Incorporating carbon into health care: adding carbon emissions to health technology assessments

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At the UN Climate Change Conference 26 in Glasgow, 50 countries committed to low-carbon health services, with 14 countries further committing to net-zero carbon health services by 2050. Reaching this target will require decision makers to include carbon emissions when evaluating new and existing health technologies (tests and treatments). There is currently, however, a scarcity of data on the carbon footprint of health-care interventions, nor any means for decision makers to include and consider carbon emission health-care assessments. We therefore investigated how to integrate carbon emissions calculated by environmental life cycle assessment (LCA) into health technology assessments (HTA). HTAs are extensively used in developing clinical and policy guidelines by individual public or private payers, and by government organisations. In the first section we explain the methodological differences between environmentally extended input-output and process-based LCA. The second section outlines ways in which carbon emissions calculated by LCA could be integrated with HTAs, recognising that HTAs are done in several ways by different jurisdictions. International effort and processes will be needed to ensure that robust and comprehensive carbon footprints of commonly used health-care products are freely available. The technical and implementation challenges of incorporating carbon emissions into HTAs are considerable, but not unsurmountable. Our aim is to lay foundations for meeting these challenges.

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Introduction

Climate change is causing an increase in flooding and wildfires in North and South America, Europe and the Asia Pacific, resulting in record temperatures, deaths, and extensive property damage.[1] These and other extreme weather events have focused attention on the effects of climate change on health.

Globally, health care is responsible for 2·0 gigatons (2×10^9 tons) of carbon dioxide equivalent emissions (CO_2e) annually, or 4·4% of global emissions.[2] Converted to disability adjusted life years (DALYs), these emissions may cause up to 3 060 000 DALYs reduction in human health annually, due to increases in undernutrition, malaria, water and vector borne diseases, and heat stress.[3] Further, converted into dollar terms using the global average GDP per capita, these DALYs result in an economic cost of between US$ 32·7 and 98·2 billion.[4]

At the United Nations Climate Change Conference COP26 in Glasgow in November 2021, thirty-six countries made commitments to develop low-carbon health systems, with a further fourteen countries setting a target for a net-zero health service by 2050.[5] The methods and evidence base for measuring the carbon emissions of healthcare and including them in clinical decision making to achieve this is, however, lacking.

Healthcare relies heavily on health technology assessments (HTA) to determine whether the economic cost of a new pharmaceutical, medical device, or model of care is justified given the health benefits the technology will provide to patients.[6] Methods of HTA include health economic evaluations and comparative effectiveness studies, and although these economic assessments are now routine and sophisticated, presently HTA does not include environmental impacts such as carbon emissions. HTAs can be undertaken as part of an internal process by individual public or private payers, and they form a vital component of clinical and policy guidance used by leading agencies such as the US Preventive Services Taskforce and the National Institute of Health and Care Excellence in the UK. The outcomes of these HTAs, including reports to regulatory bodies such as the US Food and Drug Administration, determine the scope and nature of clinical practice, guiding the day-to-day clinical decisions of physicians in hospitals and in primary care settings. In addition to determining the costs to health-care payers, they also lock in the carbon footprint of health care. Crucially, these carbon emissions influence not only current global health outcomes, but they also irreversibly influence those of future generations for centuries to millennia.[7] To be environmentally and economically sustainable, health-care decision makers and clinicians must now take account of carbon emissions. Yet, to date, little work has been done about how carbon emissions could be usefully integrated into the standard methods and processes of HTA so that this crucial information can be considered in health-care decision making now and in the future.

Earlier work considered the case for incorporating environmental impacts into HTAs and listed some of the challenges for this to occur.[8,9] This case is even stronger now in view of recent events. We therefore seek to build on previous research by resolving two main challenges. The first is that little quantification of the carbon emissions of medical devices, procedures, or pharmaceuticals associated with health care has been completed, meaning studies will be required to fill these gaps in knowledge. Second, there have been no published studies on how carbon costs should best be incorporated in HTAs.

