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The carbon footprint of treating patients with septic shock in the intensive care unit

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Abstract

Objective: To use life cycle assessment to determine the environmental footprint of the care of patients with septic shock in the intensive care unit (ICU).

Design, setting and participants: Prospective, observational life cycle assessment examining the use of energy for heating, ventilation and air conditioning; lighting; machines; and all consumables and waste associated with treating ten patients with septic shock in the ICU at Barnes-Jewish Hospital, St. Louis, MO, United States (US-ICU) and ten patients at Footscray Hospital, Melbourne, Vic, Australia (Aus-ICU).

Main outcome measures: Environmental footprint, particularly greenhouse gas emissions.

Results: Energy use per patient averaged 272 kWh/day for the US-ICU and 143 kWh/day for the Aus-ICU. The average daily amount of single-use materials per patient was 3.4 kg (range, 1.0–6.3 kg) for the US-ICU and 3.4 kg (range, 1.2–8.7 kg) for the Aus-ICU. The average daily particularly greenhouse gas emissions arising from treating patients in the US-ICU was 178 kg carbon dioxide equivalent (CO_2-e) emissions (range, 165–228 kg CO_2-e), while for the Aus-ICU the carbon footprint was 88 kg CO_2-e (range, 77–107 kg CO_2-e). Energy accounted for 155 kg CO_2-e in the US-ICU (87%) and 67 kg CO_2-e in the Aus-ICU (76%). The daily treatment of one patient with

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septic shock in the US-ICU was equivalent to the total daily carbon footprint of 3.5 Americans' CO_2-e emissions, and for the Aus-ICU, it was equivalent to the emissions of 1.5 Australians.

Conclusion: The carbon footprints of the ICUs were dominated by the energy use for heating, ventilation and air conditioning; consumables were relatively less important, with limited effect of intensity of patient care. There is large opportunity for reducing the ICUs' carbon footprint by improving the energy efficiency of buildings and increasing the use of renewable energy sources.

Climate change is one of the defining health problems for the 21st century.[1,2] Providing health care is carbon intensive: the United States health care system contributes 10% of the greenhouse gas (GHG) emissions of all US economic activity,[3] compared with 7% in Australia.[4] Within the National Health Service in the United Kingdom, two-thirds of GHG emissions arise from purchasing consumables,[5] and the other third from direct hospital energy use and transport to and from hospitals.[5] Within hospitals, operating rooms[6] and intensive care units (ICUs)[7] use many items and generate considerable waste. There is increasing awareness of health care's environmental footprint in anaesthesia[8–11] and in critical care medicine.[9,10]

Life cycle assessment (LCA) examines the environmental footprint of a product or process throughout an entire life cycle ("cradle to grave").[12,13] The Society of Environmental Toxicology and Chemistry has defined the LCA components to be analysed:

- raw material acquisition;
- processing and manufacturing;
- distribution and transportation;
- use, reuse and maintenance; and
- waste management and recycling.[14]

Health care LCAs are increasingly common;[15] from studies of single devices[16,17] to drugs[18,19] and surgical procedures.[20] Pollard and colleagues[21] found that the ICU's average electricity use for direct patient care and lighting was 15 kWh per patient per day; however, energy for heating, ventilation and air conditioning (HVAC); consumables; drugs and pathology was excluded.

We used LCA methods to quantify and compare the environmental footprint of caring for Australian and American ICU patients with septic shock, including all energy use, HVAC, consumables, drugs, radiology, and pathology tests. We focused on each patient's carbon footprint due to the increasing role of climate change in health.[1]

Methods

This LCA was performed with ethics approval (consent waived at both institutions) from Western Health (HREC/12/WH/106) at the 13-bed Australian ICU (Aus-ICU) at Footscray Hospital, Melbourne, Vic, between March and June 2017, and at the 34-bed American ICU (US-ICU) at Barnes-Jewish Hospital, St. Louis, MO, between June and September 2017. The US-ICU's surface area included nine surgical beds. We followed the Strengthening the

Reporting of Observational studies in Epidemiology (STROBE) checklist for observational studies.[22] As per the International Organization for Standardization,[23] we defined the functional unit of this LCA as the treatment of one ICU patient with septic shock, not the whole ICU. Such an approach provides more relevance to practising clinicians and could allow comparisons between countries. We studied ICU patients with septic shock because it was a common, easily identifiable condition that could allow for international comparisons of carbon footprints. Further, septic shock commonly required a variety of different ICU therapies, which could influence the carbon footprint, including mechanical ventilation and renal support. Finally, we considered that differences in ICU HVAC energy consumption due to energy efficiency and/or geography[24] could influence the carbon footprint considerably.

We predetermined a convenience sample of ten patients to each ICU with the diagnosis of septic shock (Sepsis-3);[25] all patients received vasopressors. No sample size calculation was performed as we had no a priori knowledge of any environmental footprint data, although we considered that ten patients were enough to give a reasonable data range. Patients were not chosen sequentially: all patients with septic shock admitted to the ICU during the study periods and within 08:00 am and 6:00 pm from Monday to Friday were included.

Importantly, since the functional unit of this LCA was the patient, and all energy use and consumables were aimed at treating the patient, staff use of lighting and heating and cooling was incidental to the patient's treatment. That is, even if only one ICU patient were present ("very inefficient"), all energy use would be attributed to that patient.

As all LCAs have a system boundary that defines what is and is not to be included,[23] activities occurring beyond the ICU and the environmental costs of existent hospital infrastructure and equipment were excluded[23] (Figure 1).

