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The carbon footprint of waste streams in a UK hospital

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A B S T R A C T

A number of studies have estimated the carbon footprint of healthcare provision in a variety of contexts, but the emission factors used to account for associated waste vary widely and are not healthcare specific. The aim of this study was to estimate and compare the carbon footprint of hospital waste streams. A process-based carbon footprint of hospital waste was estimated in accordance with the Greenhouse Gas Accounting Sector Guidance for Pharmaceutical Products and Medical Devices, using activity data based on waste streams found at three hospitals in one UK National Health Service organisation. This study estimates that the carbon footprint per t of hospital waste was lowest when it is recycled (21–65 kg CO_2e), followed by low temperature incineration with energy from waste (172–249 kg CO_2e). When the waste was additionally decontaminated using an autoclave prior to low temperature incineration with energy from waste, the carbon footprint was increased to 569 kg CO_2e. The highest carbon footprint was associated with the disposal of waste via high temperature incineration (1074 kg CO_2e/ t). NHS data show that the financial cost of waste streams mirror that of the carbon footprint. In conclusion, it is possible to use the carbon footprint of hospital waste streams to derive emission factors for specific waste disposal options. This may inform the optimal processing of healthcare waste in the future.

1. Introduction

The UK National Health Service (NHS) generates 538,600 tonnes (t) of waste per year in England (costing £115 million to dispose of) (NHS Digital, 2019), whilst the US produces an estimated 5.9 Mt of healthcare waste per year (Voudrias, 2018). The estimate of direct and indirect greenhouse gas (GHG) emissions associated with a product or service (such as waste disposal) is commonly termed the ‘carbon footprint’ (Berners-Lee, 2010). NHS waste is estimated to account for around 30,000 t of carbon dioxide equivalents (CO_2e) per year in England (Sustainable Development Unit, 2018), equating to 0.1% (Sustainable Development Unit, 2018) - 3% (Healthcare Without Harm, 2019) of the total carbon footprint of healthcare. Whilst there are a growing number of studies estimating the carbon footprint of healthcare provision across a variety of clinical contexts (for example renal medicine: Connor et al., 2010, dentistry: Duane et al., 2012, and surgery: MacNeill et al. (2017)), the emission factors (estimates of GHG emissions per unit of activity data) used to account for relevant waste streams are not healthcare specific and vary widely.

Healthcare generates multiple waste streams, each with a different disposal route and, as a consequence, carbon footprint. The carbon footprint of disposing of healthcare waste will depend upon the material contents, alongside the method of disposal, and options for this will depend on the nature of the waste. The principal healthcare waste streams used within the UK are domestic, offensive, dry mixed recycling, infectious, clinical, medicinally contaminated sharps, and anatomical waste (Table 1), although more specialist waste streams are also described, and classifications will vary by country (Department of Health, 2013). The regulations surrounding safe disposal of each of these waste streams differs (Department of Health, 2013). Domestic and non-infectious ‘offensive’ waste may be disposed of via recycling, landfill, or low temperature incineration (Department of Health, 2013). In low temperature incineration, domestic healthcare waste is incinerated alongside other household municipal waste, reaching temperatures of ≥850 °C (Department for Environment, Food and Public Affairs, 2013); this process can incorporate energy and material recovery,

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Table 1
Principal healthcare waste streams.

