superstorm Sandy in 2012 exceeded prior maximal predictions, causing severe damage to electrical systems and necessitating the evacuation of multiple facilities (124).

To best prepare for and effectively mitigate against future climate risks, health systems require accurate data that draws from evidence beyond historical experience; outdated assessments of anticipated flood plains, temperature ranges, and wind speeds; and current building codes. (See the sidebar titled Case Study 1: Vancouver Coastal and Fraser Health Authorities.) However, the analyses and expert consensus required for proper risk and vulnerability assessment may often be missing or fragmented or lack requisite hyperlocal data resolution (87). Current World Health Organization guidance states that building climate-resilient health care facilities requires understanding current and projected climate conditions, health system demands, and anticipated health system capacity (121). One survey found that the two inputs most needed to strengthen health system climate resilience were climate risk data and financial resources (86). A 2022 study suggested that ambitious partnerships are needed to achieve accurate kilometer-scale models that would best help inform hospital planning (101); such work is already well underway, but incomplete (94). One possible solution, cited by the Task Force on Climate-Related Financial Disclosures (TCFD) (107) of the Financial Stability Board, recommends that planners work with external experts to aid with scenario and model evaluation, selection, and interpretation and that local data may be available from governments, utilities, insurance providers, environmental agencies, and universities. For example, researchers from the University of Iowa recently modeled flooding impacts across the entire state (111) based on updated assumptions and described the impact of this flooding on hospitals. The City of Cambridge, Massachusetts, engaged scientists to create climate impact models for the entire community. These data have been published on the Internet and used by multiple hospital systems in the city and surrounding communities for planning purposes. Optimal data that are needed by hospital leadership to inform their planning include scientific predictions of precipitation and flooding severity, changes in maximal sustained winds, rises in local temperatures (and the associated need for building cooling and demand on electricity generation), and changing wildfire zones. Probabilistic data such as 100-year and 500-year storm maps may be useful for determining institutional risk tolerance, but consequence-based maps, which can show worst-case scenarios under certain conditions, are often more useful when planning to protect never-fail services, such as emergency, surgical, critical care, childbirth, and other essential health care services (5). Responsibility for production of these downscaled local predictions may be aided by governmental agencies, such as the US Federal Emergency Management System, the National Oceanic and Atmospheric Association, and the National Center for Atmospheric Research; however, none of the currently available tools from these agencies fully meets the needs for health system planning.

3.2. Addressing Identified Risks in a Changing Climate

Guidance for health system climate adaptation is generally lacking, but researchers in Canada created a tool kit that categorizes climate change resilience indicators for health care facilities and
CASE STUDY 1: VANCOUVER COASTAL AND FRASER HEALTH AUTHORITIES

A collaboration between Vancouver Coastal Health (VCH) and Fraser Health (FH), two regional health systems in British Columbia (BC), Canada, and Health Emergency Management BC (HEMBC), which provides emergency management leadership and support to provincial health systems, produced a comprehensive climate change and health vulnerability and adaptation assessment for these regions. The initiative was supported with federal funding from Health Canada, which also provided methodologic guidance. A variety of data sources were combined with internal and external consultation, including with municipalities, community-based organizations, and local Indigenous peoples, to report on susceptibility and preparedness across five climate hazards: extreme heat events; deteriorating air quality (including from wildfire smoke, ground-level ozone, and longer pollen seasons); storms and flooding; increases in infectious diseases; and impacts to ecosystems and the food, water, and cultural services they provide. Future risks were projected from 2040 to 2059 and in some cases to 2100.

Vulnerability maps for extreme heat events were generated by modeling population exposure, sensitivity, and adaptive capacity based on variables that included age, preexisting conditions, socioeconomic status, and built environment conditions. These maps were tested and proved extremely accurate for identifying the locations of residence of people who presented to the emergency department with heat-related illness during the Pacific Northwest heat dome of June 2021. This historic extreme heat event would have been essentially impossible without climate change (122). The heat event triggered a cascade of impacts, including new wildfires, air quality warnings from increased ground-level ozone, flooding events due to rapid snowpack and glacier melt, and decreased crop yields. Record electricity consumption from air conditioning led to local power outages. In total, 619 heat-related deaths were confirmed in British Columbia, making it one of the deadliest natural disasters in Canadian history. The June 2021 heat dome exceeded all projections for this time period and signaled that the timeline for adaptation must be accelerated.