We planned to perform a hybrid LCA, a process-based LCA, and an economic input–output (EIO) LCA. Process-based LCAs use directly obtained data to quantify environmental impacts (eg, using electricity for mechanical ventilators or plastics for syringes produces GHG emissions and pollutants). Environmental impacts of common products (eg, plastics) were publicly available in LCA databases.[23] Examples of GHG emissions important to this study were those stemming from electricity and natural gas use. Natural gas GHG emissions were 58.3 kg carbon dioxide equivalent (CO_2-e)/GJ. For the US-ICU, the electricity mix was 88% black coal, 5% natural gas, minimal nuclear and 7% renewable, giving carbon emissions of 0.9 kg CO_2-e/kWh electricity.[26] For the Aus-ICU, the electricity mix was 86% brown coal, 4% natural gas and 10% renewable, giving carbon emissions of 1.3 kg CO_2-e/kWh electricity.[27,28]

An EIO-LCA was used to attribute an environmental impact from the cost of pharmaceuticals, intravenous fluids, and pathology — no publicly available LCA databases exist. Each economic sector has an environmental impact per dollar spent attributed to it; for example, in Australia, there are 0.33 kg CO_2-e per dollar spent on pharmaceuticals.[4] EIO data estimate greater environmental impacts than process data due to each sector's interaction with other sectors of the economy, such as advertising, legal and accounting impacts. When possible, we obtained direct process-based data[24] rather than EIO data.

We developed a life cycle inventory (LCI) that quantified materials and energy used. We used LCI Ecoinvent version 2.1 (Ecoinvent, Zurich, Switzerland)[29] to translate patient data into environmental impacts focused on climate change. We divided our data on environmental impacts per ICU patient per day by an average European person's total daily environmental effects ("normalisation") in order to compare the environmental impacts of an ICU patient with all other people's daily routine activities.[23] We used ReCiPe, 2016 version (RIVM, CML, Pré Consultants and Radboud University Nijmegen, the Netherlands), a software LCA method, to translate emissions and resource extractions into environmental impact scores.[30,31]

Energy use in the intensive care unit

We sought ICU energy data for machines, lighting and HVAC. For the US-ICU, we could only obtain hospital-wide averages of electricity use per m^2. In the Aus-ICU, we used an electricity meter (Power Analyzer 3197, Hioki, Nagano, Japan), measuring electricity every 15 minutes for one week, for space ventilation, lighting and devices. We measured electricity use every 15 minutes for ICU devices over 4-hour periods.

The remaining energy consumption was by the Aus-ICU's HVAC, which was provided by a gas boiler (thermal efficiency, 85%) and chiller (coefficient of performance, 3.5). From the Australian hospital's building management system (StruxureWare V0419016–03, Schneider Electric, Rueil-Malmaison, France), we obtained the temperatures of the supply and return water for the chiller and boiler water circuits. We could not directly measure the energy transferred by the water, so we measured the energy transferred to and from the water in coils, this energy being equal to the energy being delivered and taken from the ventilated air brought into proximity to the water, assuming negligible losses.

We measured the total energy transfer by estimating ICU air flow rates (m^3/s) from duct outlet air speed (m/s) at the overhead grills, and the grills' cross-sectional areas (m^2), combined with the temperature difference between the Aus-ICU ventilation air supply and return vents for a fortnight (May–June 2017). From the calculated fortnight's actual electricity and gas use for cooling and heating, we calibrated our measured results with a building energy simulation model to estimate annual average ICU energy use.

For the fortnight of measurement, we obtained local weather data (www.bom.gov.au) of hourly average solar radiation, outdoor air temperatures and outdoor air relative humidity. We also obtained the Aus-ICU dimensions and orientation of windows, and the estimated number of ICU occupants for each hour. All parameters were entered into the building energy simulation model in eQUEST version 3.65, build 7173 (http://doe2.com/equest), and the values of unknown building parameters were varied to obtain the measured Aus-ICU energy consumption data. Using this calibrated model, the typical meteorological year total Aus-ICU energy consumption and energy use per patient were obtained. Separately, we estimated the Aus-ICU's energy consumption via the ratio of the ICU's over the total hospital's floor area. St. Louis, Missouri, has colder winters and more humid summers than Melbourne, Victoria. We estimated from the building energy software eQUEST that, due to differences in climate, the US-ICU would have heating loads 1.7 times per m^2 that of the

Aus-ICU,[24] and cooling loads 3.5 times that of the Aus-ICU if the ICUs were located in the same building type with the same number of people.

Consumables and equipment

We measured the types and weights of consumables used for ICU patients,[7,32] assuming that the heaviest material in any product was the products' material. Items included gloves, gowns, syringes, airway circuits and humidifiers, renal support equipment, paper towels, dressings, invasive vascular devices, bed linen, patient clothing, and laryngoscopes.

For oral and enteral nutrition, we determined an average composition from manufacturers' data. For chest x-rays, we approximated electricity use to 3 kWh.[33] Total volumes of oxygen and medical air were obtained. Energy requirements for liquid oxygen delivery were 0.001 kWh/L for oxygen gas and 0.0003 kWh/L for compressed air.[29] No waste data were available for the US-ICU, so we assumed waste to be similar to the whole US hospital except without recycling. For the Aus-ICU, waste was assumed as per our previous audit.[7]

Results

We measured resource use for 20 ICU patients, ten at each Australian and American ICUs, with septic shock from February–September 2017. Median APACHE (Acute Physiology and Chronic Health Evaluation) II score was 21.5, and median ICU stay was 5 days (range, 1–20 days). In the ICU, six out of 20 patients died, 13 were mechanically ventilated, seven received continuous renal support, five received both ventilation and continuous renal support, and five were in contact isolation. During the study of the 13-bed Aus-ICU, bed occupancy was a median of ten beds (range, 7–12 beds); for the 43-bed US-ICU, bed occupancy during the study was a median of 39 beds (range, 34–43 beds).