Waste stream		Waste receptacle	Explanation	Examples of appropriate waste
Non-hazardous waste	Dry mixed recyclable waste	Clear bag	Dependent on local recycling facilities	Sterile packaging, plastic bottles, paper, cardboard
	Domestic waste	Black bag	Items equivalent to municipal waste generated by households	Hand towels, food, drink
	Non-infectious offensive waste	Yellow/black striped bag	Items which 'may cause offense' e.g. due to the presence of body fluids, odour, or association with healthcare services	Non-infectious gloves, aprons, incontinence pads, empty fluid bags
	Infectious waste	Orange bag	Items arising from a patient known (or suspected) to have a disease caused by a microorganism or associated toxins, not fulfilling criteria of hazardous waste	Infectious surgical dressing, gloves, aprons, masks
Hazardous waste	Clinical waste	Yellow bag	Infectious waste contaminated with chemicals or pharmaceuticals	Medicated intravenous bags/lines, medicinally contaminated syringes
	Medical contaminated sharps waste	Yellow lidded yellow box	Sharp items contaminated with medications	Needles, cannulas
	Anatomical waste	Red lidded yellow container	Body parts, including anatomical waste which is infectious or contaminated with chemicals	Diagnostic specimens, placenta
	Medicinal waste	Blue lidded yellow box	Unused (or part used) medicines	Tablets, creams, liquids, patches

for example recovery of waste heat and materials (such as bottom ash and slag metal), and is then referred to as an energy from waste (EfW) process. Infectious or hazardous waste (e.g. anatomical waste, sharps, pharmaceuticals, clinical waste, or waste that is cytotoxic or cytostatic) may be disposed of via high temperature incineration, which uses temperatures $\geq$1100 °C (Department of Health, 2013) and may also involve EfW. Alternative high temperature methods less commonly used include pyrolysis, gasification, and plasma technology, which all heat waste to generate liquid or synthesis gas fuels that can be used to generate electricity or steam. The former two methods heat the waste to 1100 °C, in a fully inert atmosphere for pyrolysis, and using small amounts of oxygen for gasification, whilst plasma technology uses electricity and an inert atmosphere to generate heats of around 6000 °C (Department of Health, 2013). Infectious waste and certain sharps may alternatively be decontaminated using an autoclave, steam auger, dry heat, micro-/macrowaves or chemical disinfection, prior to disposal alongside non-hazardous waste streams (e.g. via recycling, landfill or low temperature incineration) (Department of Health, 2013).

Whilst there is clear guidance on safe disposal of healthcare waste, information on the associated carbon footprints is sparse. Supplementary Table 1 summarises the state of current knowledge from a number of geographical regions and clinical contexts, including plastic surgery in Chile (Berner et al., 2017, urology in Australia (Davis et al., 2018), ophthalmology in the UK (Morris et al., 2013), minimally invasive surgery in the USA (Power et al., 2012), obstetrics and gynaecology in the USA (Woods et al., 2015), surgery (across specialties) in Canada, UK, and USA (MacNeill et al., 2017), renal services in China (Chen et al., 2019), the UK (Connor et al., 2010), and Australia (Lim et al., 2013), alongside dentistry in the UK (Duane et al., 2012). There was a wide range of carbon emission factors used, in particular for landfill (10-1100 kgCO_2e) and recycling (12-9000 kg CO_2e), which is largely explained by differing materials and carbon footprint methodology, particularly allocation methods. For example, paper disposed to landfill has relatively high emissions because (unlike inert items such as metals and glass) it decomposes and releases greenhouse gases, most notably carbon dioxide and methane. For recycled materials there are differences in the method by which the net benefit of reduced virgin acquisition of energy and materials is allocated, and it is also dependent upon the type of material offset through recycling, for example the production of metals and plastics have higher carbon footprints than paper.