Adaptation and emergency response measures instituted for extreme heat include establishing locally specific temperature thresholds for heat warnings and the creation of a clearly defined Extreme Heat Emergency protocol, which mobilizes additional responses from the health system, local government, and partner organizations. Municipalities and public-sector organizations have seasonal readiness plans to operate cooling centers and wellness checks that target vulnerable areas and populations, and the City of Vancouver is studying, monitoring, and actively growing urban tree canopy. Facility-level climate vulnerability and risk assessments have been completed for some health care facilities and are ongoing, with design guidelines in development for climate-resilient health care infrastructure.

Case study adapted with permission from Brown et al. 2022 (9).

provides resources for adaptation and emergency preparedness (77). Tools are also available to guide resource allocation and incorporate climate resilience into health system strategic planning (33). The US Department of Health and Human Services (HHS) has compiled best practices for health care facilities to maintain quality service delivery before, during, and after weather-related disaster events (35). These include the need for community planning and action, such as recommendations to identify medically vulnerable populations and to develop response plans.

Current CMS standards for health care emergency preparedness do not require consideration of climate science in risk assessments of facilities and the communities they serve (87). In many jurisdictions, local and state building codes have not been updated to anticipate the regional effects of climate change over the next 30–50 years. Given that the expected life span of new health care facilities routinely exceeds 50 years (3), major capital projects should incorporate climate risks and resilience planning for at least that time span. (See the sidebar titled Case Study 2: Spaulding Rehabilitation Hospital.) Without appropriate updates to CMS standards and building codes, many new health care facilities may be at unnecessary near-term risk from climate-related disasters. Health systems could be better prepared for the current and future consequences of
CASE STUDY 2: SPAULDING REHABILITATION HOSPITAL

Spaulding Rehabilitation Hospital in Boston, which opened in 2013, incorporated into its design anticipated effects of sea level rise and other consequences of climate risks for the next 70 years, without being required to do so by local building codes. These changes added only 0.3–0.5% to overall building costs but resulted in a considerably more resilient facility. The building uses an estimated 30% less energy than expected, and the ongoing operational savings from these measures more than offset the additional capital investment (33). Examples of the design considerations include:

- Placing the first-floor elevation 30 feet above the projected 500-year flood elevation.
- Placing all critical patient care functions above the first floor.
- Ensuring a high-performance envelope to prevent low interior temperatures if heating is lost in winter or to prevent overheating if cooling or ventilation is inoperable in summer months.
- Incorporating key-operable windows in patient rooms so that if cooling or ventilation systems fail, indoor overheating can be avoided in summer months and patients can shelter in place.
- Placing all critical mechanical/electrical/power generation infrastructure on the roof to minimize possible interruption.
- Implementing gas-fired on-site cogeneration to provide efficiency and redundancy in the event of grid loss or diesel generator failure.
- Implementing extensive green roofs to mitigate stormwater discharge during heavy rainfalls.

climate change with widely available hyperlocal and up-to-date climate data, such as flood maps, heat and wind projections, and other natural hazard data to incorporate into their HVAs.

4. SUPPLY CHAIN SUSTAINABILITY AND RESILIENCE

Health care supply chains are complex, global systems traditionally designed to optimize cost, efficiency, and/or delivery speed; however, mounting evidence of climate-related risks has resulted in an increasing focus on sustainability and resilience (32). A medical product supply chain facilitates the flow of raw materials or components to producers and providers and finally to patients and manages the flow of information among these stakeholders. The primary goal of resilience in the supply chains is to prevent compromised public health and safety from disruptions to critical medical product flows. However, because resilience actions can come with costs, the aim must be to achieve efficient and robust supply chains that are made resilient with the right combination of cost-effective actions.