Electricity and natural gas use in the intensive care unit

The Aus-ICU's electricity use for space ventilation, machines (including computers) and lighting is shown in Table 1. Measured electricity loads were unlikely to vary and were assumed unchanged. Measurements of electricity and gas use for HVAC were modelled and modified for seasonal and hourly variations (Table 1).

When we compared directly measured Aus-ICU energy data with the hospital-wide average electricity use per m^2, which included energy used for magnetic resonance imaging scanners, −80°C refrigerators, operating theatres, and laboratories, the directly measured electricity use was only half (339/621 kWh/day). The Aus-ICU directly quantified natural gas used for space heating was greater versus hospital averaged at 2.2 versus 1.3 GJ/m^2/annum. We were unable to obtain direct measurements for the US-ICU's electricity and gas use.

The directly measured daily total energy use per Aus-ICU patient for gas heating and electricity was 143 kWh per patient per day, while the hospital averaged gas and electricity use for the US-ICU was 272 kWh per patient per day (Table 1). As noted above, we expected the US-ICU to have greater energy use per m^2 for the same building type.[24] Figure 2 describes the Aus-ICU's direct energy use over a year showing the preponderance of gas heating in the southern hemisphere's winter and importance of nocturnal heating in summer. HVAC was more energy-intensive than lighting and ICU machines (Figure 2). Per hour, the ICU machines consuming the most electricity were the haemofilter (0.1 kWh), the humidifier (0.07 kWh) and the ventilator (0.06 kWh). ICU lighting and machine electricity use was measured on one circuit board (32 kWh/day). We estimated that lighting and computers required about 20 kWh per day and machines 12 kWh per day.

Consumables and equipment in the intensive care unit Table 2 gives the masses of items used for ICU patient care.

Reusable materials were dominated by linen, with similar amounts used (3.7–4 kg) in both ICUs. The US-ICU did not routinely use sterilised cotton or stainless steel, while the Aus-ICU used minimal amounts (190 g and 20 g per day, respectively). The daily average total amount of single use materials was less than 4 kg per patient for both ICUs. Single use consumables were dominated by plastics (US-ICU, 3.1 kg; Aus-ICU, 2.1 kg). The Aus-ICU had four times the daily requirement per patient for synthetic rubbers (gloves). Paper towels were not used in large amounts as they have been replaced by chlorhexidine–alcohol hand rubs. The average daily costs for patients in the US-ICU for pharmaceuticals and pathology were twice that for the Aus-ICU.

Environmental impacts

Table 3 shows the process-based LCA carbon footprints (GHG emissions) of daily ICU care and compares this with an average American's and Australian's daily carbon footprints. We focused on GHG emissions; all other environmental effects are given in the online Appendix (available at cicm.org.au/Resources/Publications/Journal).

We summated the environmental effects from the direct ICU gas and electricity data, masses of consumables used and waste generated, and EIO data. We used ReCiPe as our impact assessment model.[30] Australian and American normalisation factors were not available except for climate change. Several of the ICU's environmental impacts (acidification, land occupation and water depletion) in Table 3 were smaller or similar to the activities of the average European citizen. The dominant source of all environmental impacts was electricity production, primarily directly for hospital energy.

The daily average of GHG emissions of treating one patient in the US-ICU was 178 kg CO_2-e (range, 165–228 kg CO_2-e), double that for the Aus-ICU at 88 kg CO_2-e (range, 77–107 kg CO_2-e) (Table 3), principally because of the greater direct energy requirements for heating and cooling (155 kg CO_2-e *v* 67 kg CO_2-e) (Figure 2). The remaining daily GHG emissions per patient were similar for the ICUs; 23 kg CO_2-e (US-ICU) versus 21 kg CO_2-e (Aus-ICU), with 19 kg CO_2-e in the US-ICU versus 18 kg CO_2-e in the Aus-ICU due to reusable and single use consumables.

Due to the dominance of fixed energy requirements, Figure 2 indicates small variations in GHG emissions with the level of patient care. The five patients receiving both renal support and mechanical ventilation required more items for their care compared with the 15 other patients (5.9 *v* 2.9 kg per day of single use items). This resulted in an average carbon footprint of 102 kg CO_2-e versus 84 kg CO_2-e for the Aus-ICU, and 179 kg CO_2-e versus 173 kg CO_2-e for the US-ICU.

Table 3 shows GHG emissions including pharmaceuticals, fluids and pathology from EIO data. This hybrid LCA gives more weighting to EIO data, given that the system boundary is expanded to include the whole economy. Cognisant of this caveat, we only give EIO data for ICU GHGs: for the US-ICU, it was 624 kg CO_2-e (range, 260–1199 kg CO_2-e) per patient per day, triple that of the process data; and for the Aus-ICU, the average CO_2-e emissions per ICU patient was 178 kg CO_2-e (range, 109–293 kg CO_2-e) per patient per day, double that of the process data.