The majority of the example studies highlighted in Supplementary Table 1 used the UK Government GHG Conversion Factors for Company Reporting database as the source of waste emission factors (DEFRA/BEIS, 2019). This is produced by the Department for Environment, Food and Rural Affairs (DEFRA/BEIS) and Department for Business, Energy and Industrial Strategy (BEIS), and hereon referred to as the 'DEFRA/BEIS database'. Some studies used older versions of the database, for example the 2009 version: Connor et al. (2010) and 2011 version: Morris et al. (2013), which differ from the current version. For example, the GHG emissions offset by recycling products, or from EfW, are attributed to the user of the recovered product in the 2019 version (DEFRA/BEIS, 2019), rather than the person or institution generating the waste, as in older versions. The current version does not reflect the net GHG emissions of waste, and the authors warn that the database should not be used to compare the carbon footprint of different waste streams (DEFRA/BEIS, 2019). Both Duane et al. (2012) and Lim et al. (2013) reference Connor et al. (2010) as the source of emission factors for clinical waste (who in turn used the DEFRA/BEIS database). These two studies used Australian (Lim et al., 2013) and US (Duane et al., 2012) government reports for other waste streams, and the latter was also used by McPherson et al. (2019). Another study used a single emission factor of 1 kg CO_2e/kg waste across all solid waste disposal, referencing reports on disposal of plastic bags, steel and laptops, and a publication on rubber production (Davis et al., 2018). This emission factor value was also used for municipal landfill by Woods et al. (2015) citing US reports and online calculators. A different online calculator, estimating the carbon footprint of incineration of plastic, was used as the source of emission factor for laparoscopic instrument biomedical waste (Power et al., 2012). A further study collected primary activity data (enabling healthcare specific carbon footprint estimations) for autoclaving but did not publish results (MacNeill et al., 2017), whilst another referenced a healthcare manufacturer document which could not be sourced (McPherson et al., 2019). Other healthcare studies have accounted for waste as part of Life Cycle Assessments (LCAs) examining a range of environmental impacts beyond carbon, using emission factors embedded in libraries restricted to database licence holders, using TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) software (for example, Campion et al., 2012), Ecoinvent (Ibbotson et al., 2013), and PEMS (Packaging Industry Research Association Environmental Management System) software (Ison and Miller, 2000).

The lack of consistent and robust emission factors undoubtedly restricts more detailed analysis of healthcare waste streams. The aim of this study was to estimate and compare the carbon footprint of hospital waste streams, and to provide robust and current values for waste emission factors.

2. Methods

2.1. Scope and boundary setting

The carbon footprint of hospital waste streams was modelled on waste processes at one NHS organisation, which includes three hospital sites sending waste to three companies (X, Y and Z). A process based carbon footprint was calculated in accordance with the Greenhouse Gas Accounting Sector Guidance for Pharmaceutical Products and Medical Devices (ERM, 2012) (referred to hereon in as the GHG Medical Devices Guideline) which builds upon the Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard (referred to from this point as the GHG Protocol Product Standard) (Institute of World Resources, 2011). Microsoft Excel for Mac Version 16.25 (Microsoft Corp, Washington, US) was used for all calculations.

The functional unit was the disposal of one t of waste generated in each waste stream. The system boundary is detailed in Fig. 1 and follows the GHG Medical Devices Guideline (ERM, 2012). Processes included were transportation of waste from hospitals to waste handling sites, energy and water for pre-treatment of waste and final waste processing, and direct GHG emissions. Capital goods involved in the waste management and infrastructure were excluded.

For EfW, a 'closed-loop method' for recycling was used that allocates the net benefit of reduced virgin acquisition of energy and materials to the waste material (Institute of World Resources, 2011). Hence, the quantity of avoided emissions (due to recovery of energy and materials) was subtracted from the carbon footprint (ERM, 2012). For recycling processes, and due to uncertainty about the amount of material recycled from hospital recycling waste streams, we used the 'recycled content method' specified in the GHG Protocol Product Standard (Institute of World Resources, 2011). This method is a form of 'open-loop' recycling, where subsequent emissions of the recycling process and net reduction of virgin material acquisition are attributed to the production of the recycled goods. These emissions were therefore omitted here.

2.2. Data collection and emission factor sources

The steps involved in the processing of each of the waste streams were determined through discussion with the hospitals' waste manager and waste contractors and were illustrative of processes used in 2019. The waste streams were processed either through low temperature incineration (with prior decontamination via autoclave steam sterilisation where necessary), high temperature incineration, or recycling. At the study site, no waste was sent directly to landfill.