4.1. Globalization of the Medical Supply Chain

Pharmaceutical and medical device manufacturing has become increasingly globalized, mostly to reduce costs (69). In the 1970s, the US pharmaceutical industry moved, first to Puerto Rico in response to tax incentives and then to Europe and lower-income countries (14, 83, 106). At the same time, with the growing use of lower-cost generic drugs in the United States, manufacturers came under increasing pressure to keep production costs low to maximize profit (31, 103). Locations such as India and China gained popularity owing to lower energy, raw materials, and shipping costs; fewer environmental regulations regarding buying, handling, and disposing of toxic chemicals; and a lack of strong labor regulations or unions, resulting in a low-cost labor force (20). A 2011 Federal Drug Administration (FDA) report noted that moving an active pharmaceutical ingredient (API) manufacturing facility from the United States or European Union to India could...
reduce production costs by 30–40% (114). Similar to the pharmaceutical industry, many medical device companies have sought to reduce costs by moving assembly to low-wage countries (104).

Medical supplies, even simple ones, may have complex, globally interconnected supply chains, as each constituent material has its own sourcing and manufacturing processes (49). Disruptions affecting any single stakeholder in a supply chain, including material suppliers, labor for production and transport, or machinery for assembly, may lead to supply not meeting demand. In general, production and inventory policies are designed to optimize profits. Hence, producers of high-margin products, such as branded drugs and complex medical devices, are more likely to be incentivized to ensure the continuity of their supply to maintain business profitability than are producers of low-margin products. Furthermore, these incentives are often not aligned with optimal levels of product availability from a public health perspective. The consequences of resilience differences in the supply chains of high- and low-margin products and the desired level of resilience from a public health perspective become particularly amplified in the case of seemingly low-frequency but potentially high-consequence events, which are occurring more often, owing to climate change. As a result, these events can pose serious risks to public health if they disrupt the supply chains of essential products that are produced by industries that have limited incentives to assure supply continuity.

Many of the components and products produced abroad have no US-based alternative sources, and even those that do may still rely on foreign supply chains. To evaluate the extent of foreign dependency in critical medical product supply chains, in 2011 the US Bureau of Industry and Security’s Office of Technology Evaluation conducted an assessment of the health care and public health sector (113), which was focused on pharmaceuticals and medical devices considered critical in various emergency scenarios. The study revealed a significant degree of foreign sourcing and dependency for critical components, materials, and finished products that are needed for US-based manufacturing operations. In contrast, onshoring and near-shoring will shorten supply chains, reduce transportation-based emissions and time to market, and decrease disruption risks due to global events (37) but will incur added costs and are not always desirable from a resilience point of view. A short domestic supply chain with few suppliers and potentially a single production facility also presents significant vulnerabilities. Global distribution of supply chains increases diversification of production, which also enhances resilience in case one production site gets shut down. Hence, as with all resilience actions, there is no one-size-fits-all strategy; rather, for a given product or group, risks, costs, and environmental impacts should be carefully evaluated to determine the most effective set of strategies.

4.2. Impact of Extreme Events on Medical Product Supply Chains

Climate change–related events such as wildfires, floods, hurricanes, and extreme heat events can precipitate surges of need for health care services that overwhelm local health systems as well as the capacity of medical product supply chains (38). Even prior to the COVID-19 pandemic, there were shortages of N-95 respirators and air filters in areas where wildfire smoke caused poor air quality (12). In 2011, a tsunami off the coast of Japan, while unlikely to be climate related, led to a surge in demand for basic food items, blankets, sanitary pads, diapers, and toilet paper (11).

Climate events may also disrupt production and flow of products along the supply chain. In September 2017, Hurricane Maria hit Puerto Rico, shutting down the electrical grid and damaging roads, fuel supplies, and airports (1). At the time, Baxter’s Puerto Rico plants supplied 50% of US hospitals with small-volume saline bags (46, 57). Baxter’s plants lost power and were not fully restored until January 2018 (68). Although the FDA helped manufacturers secure generators and
fuel for plants and coordinated with local governments to clear roads and secure transportation for raw ingredients (74), the resulting saline shortage ultimately forced US hospitals to delay elective procedures and was exacerbated by hoarding (2). Baxter subsequently invested $1 billion in its manufacturing network and now ships finished product to the US mainland for storage (26).

The COVID-19 pandemic has also resulted in major demand surges and disruptions to health care supply chains and services, providing lessons for health care environmental sustainability (65). For example, the tremendous surge in the need for personal protective equipment (PPE) led to shortages that, in some cases, entailed tragic consequences for frontline workers. Medical oxygen supplies were also strained, particularly in India, with devastating results for patients. Such shortages illustrated important principles about criticality in the health care supply chain and ways to mitigate risk by investing in on-site capacity and decentralized supply chains. Those facilities that had the inventory and capacity to reprocess single-use devices were able to reuse medical supplies and materials and thereby had alternate means of supplying PPE to their staff. Similarly, those facilities that invested in on-site oxygen generators or concentrators were able to maintain care even if external supplies of bulk liquid oxygen were insufficient to meet demand surges (28).