This manuscript brings together key methods of environmental science and health technology assessment, in order to outline how carbon emissions from health care can be best quantified, and to find ways in which carbon

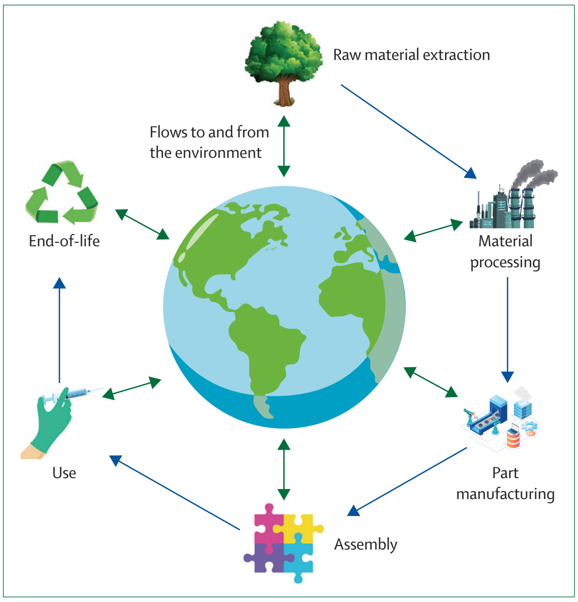

Figure 1: **Stages of life cycle assessment**

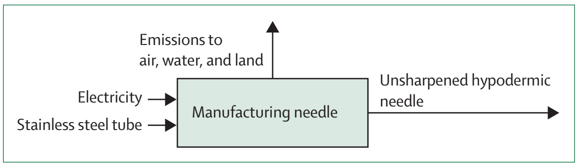

Figure 2: **Process for turning a stainless steel tube into an unsharpened hypodermic needle**

emissions can then be integrated into HTA as a decision criteria or in economic evaluation, recognising that HTAs are done in several ways by different jurisdictions.

Measuring carbon emissions

Carbon emissions are best quantified by life cycle assessment (LCA), a method of environmental impact assessment for which international standards of conduct and reporting exist (ISO 14040-44).[10] The ISO 14040-44 standards in turn, form the methodological foundation for major product carbon footprinting standards and protocols.[11,12] The basis of analysis within LCA is the functional unit, which clearly defines the functions of a product or service rather than its physical characteristics. An example of a functional unit is all anaesthesia for a total knee replacement in a hospital in St Louis, Missouri. Several LCAs have been done in health care, including calculating national carbon emissions from healthcare, comparisons of single-use and reusable items, and the impacts of patient,surgical and anaesthetic care, pathology and diagnostic imaging, pharmaceuticals, and hospitals.[13–21] Some carbon hotspots have been identified, including anaesthesia and metered-dose inhalers.[22,23]

Similar to health economic evaluation, LCA uses a system boundary of inclusions and exclusions based on the defined functional unit. For example, an LCA of a surgery might exclude the effects of postoperative monitoring. By contrast with health economic evaluation, the LCA system boundary extends out temporally to incorporate lifecycle effects of all items included in an analysis, including raw material acquisition, such as mining, the manufacture of items, and their use and disposal or recycling (figure 1).

Life cycle assessment methods

There are two methods of undertaking LCA; environmentally extended input-output analysis (EIO) and process-based LCA (P-LCA). EIO is based on the economic input and output tables produced by all major economies that track the flow of money between industries (eg, extraction of oil and gas, fishing, pharmaceuticals or health services) of the economy. The number of industries included in published input-output tables varies. For example, Finland has 64 industries, the Netherlands 76 industries, Australia 114 industries, and Canada 230 industries.[24]

Using input-output tables, carbon emissions can be calculated on a per-dollar basis of goods or services purchased from a given sector (kg CO_2e/US$). As an example, using the USA Carnegie Mellon EIO model, the carbon emissions from purchasing $100 (2022) of goods and services from the surgical and medical instrument manufacturing sector is approximately 18 kg CO_2e. Importantly, this figure is the average emissions intensity of everything purchased from the whole sector. Given the large number of heterogenous goods and services provided from all of surgical and medical instrument manufacturing, this linear relationship between price and emissions does not hold true for individual items.