Discussion

There are five major findings from our LCA of the care of 20 patients with septic shock in an American and an Australian ICU. Firstly, the daily carbon footprint of treating one ICU patient with septic shock in Missouri, USA, was equivalent to 3.5 Americans, and in Melbourne was equivalent to 1.5 Australians. Secondly, there was considerable variation in carbon footprint between ICUs: the US-ICU had about twice (178 kg CO_2-e) the average daily GHG emissions compared with the Aus-ICU (88 kg CO_2-e). Thirdly, the ICU's GHG emissions were dominated by HVAC energy use. Fourthly, the GHG emissions arising from consumables were small and, correspondingly, there was limited effect from the intensity of patient care. Finally, when we included EIO-LCA data, these altered the results in such a profound manner that they required separation from the main results.

The average American and Australian person is responsible, respectively for 18.5 tonnes and 22.1 tonnes CO_2-e annually,[34–36] including all GHG emissions from the economy, such as industry and agriculture. Treating ICU patients with septic shock in the US-ICU had a higher carbon footprint than the Aus-ICU, primarily because more energy per m^2 was used — 1.5 times the natural gas per m^2 for heating and 3.5 times the electricity per m^2 for cooling.

Natural gas use for both ICUs was the highest source of GHG emissions. The Aus-ICU natural gas use by direct measurement was 50% greater than the average hospital use per m^2 due to both the high ventilation rates required by an ICU[37] and because other sections of the hospital are closed overnight when not in use. Conversely, directly measured Aus-ICU electricity use was half that indicated by hospital-wide use per m^2, potentially because of large electricity loads from cooling the operating rooms, which require 20 air changes per hour (ν6 h in the ICU); operation of radiology and pathology machines; and −80°C refrigerators.

We were unable to directly measure the US-ICU's energy use, and it is possible also that its electricity use was lower than that predicted by hospital average per m^2. Nevertheless, the US-ICU would be expected to have greater gas and electricity usage due to climate factors.[24] Further, there may have been considerable differences in building energy efficiency between the US-ICU and the Aus-ICU. MacNeill and colleagues[38] compared the carbon footprint of operating theatres in three hospitals in Canada, the US and England. The researchers found that building energy (gas and electricity) use contributed considerably to the overall operating theatre carbon footprint and varied considerably between the hospitals, such that the least efficient operating rooms used twice the energy per m^2 as the most energy efficient.[38] The British National Health Service also provides data about the majority of England's hospital energy use.[39] For 2016–17, for acute English hospitals, the energy (gas and electricity) use per hospital m^2 was a median of 423 kWh/m^2 (10–90%, 195–583 kWh/m^2).[39] That is, the more energy-efficient hospitals consumed one-third of the energy per m^2 compared with the less efficient hospitals. Neither of the ICUs in this study had undertaken significant energy efficiency upgrades recently, which could be considered common practice for many hospitals.

Lighting and ICU machine energy use were minor contributors to total ICU energy use. Pollard and colleagues[21] found that the ICU electricity use for lighting and bedside machines was 14 kWh per patient per day — considerably more than our Aus-ICU finding of 3.2 kWh per patient per day, although our study may be influenced by newer, more efficient lights.

The GHG emissions arising from all consumables (reusable and disposable) were less than one-quarter of the total. Recycling ICU waste saves money and reduces waste,[5] but may only modestly mitigate the ICU's carbon footprint. Previous studies have shown that consumables accounted for the largest proportion of the carbon impact for a dialysis unit,[40] a hysterectomy,[20] and a cataract surgery,[41] although the study of operating suites by MacNeill et al[38] indicated similar carbon footprints for consumables and energy supply. Nevertheless, in descending order, avoiding, reducing, reusing and recycling ICU consumables, pathology and radiology tests are activities that ICU clinical staff can readily and positively influence. Further, the potential patient, societal and financial savings from reduced consumable waste may far outweigh any carbon gains.[7]

The LCA methods applied in our study are generalisable to other ICUs and countries, but we recognise our study's limitations. A convenience sample of ten patients per ICU was chosen to include a reasonable range of differing patient therapies, although we did not include treatment occurring beyond the ICU. We were unable to measure the direct energy use of the US-ICU, relying on hospital-wide energy use per m^2. Even if the energy use for the US-ICU was half that approximated, energy use would still form about half the US-ICU's GHG emissions. We did not discuss at length all of the other environmental impacts (toxicities, pollutants) of ICU care, as our main concern was the carbon footprint.

Including EIO-LCA data altered the results so profoundly that we considered it prudent to separate them. Items purchased for the US-ICU cost up to ten times as much as identical Aus-ICU items. Such a cost considerably increased the US-ICU's carbon footprint as there is the linear assumption intrinsic to EIO-LCA (kg CO_2-e per dollar); a product that costs ten times as much has ten-fold the environmental footprint.[3] While this may be true for many publicly available products, in health care, environmental reporting is opaque. Although pharmaceuticals form a considerable part of health care's carbon footprint,[3,4,42] there are few publicly available studies of individual drugs.[18] Further, it is unlikely that an expensive, patented drug that costs ten-fold a non-patented drug has ten-fold the GHG emissions, or that GHG emissions would really fall ten-fold when no longer patented. Such uncertainty makes it difficult to clearly compare the environmental effects of drugs (and pathology) with our process LCA data. Rather than accept such assumptions, we have cautiously avoided mixing EIO-LCA data, recognising that hybrid LCAs are an evolving field.