4.3. Bolstering Supply Chain Resilience

Measures to mitigate supply chain disruptions due to climate change can be generalized from overall supply chain resilience strategies. First are strategies to reduce demand for medical supplies and equipment. This goal can be achieved through targeting wasteful practices that lead to discarding of unused or partially used supplies, prolonging the lifetimes of durable items through effective maintenance, addressing arbitrary use-by dates with new regulatory requirements, and curtailing overprescribing. Strategies for ensuring availability of alternate supplies during disruptions are also critical. Most obvious is keeping larger inventories for essential supplies, but health care facilities are often highly space-constrained and supplies may expire. Instead, institutionalizing systems for the widespread use of reusable medical devices means that facilities can serve as their own suppliers with operational control to prioritize items that are most urgently needed (4). For nonreusable consumable items, maintaining procurement contracts with multiple suppliers in different geographic regions (preferring domestic suppliers where economically competitive) can be a hedge if one supplier is taken offline by a climate-related event. A recent national report (69) also called for modernized and potentially regionalized stockpiles that are managed by a coalition of stakeholders rather than by a centralized governmental entity.

In the longer term, facilities in the health care supply chain and transportation hubs such as ports (115) can take measures to adapt to climate change realities (73). Facilities located on the coast where flooding and sea level rise are predicted can raise access points, relocate utilities, and build additional backup systems to ensure operational continuity (121). Increasing temperatures will pose significant challenges for maintaining cold chains, especially in remote regions, so supporting innovation in low-power refrigeration systems that can integrate with off-grid renewable installations will be helpful.

4.4. Climate-Related Risks and Disclosures

Health care supply chains must be ready to respond to large-scale climate events, such as heat waves that affect thousands or millions of people at once. Anticipating the at-risk locations and necessary supplies will help governments and relief agencies prepare and respond effectively. To predict risk and devise an effective set of resilience strategies, meaningful data-sharing protocols must be established among health care supply chain stakeholders (84). These data should at minimum identify raw material and component suppliers, manufacturing capacity and quality-related
metrics, and meaningful resupply dates in case of disruptions. Only with such information disclosed could the health sector work with analysts and academics to calculate associated supply chain risks (climate related and otherwise) to their critical products to make informed decisions.

5. HEALTH CARE EMISSIONS

Advancing health care sustainability requires the development of environmental performance benchmarks against which progress can be measured. Environmental performance has many facets, but, in general, impacts are caused by depletion of resources, emission of pollutants, and impacts on ecosystems and human health. Past research has sought to estimate such measures at various scales—for national health systems, for health care facilities, for care pathways and procedures, and for individual products and services—to make quantitative comparisons that inform decision-making and policy.

5.1. Health Systems–Level Emissions

To assess health care–related emissions at the national level, researchers have employed Environmentally-Extended Input-Output (EEIO) modeling, which tracks monetary flows through the economy and links these to national emissions inventories for each economic sector. Each sector’s expenditures (including those of health care) are then associated with an emissions intensity that reflects all emissions that occur throughout the economy (including trade with other nations) as a result of that final demand (66). EEIO modeling has been used extensively in other sectors and forms the basis of international environmental footprinting.

In 2008, the National Health Service (NHS) in England was the first entity to publish a national estimate of health care carbon emissions (71) using a mix of physical and economic data, finding that health care represented 3% of England’s total CO₂ emissions at that time. A subsequent EEIO paper by two US health researchers in 2009 found much higher results for US health care: 8% of national GHG emissions (13). National studies have since been conducted for Austria (119), Australia (55), Canada (25), China (123), England (108), and Japan (67), and several updates have been published for the United States (22–24). National-level results reveal which health care activities and supply sectors have the largest emissions, providing a basis for decarbonization policy, planning, and action (see Figure 3).