Although EIO has been used extensively for calculating carbon emissions of the health-care sector at a regional, national, or international level, the absence of relationship between price and emissions means that its use is not recommended to quantify emissions of specific health-care items or services.

By contrast, P-LCA quantifies the carbon emissions of the functional unit using a series of interlinked processes. A process describes all the material and energy inputs, and associated environmental emissions, for an individual activity at a high level of detail, such as forming stainless steel into a hypodermic needle (figure 2). Processes are then linked together to form a process tree consisting of raw material extraction at the bottom and the functional unit at the top, with a typical process tree having upwards of 1000 individual processes.[25]

There are two types of P-LCA, attributional and consequential. Attributional P-LCA estimates what proportion of the total carbon footprint of a health-care service can be attributed to a specific clinical activity, whereas consequential P-LCA only estimates the change in emissions that occur by performing an additional clinical activity (the marginal impact). As an example, hospital X-ray machines run 24 h a day and 7 days a week so they can be used in emergencies. An attributional analysis would include this standby power when the machine is on, but is not being used for imaging. By comparison, the consequence of ordering an X-ray is not that the X-ray machine is turned on, it is operating regardless of whether an X-ray is ordered or not. The consequence of ordering an image, therefore, is the small change in power when an image is taken. These two approaches complement each other by providing information on the overall impact of a clinical activity in addition to the impact of a change in clinical behaviour. We therefore recommend both attributional and consequential LCAs be done and reported.

P-LCA enables individual interventions to be modelled at a fine level of detail, thereby identifying carbon hotspots that can be targeted for mitigation. Importantly, and similarly to health economic evaluation, P-LCA makes comparison possible between a health-care technology or intervention and an alternative (eg, standard surgery versus robotic surgery). This is essential to enable informed choices to be made between two clinical options on the basis of individual health outcomes, economic costs, and environmental impact.

Converting LCA results to carbon reference units

The worldwide reference unit for carbon emissions is CO_2e, which might be expressed as kg CO_2e, kilotons CO_2e, or megatons CO_2e. A reference unit is used as there are a range of greenhouse gases, all with different global warming potentials, which contribute to climate change. To allow for their respective impacts to be added together to calculate a total carbon footprint, each greenhouse gas must be multiplied with an emission factor on the basis of their global warming potential, with these factors being published by the International Panel on Climate Change.[26] Using gaseous anaesthetics as an example, 1 kg desflurane is equivalent to 1790 kg CO_2e, whereas 1 kg sevoflurane is equivalent to 216 kg CO_2e.[26] An LCA does these calculations for greenhouse gas emissions from all stages of a life cycle.

Health technology assessments and carbon emissions

Next we explore how carbon emissions could be included in HTA. Carbon emissions are examples of externalities. An externality is a cost or benefit from the activity of a person or organisation that is borne by an unrelated third party, and, as such, the cost or benefit of the externality is excluded from the market transaction. For example, the market price of fossil fuels does not include the cost of morbidity and mortality resulting from forest fires caused by climate change, even though combustion of fossil fuels is the chief cause of rising atmospheric carbon dioxide concentration driving climate change.