Conclusion

The carbon footprint of treating patients in the ICU arises not so much from what is seen such as lights, consumables, and waste, but rather from what is unseen but felt, such as HVAC. Considerable opportunities exist for doctors and intensive care societies to collaborate with our engineering colleagues to improve the energy efficiency of the ICU's HVAC, increase renewable energy generation, and influence a more sustainable built environment. Although it is moderately important to "reduce, reuse and recycle" to reduce the carbon footprint associated with consumables used in ICU patient care, such efforts will not reduce the majority of the carbon footprint, but will often save money and bring people together to raise environmental concerns. Rather, it is in the design of new ICUs, in the maintenance of old ICUs, in the use of efficient HVAC systems, and in the energy sources used for such ICUs that one can have the greatest effect in mitigating the ICU's carbon footprint.

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References

1. Whitmee S, Haines A, Beyrer C, et al. Safeguarding human health in the Anthropocene epoch: report of the Rockefeller Foundation–Lancet Commission on planetary health. Lancet 2015; 386: 1973–2028. [PubMed: 26188744]
2. Costello A, Abbas M, Allen A, et al. Managing the health effects of climate change. Lancet 2009; 373: 1693–733. [PubMed: 19447250]
3. Eckelman MJ, Sherman J. Environmental impacts of the US health care system and effects on public health. PLoS One 2016; 11: e0157014. [PubMed: 27280706]
4. Malik A, Lenzen M, McAlister S, McGain F. The carbon footprint of Australian health care. Lancet Planet Health 2018; 2: e27–e35. [PubMed: 29615206]
5. Sustainable Development Unit. Carbon footprint update for the NHS in England 2015. Cambridge: National Health Service; 2016 http://www.sduhealth.org.uk/documents/publications/2016/Carbon_Footprint_summary_NHS_update_2015_final_v2.pdf (viewed Apr 2017).
6. McGain F, Jarosz KM, Nguyen MNHH, et al. Auditing operating room recycling: a management case report. A A Case Rep 2015; 5: 47–50. [PubMed: 26230308]
7. Kubicki M, McGain F, O'Shea C, Bates S. Auditing an intensive care unit recycling program. Crit Care Resusc 2015; 17: 135–40. [PubMed: 26017132]
8. Sneyd JR, Montgomery H, Pencheon D. The anaesthetist and the environment. Anaesthesia 2010; 65: 435–7. [PubMed: 20522026]
9. Sherman J, McGain F. Environmental sustainability in anesthesia. Adv Anesth 2016; 34: 47–61.
10. Chapman M, Chapman A. Greening critical care. Critical Care 2011; 15: 302. [PubMed: 21635700]

11. Huffling K, Schenk E. Environmental sustainability in the intensive care unit: challenges and solutions. Crit Care Nurs Q 2014; 37: 235–50. [PubMed: 24896556]

12. Rebitzer G, Hunkeler D. Life cycle costing in LCM: ambitions, opportunities, and limitations. Int J Life Cycle Assess 2003; 8: 253–6.

13. Weidema BP, Bauer C, Hischier R, et al. Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent report 1 (v3). St Gallen: Ecoinvent Centre; 2013 http://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf (viewed June 2018).

14. Klöpffer W The role of SETAC in the development of LCA. Int J Life Cycle Assess 2006; 11: 116–22.

15. McGain F, Story D, Kayak E, et al. Workplace sustainability: the "cradle to grave" view of what we do. Anesth Analg 2012; 114: 1134–9. [PubMed: 22523411]

16. McGain F, McAlister S, McGavin A, Story D. The financial and environmental costs of reusable and single-use plastic anaesthetic drug trays. Anaesth Intensive Care 2010; 38: 538–44. [PubMed: 20514965]

17. Eckelman M, Mosher M, Gonzalez A, Sherman J. Comparative life cycle assessment of disposable and reusable laryngeal mask airways. Anesth Analg 2012; 114: 1067–72. [PubMed: 22492190]

18. 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.

19. Sherman J, Le C, Lamers V, Eckelman M. Life cycle greenhouse gas emissions of anesthetic drugs. Anesth Analg 2012; 114: 1086–90. [PubMed: 22492186]

20. Thiel CL, Eckelman MJ, Guido R, et al. Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the US. Environ Sci Technol 2015; 49: 1779–86. [PubMed: 25517602]

21. Pollard A, Paddle J, Taylor T, Tillyard A. The carbon footprint of acute care: how energy intensive is critical care? Public Health 2014; 128: 771–6. [PubMed: 25192883]

22. STROBE. STROBE statement: checklist of items that should be included in reports of observational studies. https://www.strobe-statement.org/fileadmin/Strobe/uploads/checklists/STROBE_checklist_v4_combined.pdf (viewed Aug 2018).

23. International Organization for Standardization. ISO 14040: 2006. Environmental management — life cycle assessment — principles and framework [website]. www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en (viewed Mar 2018).

24. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Chapter 14: climatic design information In: ASHARE handbook-fundamentals. ASHRAE; 2017 https://www.ashrae.org/technical-resources/bookstore/ashrae-climate-data-center (viewed Aug 2018).

25. Singer M, Deutschman CS, Seymour CW, et al. The third international consensus definitions for sepsis and septic shock (Sepsis-3). JAMA 2016; 315: 801–10. [PubMed: 26903338]

26. United States Environmental Protection Agency. Inventory of US greenhouse gas emissions and sinks 1990–2016: executive summary. https://www.epa.gov/sites/production/files/2018-01/documents/2018_executive_summary.pdf (viewed Aug 2018).

27. Australian Government Department of the Environment and Energy. National greenhouse accounts factors — 7 2017 http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications/national-greenhouse-accounts-factors-july-2017 (viewed June 2018).

28. Australian Government Department of Industry, Innovation and Science. Office of the Chief Economist, Australian energy statistics [website]. https://archive.industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Australian-energy-statistics.aspx (viewed Aug 2018).