It is difficult to compare national-level studies directly because of differences in how input-output tables are constructed and how health expenditures are classified in each country. To make fair comparisons across countries, several studies have used larger multiregion input-output (MRIO) models that cover multiple countries and regions and the trade among them so that goods such as pharmaceuticals, which are produced in one country but used in another, can be properly accounted for. International studies over the past several years have consistently found that health care is responsible for between 4.4% and 5.2% of global GHG emissions, emphasizing that health care has a vital role to play in mitigating emissions and meeting net zero targets (48, 79, 81, 82, 117, 118).

When making comparisons among health systems, it is critical to consider their function of achieving health outcomes. Thus, this work should also reflect measures of equitable access and quality of care, in addition to emissions performance. The Lancet Countdown on Health and Climate Change has tracked global health care GHG emissions over several annual reports, on both national and per capita levels, and also normalized these against such measures such as the Healthcare Access and Quality (HAQ) index (117), the human development index (HDI) (82), and the health life expectancy (HLE) (81). Figure 4 shows the 2017 per capita health care GHG results versus the HAQ index, revealing a familiar trend of saturation, where additional emissions (driven by expenditures) do not necessarily lead to better health outcomes. Conversely, this finding shows
5.2. Health Care Building Emissions

Hospitals are among the most energy-intensive building types owing to their constant operation, stringent HVAC requirements, and plug loads from high-powered medical equipment. Fuel...
and electricity use are often reported in physical units on utility bills, and decades of work on health care building energy efficiency have used these to track energy use and efficiency (6) and, more recently, energy-related emissions. An entire branch of architectural engineering focuses on the design of health care facilities and the specification and operation of equipment to reduce energy use (https://www.ashrae.org/technical-resources/bookstore/health-care-facilities-resources). Because of the energy intensity of health care building operations, several studies of clinical procedures or care pathways have found HVAC to be among the largest contributors to health care facilities’ overall energy use and carbon emissions (53, 109). Other work has taken a more granular approach by analyzing energy use by individual pieces of equipment and electricity use in idle modes (27, 61) or by attributing medical equipment energy use to patients and procedures (80).

Compared with the energy and resource intensity of hospitals, care delivered in the community setting typically generates fewer emissions. This level of care includes ambulatory clinics and physicians’ offices as well as care provided in patient homes. Building-related GHG emissions from NHS England’s hospitals and related acute-care facilities are estimated at 2,351 kt CO₂e in comparison to only 167 kt CO₂e from primary care facilities; together, these represent 15% of NHS England’s total footprint (70, 108). Community-based care can often provide a better patient experience than can acute care settings, aligning patient preference with health care sustainability goals. Displacing care from the protocolized hospital setting allows a tailored approach to
resource use and the potential for considerable savings. For example, carpal tunnel release surgery performed in the clinic or office setting has been shown to cost 26% and 38%, respectively, of the same surgery performed in a hospital operating room (47). Carbon savings from avoided material resource use would be expected to mirror cost savings. Hospital-at-home programs such as those overseen by the CMS (15) are gaining in popularity, as these have been shown to be safer, cheaper, and more effective than traditional inpatient programs for some conditions and patient populations (10, 44). The Greener NHS program’s proposed sustainable service model incorporates shifting care from hospitals to community settings, including through the use of a telephone triage system to direct patients to the most appropriate site for their care. This approach is expected to avoid 8.5 million kilometers of unnecessary patient travel per year with associated carbon savings of 1.7 kt CO$_2$e (70, 108).

5.3. Pharmaceuticals and Medical Device Emissions

Research has consistently shown pharmaceuticals to be one of the largest contributors to overall health care GHG emissions (22–23, 25, 48, 55, 79, 108). As such, several efforts have aimed to quantify carbon emissions of individual medicines in order to identify differences in environmental performance among drugs with similar clinical utility and to enumerate the benefits of reducing drug waste and overprescribing (76, 95). Anesthetic agents have received particular attention owing to the fact that the most widely used anesthetic gases are halogenated ethers or nitrous oxide, which are themselves potent GHGs and are released into the environment, uncontrolled, after use. Inhaled anesthetics can account for 3% of national health sector emissions (63, 108), 5% of hospital emissions (63), and 50% of perioperative services emissions (53); thus, mitigation options are of great interest. A life cycle assessment comparing these anesthetic gases with the intravenous alternative, propofol (95), demonstrated that, from a GHG perspective, the emissions intensity of inhaled anesthetics was several orders of magnitude greater than that of intravenous propofol. Furthermore, two inhaled drugs (desflurane and nitrous oxide) had significantly higher emissions than did the other two commonly used inhaled anesthetics (sevoflurane and isoflurane) in clinically equivalent doses. NHS England commissioned a study of their top 20 drugs based on expenditures, which included carbon estimates, and other single-drug studies have been conducted, for example, for morphine (58) and ibuprofen (99). Parvatker et al. (76) set out to establish a standard analytical approach for estimating carbon intensities of drugs and created new data sets for 20 APIs and 130 precursors and chemical intermediates, finding a large range of values from 3 to 3000 kgCO$_2$e per kg API. Despite the recent work in this area, entire classes of drugs remain unstudied in terms of embodied carbon. Apart from studies on the drugs themselves, prior work has also noted the potential importance of packaging (40), sterilization (58), and drug administration supplies (95) to life cycle carbon emissions.