Environmental externalities caused by health-care production and consumption are not included in HTAs because of their focus on optimising the allocation of health-care resources relative to health outcomes. Environmental externalities must be internalised, that is, included and considered in HTAs alongside the costs and benefits to the health-care sector and to individuals. This internalisation will require a broader societal perspective to be adopted rather than the narrowly focused health-system or payer perspective that is typically applied. Furthermore, this societal perspective will need to extend beyond the traditional framework to include environmental impacts.[27]

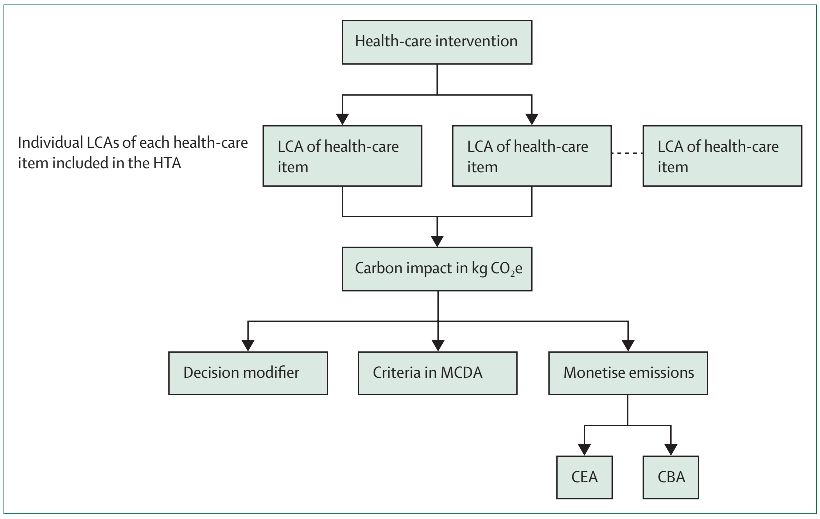

Figure 3: **Stages to integrate LCA with HTA**
CBA=cost-benefit analysis. CEA=cost-effectiveness analysis. HTA=health technology assessment. LCA=life cycle assessment. MCDA=Multi Decision Criteria Analysis.

Broadly, carbon emissions could be internalised in HTA using four different approaches, enabling a comprehensive assessment of the health, economic, and environmental impacts of a specific health-care technology or intervention (by comparison with alternatives). These approaches include modifying a decision, being one criterion of a Multi Decision Criteria Analysis (MCDA), monetisation and inclusion in a cost-benefit analysis, or being included as an additional cost in a cost-effectiveness analysis. We build on the scarce research to date.[9]

Linking LCA to health technology assessments

The first stage of linking carbon emissions to an HTA is to quantify all the emissions resulting from all the health interventions contained within the assessment (figure 3). All four approaches will require that an individual P-LCA for each specific health-care activity (eg, a prostate cancer biopsy administered under general anaesthetic in a public hospital) be undertaken. The functional unit of each P-LCA should match the system boundary of the health-care activity as closely as possible. Initially, the work required to do the necessary P-LCAs will be considerable, but each one could contribute to a library or inventory of the environmental footprint of specific health-care interventions. Inventories could be housed nationally or shared internationally, similar to current international LCA databases of materials and products such as ecoinvent.[25,28]

For single-year economic evaluations, such as calculating the expenditure per year associated with false-positive mammograms,[29] we recommend that the environmental impacts from the whole life cycle (cradle-to-grave) of each LCA should be calculated as a single value (eg, kg CO_2e). This temporal aggregation of emissions is the way LCAs are typically performed.[15,19]

For multiyear economic evaluation models, such as establishing the lifetime cost-effectiveness of breast cancer screening,[30] an individual LCA will need to be done for each year of the economic analysis, so that monetised emissions can be discounted alongside other economic costs and benefits. This will require that anticipated changes in technology, such an expected increased use of renewable energy, be temporally integrated into the LCA of each year. Additionally, the LCA will need to be dynamic, with environmental emissions assigned to specific years.[31] Fortuitously in health care, the life cycle of many items (from manufacture through use to disposal) is typically less than 5 years, and there are few long-term emissions caused by disposal because most medical equipment is inert (metal and plastic), with biodegradable items such as cotton gauzes making up only a small proportion by mass of items used clinically.[19] This makes dynamic modelling easier to achieve compared with other sectors such as buildings.