29. Ecoinvent. Ecoinvent database version 2. https://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/ecoinvent-version-2.html (viewed Feb 2018).

30. Goedkoop MJ, Heijungs R, Huijbregts M, et al. ReCiPe 2008 — a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition report I: characterisation; 6 1 2009 https://sites.google.com/site/lciarecipe/publications (viewed March 2018).

31. Rijksinstituut voor Volksgezondheid en Milieu; National Institute for Public Health and the Environment; Ministry of Health, Welfare and Sport. Life cycle assessment, the ReCiPe model;

2008 [website]. https://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/Downloads (viewed March 2018).

32. McGain F, Clark M, Williams T, Wardlaw T. Recycling plastics from the operating suite. Anaesth Intensive Care 2008; 36: 913–4. [PubMed: 19115664]
33. Jensen AH, Petersen PM. Energy efficiency in hospitals and laboratories In: Energy efficiency first: the foundation of a low-carbon society. Proceedings of the European Council for an Energy Efficient Economy; 2011 Summer Study on Energy Efficiency https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2011/6-innovations-in-buildings-and-appliances/energy-efficiency-in-hospitals-and-laboratories (viewed Feb 2018).
34. United Nations. Framework Convention on Climate Change, GHG profiles — annex I, 2015 [website]. http://di.unfccc.int/ghg_profile_annex1 (viewed Jan 2018).
35. United States Census Bureau. US and World Population Clock [website]. https://www.census.gov/popclock (viewed March 2018).
36. Australian Bureau of Statistics. 3101.0 Australian demographic statistics, 6 2015 [website]. http://www.abs.gov.au/AUSSTATS/abs@.nsf/
37. State Government of Victoria, Department of Human Services. Design guidelines for hospitals and day procedure centres. Part E: building services and environmental design [website]. State of Victoria; 2004 http://www.healthdesign.com.au/vic.dghdp (viewed Sept 2017).
38. MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. Lancet Planet Health 2017; 1: e381–e8. [PubMed: 29851650]
39. National Health Service. Estates return information collection 2016/17. England, NHS; 2017 https://digital.nhs.uk/data-and-information/publications/statistical/estates-returns-information-collection/estates-return-information-collection-2016-17 (viewed June 2018).
40. Connor A, Lillywhite R, Cooke MW. The carbon footprints of home and in-center maintenance hemodialysis in the United Kingdom. Hemodial Int 2011; 15: 39–51. [PubMed: 21231998]
41. Morris DS, Wright T, Somner JEA, Connor A. The carbon footprint of cataract surgery. Eye (Lond) 2013; 27: 495–501. [PubMed: 23429413]
42. Sustainable Development Unit. International pharmaceutical and medical device guidelines: carbon footprinting pharmaceutical and medical devices [website]. National Health Service England; 2012 https://www.sduhealth.org.uk/areas-of-focus/carbon-hotspots/pharmaceuticals.aspx (viewed Jan 2018).

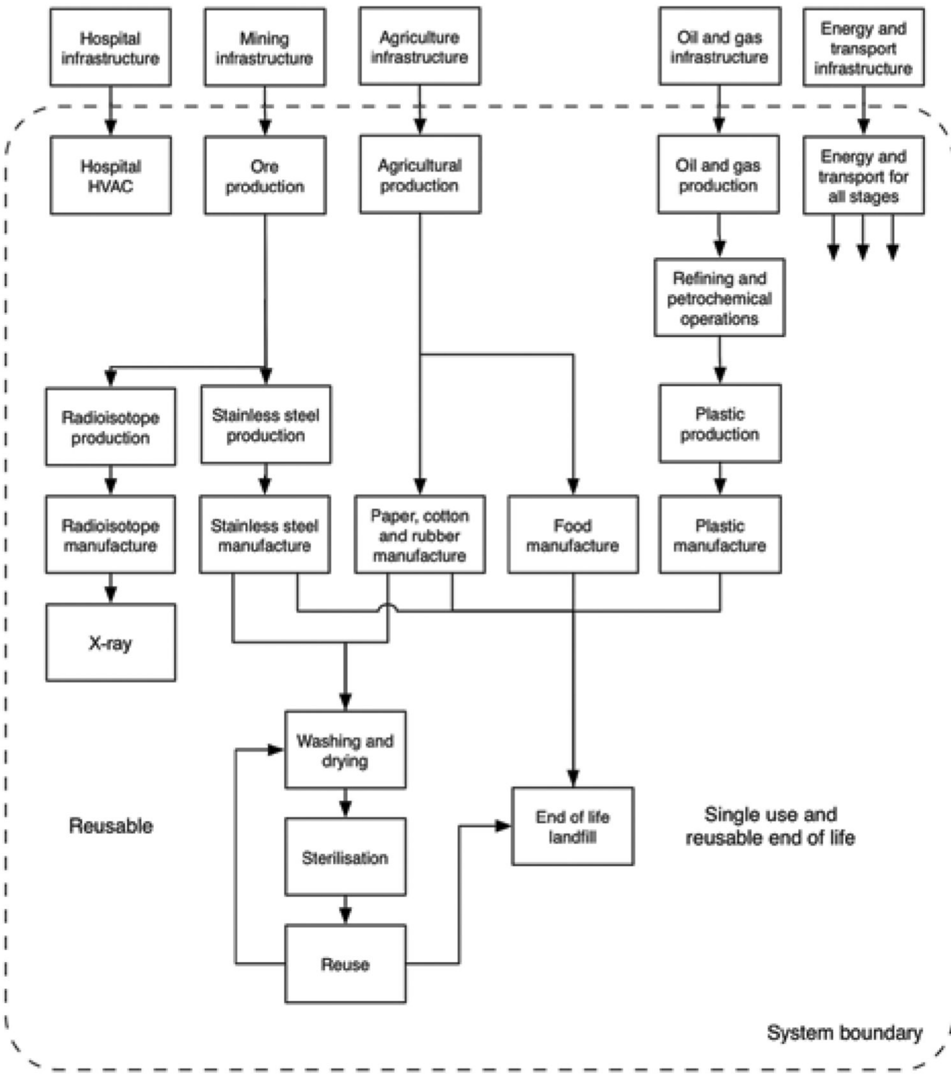

Figure 1. System boundary of what was included (within the dotted boundary) and excluded in this life cycle assessment

HVAC = heating, ventilation and air conditioning.