2.2.1. Carbon footprint of transportation

Distance travelled was defined as the mean between each waste processing site and the three hospitals, determined using Google Maps (Google, California, US). The registration plate of typical delivery vehicles were determined, enabling the vehicle weights to be established using the Driver & Vehicle Licensing Agency website (UK Government, 2019). The DEFRA/BEIS database (2019) was used to determine the carbon footprint of travelling the calculated distances in these vehicles (0.98−1.91 kg CO_2e/mile, depending on vehicle weight), and this was allocated by the weight of waste carried. Details of the emission factors used for all components can be found in Supplementary Table 2. The average weight of the loads carried by the trucks for each waste type were obtained over a one-month period (April 2019), or using company reported averages where such data were unavailable. The carbon footprint of transportation was included in the emission factors used for recycling so was not calculated separately.

2.2.2. Carbon footprint of autoclave decontamination

Annual electricity, gas oil, and water consumption were determined for the site decontaminating the hospital's infectious waste stream (Company X, 1 January- 31st December 2018). A steam sterilisation autoclave was used to decontaminate infectious waste (at temperatures ≥146 °C for at least 2 min). The autoclave was pressurised with steam produced via an industrial boiler, and at the end of the cycle steam was extracted using a vacuum pump that ensures the resultant waste was as dry as possible, reducing the cost of onward transportation. Natural gas use was omitted as this was not involved in processing of waste. The carbon footprint of gas oil (3.97 kg CO_2e/kg), water (1.05 kg CO_2e/m^3), and electricity consumption (0.32 kg CO_2e/kWh) was estimated using the DEFRA/BEIS (2019) emission factors, and allocated across the weight of infectious waste handled at the site annually.

2.2.3. Carbon footprint of thermal treatment

The carbon footprint of thermal treatment (i.e. low temperature incineration with energy from waste, and high temperature incineration, at temperatures of ≥850 °C and 1000 °C respectively) was determined using the Greenhouse Gas Protocol Emissions from Waste Management Activities database emission factors (Enterprises pour l'Environment Working Group, 2013), referred to hereon in as the 'GHG Protocol Waste database'. Emission factors for direct emissions quoted comprise GHG emissions from fuel consumption and process emissions (880 kg CO_2/t for high temperature incineration, 332 kg CO_2/t for low temperature incineration) (Enterprises pour l'Environment Working Group, 2013). The latter relate to the carbon dioxide released due to burning of waste, produced when carbon within the waste combines with oxygen.

EfW involves thermal treatment of waste, with generation of electricity, slag metal and bottom ash. Avoided emissions were calculated through offsetting the carbon footprint of generated products (electricity and slag metal) against that of incineration.