A wide range of medical devices and supplies have also been evaluated using life cycle assessments. One vein of research is from the manufacturer’s perspective, examining material and processing options to inform design strategies and reduce embodied carbon in products (42). Other research is intended to provide information to clinical decision makers and procurement professionals where choices exist. One of the most common questions underlying comparative studies is between single-use and reusable versions of the same device (21, 52, 56, 59, 60, 64, 97, 98). Assessing factors across a device life cycle, including material and energy inputs for manufacturing, transportation, cleaning, waste disposal management, and number of device reuses, is essential to determine environmental preference among alternative options. A comparison of single-use disposable and reusable blood pressure cuffs in four different clinical settings found lower emissions for reusables across all scenarios (92). This finding has been corroborated across nearly every comparative life cycle assessment of medical devices (52, 98).
5.4. Low-Carbon Clinical Services

A variety of clinical services have been studied from an environmental perspective, but interpretation of this literature is limited by considerable methodologic heterogeneity, varying clinical relevance, and geographic variations in clinical and operational practices and energy and material inputs. The application of life cycle assessments to clinical services requires a different approach than that for comparative assessment of products, as care delivery rarely involves equivalent clinical scenarios in which environmental considerations can determine recommended treatments. In most instances, there are clear indications for a given clinical pathway or clinical circumstances that dictate “right care.” Evidence-based considerations of risks and benefits shaped by patient values and preferences should always guide clinical decision-making. The role of environmental impact data gleaned from life cycle assessments of clinical services is not to determine a pathway of care but rather to provide a road map of opportunities for improved environmental performance or resource stewardship within a given process of care.

Life cycle assessments of clinical services have focused largely on surgical care. The utility of these studies is not to inform recommendations for a given surgical technique but rather to optimize each process for its appropriate clinical application, identifying hot spots and mitigation strategies. For example, a study of different surgical approaches to hysterectomy revealed that for open procedures (abdominal and vaginal hysterectomy), inhaled anesthetics comprised the largest proportion of the procedural footprint. Strategies to minimize the impact of anesthetics in general—some of which could be applied to hysterectomy—include minimizing fresh gas flows, using sevoflurane instead of desflurane and nitrous oxide, and forgoing inhaled agents in favor of total intravenous anesthesia or neuraxial or regional anesthesia when clinically appropriate. For minimally invasive hysterectomy (laparoscopic or robotic), single-use disposable surgical instruments accounted for the largest proportion of total environmental impacts, which could be mitigated by the procurement and use of reusable and reprocessed alternatives.

Studies of alternative surgical techniques highlight the challenge of comparing environmental costs of different care pathways. First, there are clinical indications for performing open procedures in favor of minimally invasive ones (e.g., large uteri). Furthermore, while minimally invasive surgery has a higher footprint than open surgery, most studies of surgical approaches have compared the environmental costs of only the procedure itself, ignoring differences in short- and long-term postoperative outcomes that might modify the life cycle environmental costs of care. Compared with open surgery, laparoscopic and robotic surgeries typically entail shorter lengths of stay, lower complication rates, and lower rates of incisional hernia and intestinal obstruction requiring subsequent procedures, all of which could shift the relative environmental performance of each technique in favor of minimally invasive approaches. Thus, these studies cannot be considered true comparisons of the environmental costs of care of alternative clinical processes; rather, they outline improvement opportunities for each. A study comparing medical to surgical treatment of gastroesophageal reflux illustrates this principle by showing that despite the high upfront carbon cost of surgery, subsequent year-on-year emissions were lower for patients who had antireflux surgery in the ninth postoperative year compared with proton pump inhibitor therapy alone (30).