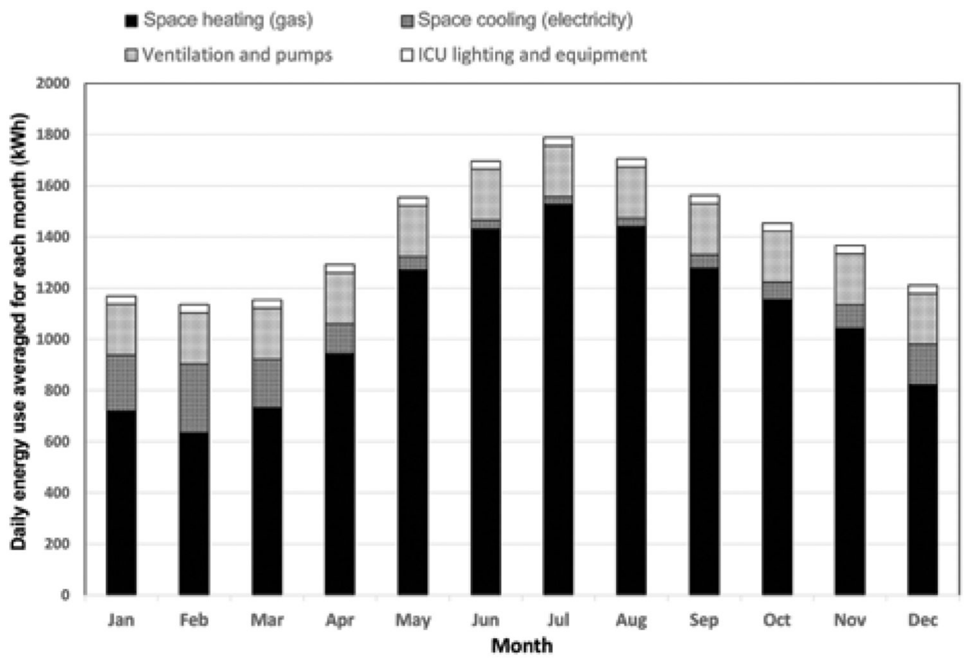

Figure 2.

Daily Australian intensive care unit (ICU) gas and electricity use (kWh)

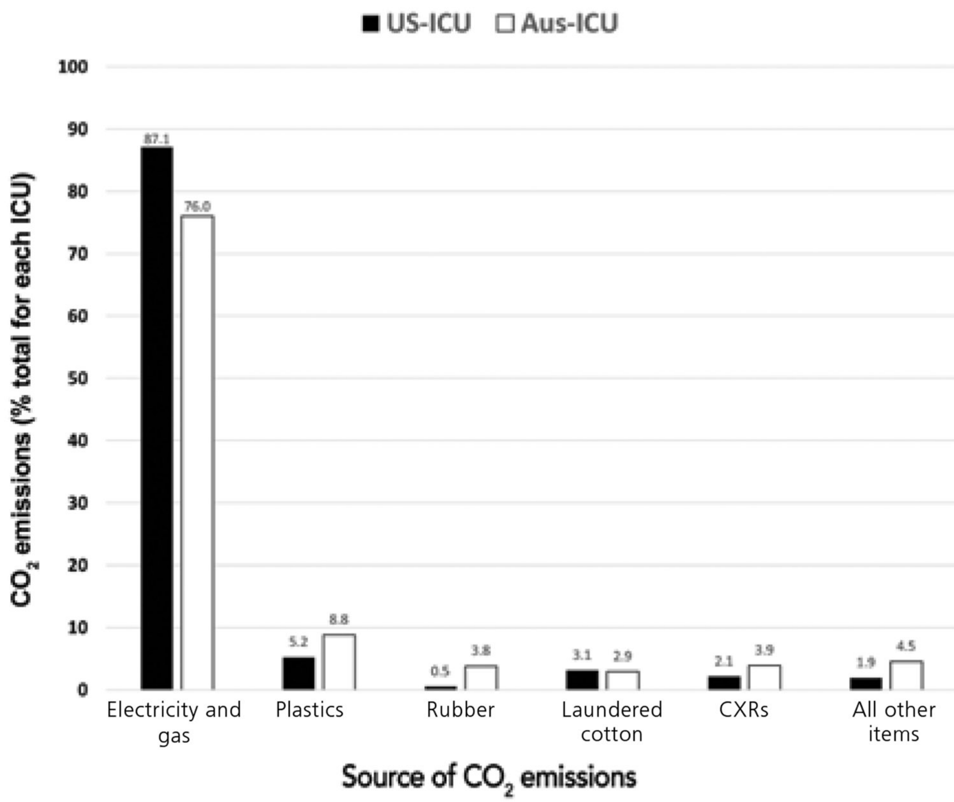

Figure 3. Components of the intensive care unit (ICU) process-based* greenhouse gas emissions (%)

Aus = Australian. CO_2 = carbon dioxide. CXRs = chest x-rays. US = United States. * Process-based data do not include pharmaceuticals, intravenous fluids and pathology.