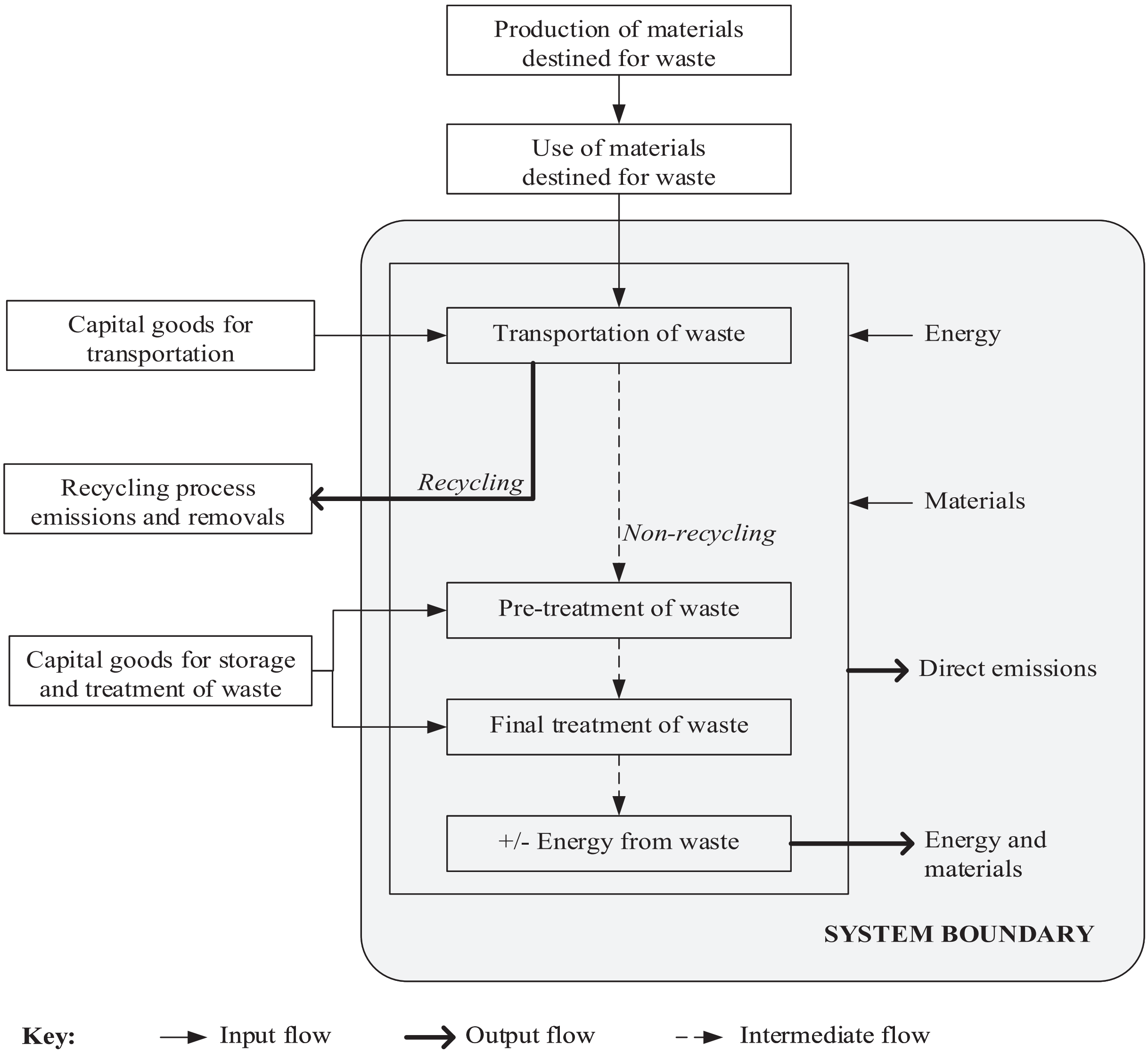

Fig. 1. System boundary
System boundary for carbon footprint of hospital waste. Processes included were transportation of waste from hospitals to waste handling sites, energy and water for pre-treatment of waste and final waste processing, and direct greenhouse gas emissions produced. Capital goods involved in the waste management and infrastructure were excluded.

The bottom ash generated was not included, as the use of this in road construction does not equate to any GHG savings (Enterprises pour l'Environment Working Group, 2013). The net electricity generated per t of waste was determined using the Waste and Resources Assessment Tool for the Environment (WRATE) database (Golder, 2017). The carbon footprint of electricity generation via EfW was estimated using DEFRA/BEIS (2019) database UK emission factors.

The metal component of hospital waste was assumed to be ferous metals, comprising 2.2% of waste generated (Stall et al., 2013). The recycling factor (amount actually recycled) for ferrous metal recovery was set at 55%, based on the WRATE database (Golder, 2017). Together, this means that for every t of waste processed via EfW, an estimated 12 kg of slag metal was recovered. The carbon footprint offset of slag metal generated was estimated using GHG Protocol Waste database emission factors (1.49 kg CO_2/t) (Enterprises pour l'Environment Working Group, 2013).