Impacts in kilograms of CO_2e calculated from each LCA can then be included as an additional cost in decision-analytical or Markov models, to be incorporated alongside other economic costs and health outcomes. This process has the additional important benefit of identifying hotspots associated with interventions, enabling potential mitigation measures, such as quality-improvement projects or behaviour-change interventions, to be undertaken.

Carbon emissions as a decision modifier

At this point, the modelled greenhouse gas emissions from each intervention can be used as a simple modifier. This use as a decision modifier can occur when costs and health outcomes of any two or more technologies are similar, so that the choice of which one to adopt is dependent on the greenhouse gas emissions. An example of this is demonstrated in anaesthesiology departments moving from the gaseous anaesthetic desflurane to sevoflurane to reduce carbon emissions.[32]

Carbon emissions as part of MCDA

In cases in which there are differences in costs and health outcomes between technologies, or in which there are additional criteria that the decision maker wants to include, such as health equity, an MCDA could be undertaken. Although there are several ways MCDA can be operationalised, most are based on weighted-sum models.[33] Criteria are weighted on the basis of their relative importance to the decision maker, with the sum of all the weightings equalling 100%. Each intervention or technology is then given a performance score for each criterion (including a criterion on carbon emissions) that is then multiplied by the weighting of the criteria to give a weighted score. All weighted scores are added to create a final score, which can then be used to identify a single preferred option or to rank the alternatives.[33]

Monetising carbon emissions

Carbon emissions can be monetised and included as an additional cost in a cost-effectiveness analysis (CEA), an approach that would facilitate their inclusion in HTA in jurisdictions that rely heavily on CEAs, such as the UK, Australia, and New Zealand. Alternatively, monetised emissions could be included alongside health benefits in a cost-benefit analysis (CBA), in which the outcomes remain in their natural units. There are several ways to monetise carbon emissions, including: the social cost of carbon, which uses integrated assessment models of ecosystems, economics, and political responses to estimate the damage cost of an additional ton of carbon emitted;[34] the price of carbon offsetting credits from schemes such as forestry or soil sequestration or methane capture; and marginal abatement costs, which are calculated on the basis of engineering costs to reduce emissions to reach a given target.[35]

Some countries and individual states such as California, USA, have a price on carbon that uses the aforementioned methods of monetisation. For example, the cap-and-trade emissions trading scheme of California, which sets an emissions target that declines over time, follows prices predicated by marginal abatement costs.[36] By comparison, in Australia there is no official carbon market, with the unofficial carbon price being the cost of carbon offsets.[37] Different jurisdictions, therefore, have different carbon prices.

It should be noted that if monetised emissions are used in a multiyear economic model, we recommend that they be treated like any other cost and be discounted at the same rate as health-care costs. We recommend, however, that greenhouse gas emissions in kilograms of CO_2e should not be discounted, but rather be considered constant over time, hence maintaining intergenerational equity.[31]

Discussion

Health services globally are starting to commit to net-zero targets for carbon emissions, although with little detail on how this will be achieved. We propose that an important method to achieve carbon neutrality will be the inclusion of carbon emissions in health technology assessments. The main challenge is that, unlike other major sectors of the economy in which extensive LCA studies have quantified emissions, to date there have been very few studies undertaken in health care.

LCA practitioners currently use background databases, such as ecoinvent, to obtain high-quality process-based life-cycle data on basic materials such as plastic and steel, manufactured goods such as computers, and processes such as recycling plastic, to accurately model whole supply chains without needing vast multidisciplinary expertise.[25] Further, specific sectors that are arguably more complex than health care, such as agriculture that has a high degree of variability caused by local conditions and farming practices, have developed sector-specific databases.[38] Given that there is no technical difference in undertaking an LCA using ISO 14040 in health care compared with other sectors, a healthcare-specific database containing common items such as syringes, procedures such as MRI, or processes such as sterilisation, to enable expeditious and accurate modelling can be developed.