Interpretation of comparative assessments of clinical services is complicated by variability in clinical practice, procurement practices, and energy sources across health systems and regions. A recent study of general, regional, and combined anesthesia for total knee arthroplasties in Australia suggested a higher footprint for spinal than for general anesthesia (16.9 kgCO₂e versus 14.9 kgCO₂e, respectively) (63). However, important contributors to the carbon footprint of
spinal anesthesia were the administration of unnecessary high-flow supplemental oxygen and creation of an extensive sterile field, which are not standard practices. At centers in which spinal anesthesia is provided under conditions of room air and a limited sterile field, the results would be expected to be significantly different and the preferability for spinal anesthesia as a low-carbon service maintained. Similarly, the relative environmental performance of a product or process can be dramatically influenced by energy source, ranging from clean energy in the public electricity grid in British Columbia, Canada (0.023 kgCO₂e/kWh) to the carbon-intensive brown coal–powered electricity grid in Victoria, Australia (1.2 kgCO₂e/kWh) (53, 61). This variability must inform interpretation of health care life cycle assessments and hot spots for improvement (e.g., sourcing renewable electricity in Victoria, Australia) instead of being viewed as universal verdicts on preferability for a given product or process.

5.5. Low-Carbon Care Paradigm

The goal of net zero health care emissions requires a whole systems approach in which low-carbon care is provided within an appropriately designed and resourced health infrastructure with aligned incentives and in the context of public policy to optimize population health. A planetary health care framework for low-carbon, sustainable health systems (54, 96) outlines three operating principles: (a) reduce demand for health services through health promotion, disease prevention, and good chronic disease management; (b) match supply of health services to demand by focusing on appropriate care; and (c) reduce emissions embodied within the supply of health services through the low-carbon care strategies outlined above. The strategic position of the health sector in climate action is highlighted in this framework, in that by prioritizing healthy populations and advocating for structures and policies that promote health (e.g., active transport infrastructure and elimination of fossil fuels), health systems will benefit from reduced demand, which, in turn, helps mitigate the health care footprint.

A frequently overlooked element of health care decarbonization is the need to avoid low-value or inappropriate care, in which harms outweigh benefits. Globally, 25% of health care is considered low value, which affords a sizeable opportunity for resource stewardship and environmental performance improvement (51). Appropriate care requires avoidance of both underuse of necessary health services (e.g., vaccinations, screening) and overuse of health services (e.g., excessive diagnostics). Health sector GHG mitigation plans must move beyond a lens of low-carbon care delivery and include strategies to ensure appropriate care and to maximize opportunities for prevention and health promotion.

6. CONCLUSIONS

Climate change exacerbates underlying vulnerabilities and harms public health; however, the health impacts at the individual patient level may be difficult for clinicians to perceive or attribute to a changing climate. Better methods of tracking climate-related morbidity and mortality are required to inform policy and response. Health systems must incorporate climate risk assessment into capital projects and operations and bolster resilience within facilities, critical infrastructure, and the health care supply chain. This process could be accelerated by regulation and facilitated by access to data and scientific expertise. The mission to do no harm should drive health care sector action on environmental stewardship. This effort requires a transformative sustainability strategy that recognizes upstream drivers of demand and opportunities for low-carbon care, standardized accounting methods, data-driven interventions, and benchmarking for timely progress toward net zero emissions.
SUMMARY POINTS

1. Information systems must be developed that capture health and health system impacts of climate change and identify vulnerabilities to better understand evolving disease patterns, serve as early warning systems, and inform interventions.

2. To bolster health system resilience, hazard vulnerability analysis of anticipated climate risks and consequences should be undertaken based on hyperlocal data and incorporate climate change projections.

3. Supply chain resilience strategies should include transparency of raw material, component and finished product suppliers, and disclosure of their climate change–related risks.

4. Health care sector emissions mitigation requires comprehensive (inclusive of the supply chain) standardized, transparent accounting methods.

5. A whole systems approach to health care delivery is needed, including disease prevention/health promotion, appropriate care, and low-carbon service delivery.

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