Indirect emissions of thermal processing of waste (during low temperature incineration with EfW and high temperature incineration) due to electricity and fuel consumption were also included, as specified in the GHG Protocol Waste database (Enterprises pour l'Environment Working Group, 2013). The indirect emissions due to water consumption were also accounted for. The energy consumed during processing of waste via EfW was accounted for by using net electricity generation figures. The consumption of fuel and water at EfW sites were estimated using the WRATE database company Y data (Golder, 2017). Energy and water consumption during high temperature incineration was extracted from the UK Corporate Sustainability Report of company Z, using annual energy consumption (reported in megawatts) specific to the site at which the hospitals' hazardous waste is processed (Tradebe, 2016), and the plant was assumed to operate for 8000 h per year (US Environmental Protection Agency, 1999). Bottom ash and air pollution control residues generated during high temperature incineration were sent to deep burial landfill sites, the impact of which was beyond the scope of this study.

2.2.4. *Carbon footprint of recycling*

The end of life disposal routes for reusable surgical linens, surgical instruments, and batteries were identified through the external surgical linens supplier, internal sterilisation services, and internal waste department. The GHG Protocol Waste database (Enterprises pour l'Environment Working Group, 2013) allocates European emission factors for recycling to the original product (closed-loop). Therefore DEFRA/BEIS (2019) database emission factors were used instead (21.35–64.64 kg CO_2e, depending on recycled material) as these only take into account the transportation of waste to recycling facilities, and can be considered open-loop in line with the GHG Protocol Product Standard definition (Institute of World Resources, 2011) (although the DEFRA/BEIS (2019) database itself defines closed-loop recycling as where waste is recycled into the same original product, and open-loop where this is into a different product).

3. Results

3.1. Waste stream overview

Eight principal waste streams (with a number of recycling sub-streams) were in use at the hospital sites, in line with those identified in Table 1. The processes for each of the waste streams are summarised in a process map (Fig. 2), including the mean distance between sites. Dry mixed recyclable and domestic waste streams were both taken from hospital sites to company Y (site 1) and processed via low temperature incineration with EfW. Non-infectious offensive waste was taken from hospital sites and bulked up at a transit site (company X), from where it was taken to company Y (site 2) and processed via EfW. Infectious waste was taken from hospital sites to company X, where it was decontaminated using a steam sterilisation autoclave, after which it is compacted through a bulking process, and then taken for EfW at company Y (site 2). All EfW sites relevant to the NHS organisation used low temperature incineration. Clinical waste, anatomical waste, medicinal contaminated sharps, and medicinal waste were taken from hospital sites to be bulked up at company X prior to being sent for high temperature incineration by company Z. The weight of waste carried by vehicles travelling from hospitals to company X during the month of April 2019 is provided in Fig. 2 (journey A-B). The average weight of waste carried during all other journeys was a mix of observed and modelled data based on company estimates (Fig. 2).

The majority of reusable stainless-steel surgical instruments and batteries were sent for recycling at the end of life, although a small proportion of surgical instruments were sent for reuse in low- and middle-income countries. In this study, all instruments were assumed to be sent for recycling. At the end of life, reusable surgical linens (such as scrubs, gowns and drapes), were sent to 'ragging merchants' and downcycled, for example, as sound insulation materials.