Several approaches to establishing a database are possible. Although a database could be developed from scratch, by initially focussing on a small number of the most common health-care products and processes, this would inevitably be time consuming because of the necessity of collecting background data on processes such as the extraction of natural gas and the resultant manufacture of plastics. A more expedient approach would be to integrate with an existing established database, already containing high-quality background data such as ecoinvent,[28] by licensing their data so that it could be used to accurately model healthcare-specific items. This approach would mean that data collection could be focused on components specific to health care. Establishment of a database with either approach would be financially costly, as would the ongoing maintenance of the database, including the data-quality review processes needed for the inclusion of new items.

It is paramount, furthermore, that access to the database be free or affordable, at both the aggregate level (eg, a 10 mL syringe produces approximately 30 g CO_2e) so that it could be used by clinicians, and at a database level so that LCA practitioners could perform detailed modelling. Free or low-cost access is essential so that health services with scarce resources are not perversely incentivised to avoid inclusion of carbon quantification in their decision-making processes, or repeat what others have already done, potentially at lower levels of accuracy or quality. Similar to current public sector investment in the regulation of medicines and in health technology assessments, this approach will require substantial public sector financial support or subsidies (eg, through a licence-fee system).

Part of the cost of establishing and maintaining the database could be offset, however, by manufacturers undertaking LCAs of their products, thereby reducing the costs associated with data collection and modelling. The procurement requirements of health-care systems could help drive this by including carbon emissions as one of the procurement criteria, incentivising manufacturers to undertake LCAs and reduce the carbon footprint of their products to make them more competitive. To reduce the risk of so-called greenwashing by manufacturers of their LCAs for competitive advantage, a system, such as the international Environmental Product Declaration,[39] would be needed, with verification possible by an independent third-party agency using a uniform, evidence-based, non-proprietary framework and methods.

Once this initial start-up work has been done however, it will be relatively quick and inexpensive to quantify carbon emissions as is now routinely done in other sectors. The process should, with time, become as routine as quantifying costs is currently.

Once quantified, the second challenge is how to best include carbon emissions in health technology assessments, as decision makers have not yet had to consider environmental externalities when choosing between technologies. As we move into a carbon-constrained world, environmental impacts will become a major consideration for decision makers. Including carbon emissions in HTA will ensure their decisions will result in genuinely sustainable health care for present and future generations. This work is also vital for health equity because, without it, the greatest health impacts of climate chance will disproportionately fall on vulnerable populations and low-income countries.

The choice of whether to use carbon emissions as a decision modifier, as in an MCDA, or as a monetised cost in a CEA or CBA will probably be dependent on the funding organisation, jurisdiction, or decision makers and may be guided by purely technical considerations. The benefit of having several options is that they can be incorporated into standard health-technology assessment agency processes, even where countries differ markedly in their need for comparative effectiveness evidence. As such, we have avoided being overly prescriptive, and have chosen to offer suggestions that are flexible enough to be applicable in a range of HTA approaches and methods. We offer these suggestions as a step forward and anticipate further development by HTA practitioners within their local contexts, so that they can best establish how carbon emissions would influence their decision making.

We note that carbon emissions are not the only environmental impact associated with health care, with emissions such as particulate matter ($PM_{2.5}$), and those causing ozone depletion and human toxicity, all contributing to human health impacts, along with damage to ecosystems through ecotoxicity, acidification, and eutrophication.[40] All of these emissions can be quantified by LCA, and therefore could, in the longer term, be included in the integration between LCA and HTA. We feel, however, that carbon emissions should be the primary immediate focus, given that countries have to rapidly reduce their carbon emissions in line with the Paris Agreement, which seeks to limit global warming to within 1·5–2·0°C above preindustrial levels.

The challenge of incorporating carbon emissions into health technology assessments is considerable, but not unsurmountable. We hope this work will lay the foundation to meet this important challenge.