Table 1.

Electricity and natural gas use in the intensive care unit (ICU)

	kWh	% Total ICU electricity use
Electricity use of ICU fans (ventilation)	176 kWh/day	52%
Electricity use of ICU cooling system averaged and modelled over the typical meteorological year	131 kWh/day	39%
Electricity use of all ICU lights, patient machines, bedside equipment, computers	32 kWh/day	9%
Total electricity use per day (averaged and modelled over typical year)	339 kWh/day (= 34 kWh/patient/day)	
Gas use for ICU per day for heating (averaged and modelled over typical year)	3911 MJ/day (= 1086 kWh/day; or = 109 kWh/patient/day)	
Hospital average per m^2 engineering data for ICU electricity and gas use (averaged over a year)		
	United States ICU	**Australian ICU**
Engineering data	39 occupied beds *	10 occupied beds †
Electricity use/patient/day	124 kWh/patient/day	62 kWh/patient/day
Gas use/patient/day	0.53 GJ/patient/day (= 148 kWh/patient/day)	0.24 GJ/patient/day (= 67 kWh/patient/day)

* The United States ICU (US-ICU) used electricity at 4843 kWh electricity/day, and natural gas totalling 20.8 GJ (5778 kWh) per day. The US-ICU included space for nine surgical patients; these beds were 51% occupied during August–September 2017, taking the number of patients that on average occupied the ICU from 34 to 39 (of 43 possible). The US-ICU had a floor area of 2615 m^2; that is, 67.1 m^2 per patient.

† The Australian ICU (Aus-ICU) used 621 kWh electricity per day, and natural gas totalling 2.4 GJ (667 kWh) per day. The Aus-ICU had an average of ten occupied beds (of 13 total) per day, and a floor area of 657 m^2; that is, 65.7 m^2 per patient.

Table 2.

Masses of consumables used in the intensive care unit*

	United States ICU Median (range)†	Australian ICU Median (range)†
Reusable items		
Cotton laundered (g/day)	4000 (1880–53 070)‡	3660 (2280–4600)
Cotton sterilised (g/day)	0	190 (30–680)
Stainless steel sterilised (g/day)	0	20 (0–30)
Single use items		
Cotton (g/day)	5 (0–20)	130 (60–480)
Synthetic rubbers (g/day)	270 (102–426)	1140 (330–2000)
Paper (g/day)	10 (0–20)	60 (50–120)
Plastics (non-PVC) (g/day)	2580 (670–4820)	1830 (680–2950)
Plastic (PVC) (g/day)	560 (230–920)	280 (80–3160)
Stainless steel (g/day)	21 (0–70)	5 (2–10)
Total-single use items	3400 (1000–6300)	3440 (1200–8700)
Oxygen (L)	1844 (0–4410)	2137 (0–7210)
Compressed air (L)	2550 (0–6356)	3878 (0–9585)
Other process data		
Nasogastric feed (mL)	70 (0–670)	510 (0–1640)
Meals§ (meals/day)	1 (0–2)	0§
Chest x-rays (3 kWh/CXR)¶	1.3 (0–4)	0.9 (0.4–1)
Economic input-output data**		
Pharmaceuticals†† (dollar/day)	US$591 (US$1 17–1260)	A$119 (A$18–265)
Intravenous fluids (blood, albumin, crystalloids) (dollar/day)‡‡	US$16 (US$0–83)	A$100 (A$1–328)
Pathology tests (dollar/day)	US$945 (US$271–3671)	A$260 (A$161–329)

A$ = Australian dollar. CXR = chest x-ray. ICU = intensive care unit. PVC = polyvinyl chloride. US$ = United States dollar.

*Masses are given to the nearest 10 g.

†Ranges are not given when the median daily use was < 10 g per day, as they were small, and in all cases < 50 g/day.

[‡]One patient in the United States ICU (US-ICU) required multiple daily bed linen changes for diarrhoea.

[§]Food intake was calculated according to the amount of food assigned to the patient per day regardless of whether it was eaten, absorbed or discarded. No patient received total parenteral nutrition.

[¶]This average electricity use per CXR (3 kWh) included electricity required for standby mode.[33]

[**]Glass ampoules (for storing drugs) were included in these input output data. A$1 = US$0.79 (Google Currency Converter; 10 Mar 2018).

[††]The Australian ICU had a greater use of blood products than the US-ICU, thus the daily costs were greater.

[‡‡]No blood products were used in the US-ICU during the study.

Table 3.

Process-based and economic input–output (EIO) carbon footprint of intensive care unit (ICU) care

Greenhouse gases	United States ICU			Australian ICU		
	Normalised daily[34,35] impact	Daily average	Daily range	Normalised daily[34,36] impact	Daily average	Daily range
All process-based data (ie, energy, consumables, and CXRs), per patient (kg CO_2-e)	50	178	165–228	61	88	77–107
Consumables only (ie, reusable and single use; fraction, and %, of total process-based data), per patient (kg CO_2-e)		19/178 (11%)	10–57		18/88 (20%)	8–31
Climate change with EIO data included (ie, pharmaceuticals, fluids, pathology), per patient (kg CO_2-e)		624	260–1199		178	109–293

kg CO_2-e = carbon dioxide equivalent. CXR = chest x-ray.