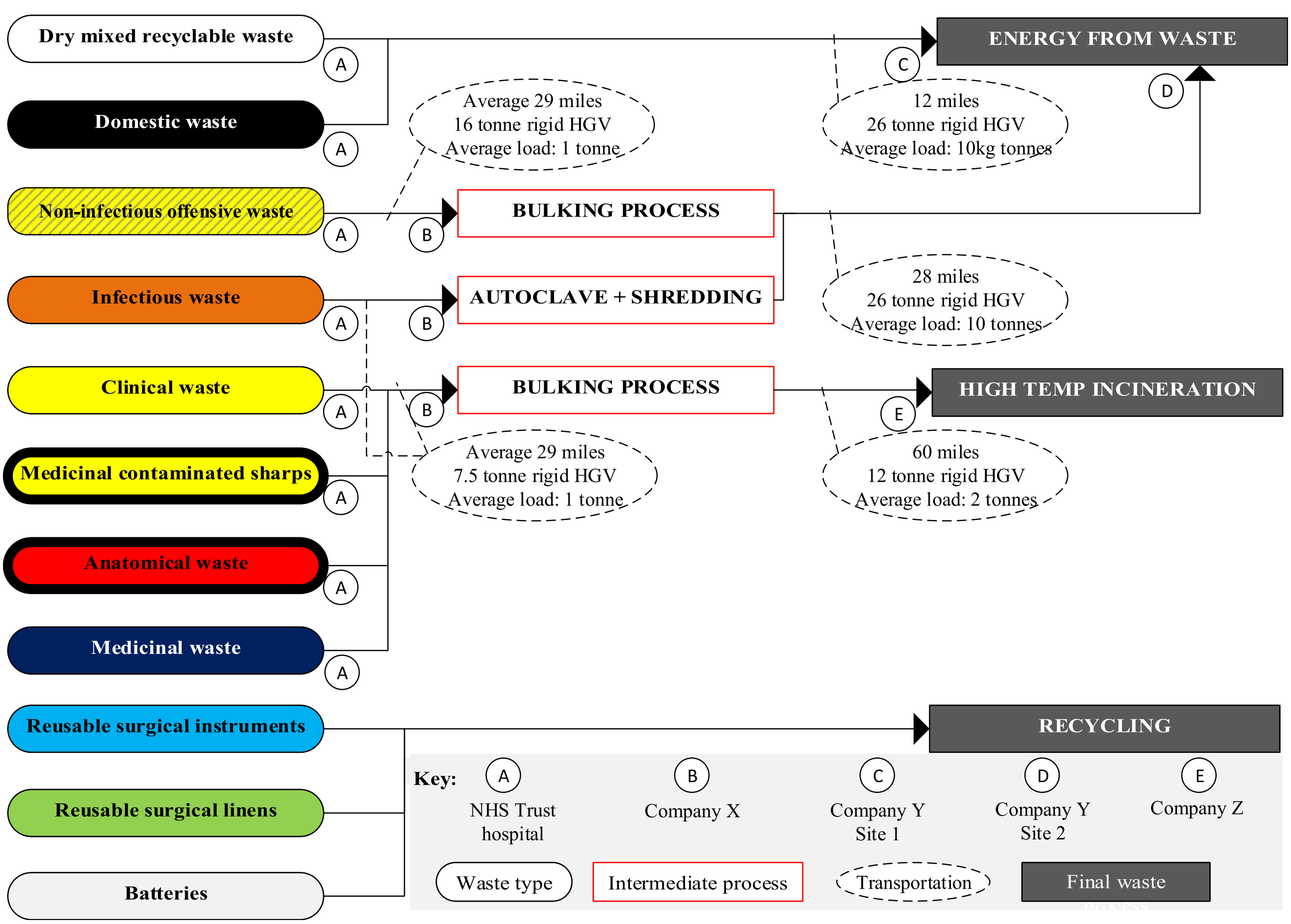

Fig. 2. Process map of processing of hospital waste streams
Different waste streams are listed on the left, within coloured boxes reflecting the colour of the waste receptacle where relevant. The final waste process is indicated in dark grey boxes to the right, with intermediate processes in boxes with a red outline. The start and end location of each leg of the journey specific to each waste stream is denoted by circled letters, corresponding to companies in the key. The distance of each of these journeys, vehicle type and average load carried is indicated in ovals. HGV = heavy goods vehicle, Temp = temperature.. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Carbon footprint of transportation of hospital waste.

Waste stream	Mean round trip distance (miles)	Vehicle type	Weight of transported waste (t)	Carbon footprint (kg CO_2e/t waste)	
				Sub-total	Total for waste stream
Dry mixed recyclable waste transportation	24	26 t HGV rigid diesel	10	5	5
Domestic waste transportation	24	26 t HGV rigid diesel	10	5	5
Non-infectious offensive waste transportation	58	16 t HGV rigid diesel	0.98	71	82
	56	26 t HGV rigid diesel	10	11	
Infectious waste transportation	58	7.5 t HGV rigid diesel	1.07	53	64
	56	26 t HGV rigid diesel	10	11	
Clinical waste, medicinal contaminated sharps, anatomical waste, and medicinal waste transportation	58	7.5 t HGV rigid diesel	1.07	53	125
	120	12 t HGV rigid diesel	2	72	

CO_2e = carbon dioxide equivalents, HGV = heavy goods vehicle, t = tonnes.