Contributors
SM did the project administration, methods development, and wrote the original draft. RLM developed the health-technology assessment methods. RLM and AB both did the critical review of the methods. All authors reviewed and edited the manuscript and agreed to submit the manuscript for publication. All authors had final responsibility for the decision to submit for publication.

Declaration of interests
We declare no competing interests.

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References
1 O'Malley N, Perkins M, Singhal P, Carter D. How the world ran out of time. The Sydney Morning Herald. Oct 25, 2021. https://www.smh.com.au/interactive/2021/how-the-world-ran-out-of-time/ (accessed Nov 25, 2021).

2 Pichler P-P, Jaccard IS, Weisz U, Weisz H. International comparison of health care carbon footprints. *Environ Res Lett* 2019; **14:** 064004.

3 Tang L, Furushima Y, Honda Y, Hasegawa T, Itsubo N. Estimating human health damage factors related to CO2 emissions by considering updated climate-related relative risks. *Int J Life Cycle Assess* 2019; **24:** 1118–28.

4 The World Bank. GDP per capita (current US$). 2021. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD (accessed Nov 25, 2021).

5 Wise J. COP26: fifty countries commit to climate resilient and low carbon health systems. *BMJ* 2021; **375:** n2734.

6 Mulligan K, Lakdawalla D, Goldman D, et al. Health Technology Assessment for the U.S. Healthcare System. Feb 26, 2020. https://healthpolicy.usc.edu/research/health-technology-assessment-for-the-u-s-healthcare-system/ (accessed Aug 25, 2021).

7 IPCC. Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY, USA: Cambridge University Press, 2021.

8 Marsh K, Ganz ML, Hsu J, Strandberg-Larsen M, Gonzalez RP, Lund N. Expanding health technology assessments to include effects on the environment. *Value Health* 2016; **19:** 249–54.

9 Hensher M. Incorporating environmental impacts into the economic evaluation of health care systems: perspectives from ecological economics. *Resour Conservation Recycl* 2020; **154:** 104623.

10 International Organization for Standardization. ISO standards for life cycle assessment to promote sustainable development. July 7, 2006. https://www.iso.org/news/2006/07/Ref1019.html (accessed Sept 23, 2021).

11 The International Organization for Standardization. ISO 14067:2018. greenhouse gases: carbon footprint of products—requirements and guidelines for quantification. 2018. https://www.iso.org/standard/71206.html (accessed Oct 1, 2020).

12 British Standards Institute. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. 2011. https://www.bsigroup.com/globalassets/localfiles/en-th/carbon-footprint/pas-2050-2011-guide.pdf (accessed Nov 23, 2022).

13 Malik A, Lenzen M, McAlister S, McGain F. The carbon footprint of Australian health care. *Lancet Planet Health* 2018; **2:** e27–35.

14 Sherman JD, Raibley LA, Eckelman MJ. Life cycle assessment and costing methods for device procurement: comparing reusable and single-use disposable laryngoscopes. *Anesth Analg* 2018; **127:** 1–443.

15 McAlister S, Ou Y, Neff E, et al. The environmental footprint of morphine: a life cycle assessment from opium poppy farming to the packaged drug. *BMJ Open* 2016; **6:** e013302.

16 McAlister S, Barratt AL, Bell KJ, McGain F. The carbon footprint of pathology testing. *Med J Aust* 2020; **212:** 377–82.

17 Marwick TH, Buonocore J. Environmental impact of cardiac imaging tests for the diagnosis of coronary artery disease. *Heart* 2011; **97:** 1128.

18 McAlister S, McGain F, Petersen M, et al. The carbon footprint of hospital diagnostic imaging in Australia. *Lancet Regional Health West Pac* 2022; **24:** 100459.

19 McGain F, Burnham JP, Lau R, Aye L, Kollef MH, McAlister S. The carbon footprint of treating patients with septic shock in the intensive care unit. *Crit Care Resusc* 2018; **20:** 304–12.

20 Drew J, Christie SD, Tyedmers P, Smith-Forrester J, Rainham D. Operating in a climate crisis: a state-of-the-science review of life cycle assessment within surgical and anesthetic care. *Environ Health Persp* 2021; **129:** 076001.

21 Seifert C, Koep L, Wolf P, Guenther E. Life cycle assessment as decision support tool for environmental management in hospitals: a literature review. *Health Care Manage* 2019; **46:** 12–24.

22 Sherman JD, Chesebro BB. Inhaled anaesthesia and analgesia contribute to climate change. *BMJ* 2022; **377:** o1301.

23 Janson C, Henderson R, Löfdahl M, Hedberg M, Sharma R, Wilkinson AJK. Carbon footprint impact of the choice of inhalers for asthma and COPD. *Thorax* 2020; **75:** 82–84.

24 United Nations. Handbook on supply and use tables and input output-tables with extensions and applications. 2018. https://unstats.un.org/unsd/nationalaccount/docs/SUT_IOT_HB_Final_Cover.pdf (accessed Nov 23, 2022).

25 Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 2016; **21:** 1218–30.

26 Myhre G, Shindell D, Bréon F-M, et al. Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K, et al, eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press, 2013.

27 Sanders GD, Neumann PJ, Basu A, et al. Recommendations for conduct, methodological practices, and reporting of cost-effectiveness analyses: second panel on cost-effectiveness in health and medicine. *JAMA* 2016; **316:** 1093.

28 ecoinvent. Aug 1, 2022. https://ecoinvent.org/the-ecoinvent-database/ (accessed Aug 1, 2022).

29 Ong M-S, Mandl KD. National expenditure for false-positive mammograms and breast cancer overdiagnoses estimated at $4 billion a year. *Health Aff* 2017; **34:** 576–83.

30 Pashayan N, Morris S, Gilbert FJ, Pharoah PDP. Cost-effectiveness and benefit-to-harm ratio of risk-stratified screening for breast cancer: a life-table model. *JAMA Oncol* 2018; **4:** 1504.

31 Yuan C, Wang E, Zhai Q, Yang F. Temporal discounting in life cycle assessment: a critical review and theoretical framework. *Environ Impact Asses* 2015; **51:** 23–31.

32 Patel SD, Smith-Steinert R. Greening the operating room, one procedure at a time. *J Clim Change Health* 2021; **2:** 100014.

33 Hansen P, Devlin N. Multi-criteria decision analysis (MCDA) in healthcare decision-making. Oxford: Oxford University Press, 2019.

34 Metcalf GE, Stock JH. Integrated assessment models and the social cost of carbon: a review and assessment of US experience. *Rev Env Econ Policy* 2017; **11:** 80–99.

35 Dong Y, Hauschild M, Sørup H, Rousselet R, Fantke P. Evaluating the monetary values of greenhouse gases emissions in Life Cycle Impact Assessment. *J Clean Prod* 2018; **209:** 538–49.

36 Narassimhan E, Gallagher KS, Koester S, Alejo JR. Carbon pricing in practice: a review of existing emissions trading systems. *Clim Policy* 2018; **18:** 1–25.

37 Foley M. Corporate Australia sets its own carbon price amid global dash to net zero. The Sydney Morning Herald. July 8, 2021. https://www.smh.com.au/politics/federal/corporate-australia-sets-its-own-carbon-price-amid-global-dash-to-net-zero-20210707-p587nd.html (accessed July 29, 2021).

38 ESU-services. ESU world food LCA database. 2021. http://esu-services.ch/data/fooddata/ (accessed Sept 24, 2021).

39 EPD International AB. The international EPD system. Aug 10, 2022. https://www.environdec.com/home (accessed Aug 10, 2022).

40 Eckelman MJ, Sherman J. Environmental impacts of the US health care system and effects on public health. *PLoS One* 2016; **11:** e0157014.