3.2. Transportation

The transportation carbon footprint of each waste stream was between 5 and 125 kg CO_2e/t waste, depending on waste type, distances travelled, vehicle type, and the mean weight of waste transported per journey (Table 2). The vehicle weight capacity was largely determined by whether the waste was transported in its original form, or whether waste was compacted allowing bulk-loading, and this was the primary determinant of the variation between the carbon footprint of transportation between waste streams.

3.3. Autoclave decontamination

The carbon footprint of the electricity, gas and water used during decontamination of hospital waste via autoclave sterilisation is summarised in Table 3, totalling 338 kg CO_2e/t, with the majority (92%) of this due to use of gas oil.

3.4. Thermal treatment

Direct and indirect emissions due to processing of waste via low temperature incineration with EfW produced an estimated 337 kg CO_2e/t. This was offset by 170 kg CO_2e/t due to electricity generation and recycled slag metal, with net generation of 167 kg CO_2e/t waste processed. The carbon footprint of high temperature incineration totalled 949 kg CO_2e/t, and company Z confirmed no avoided emissions during this process. The majority of impacts across incineration were due to direct emissions associated with the burning of waste (Table 4).

3.5. Overall carbon footprint of disposing of hospital waste

The total estimated carbon footprint of disposing of hospital waste (including waste processing and transportation) via each of the waste streams is detailed in Table 5 and compared in Fig. 3. The carbon footprint per t of hospital waste was lowest when it is recycled (21–65 kg CO_2e), followed by low temperature incineration with energy from waste (172–249 kg CO_2e). When the waste was additionally decontaminated using an autoclave prior to low temperature incineration with energy from waste, the carbon footprint was increased to 569 kg CO_2e. The highest carbon footprint was associated with the disposal of waste via high temperature incineration (1074 kg CO_2e/t).

4. Discussion

This study estimated the carbon footprint of different waste streams and found considerable variation between them. Disposing of hospital waste via high temperature incineration generated the highest carbon footprint at 1074 kg CO_2e/t, and this disposal method was used for clinical waste, medicinal contaminated sharps, anatomical waste and medicinal waste, as mandated in Department of Health guidelines (2013). The footprint of low temperature incineration with EfW (as used for domestic and dry mixed recyclable waste) was only 16–23% of this (172–249 kg CO_2e/t), and recycling of linens and surgical instruments only 2% of that (21 kg CO_2e/t). Where pre-treatment with decontamination of infectious waste was required prior to EfW, the carbon footprint of waste disposal was 53% that of high temperature incineration (569 kg CO_2e/t). This variation suggests that careful segregation of waste streams is required to prevent unnecessary carbon burdens.

NHS waste in England is most frequently processed via EfW

Table 3
Carbon footprint of decontaminating hospital waste.

Input	Quantity used per t of waste	Carbon footprint (kg CO_2e/t waste)	
		Sub-total	Total for decontamination
Electricity	74.78 kWh	24	338
Gas oil	92.17 L	313	
Water supply and treatment	1.93 m^3	2	

CO_2e = carbon dioxide equivalents, kg = kilograms, kWh = kilowatt hours, L = litres, m = metres, t = tonnes.

Table 4
Carbon footprint of direct and indirect emissions, and avoided emissions, for incineration. CO_2e = carbon dioxide equivalents, kg = kilograms, kWh = kilowatt hours, m = metres, t = tonnes.

<table>
<tr><td rowspan="10">Low temperature incineration with energy from waste</td><td colspan="2" rowspan="2">Input</td><td rowspan="2">Quantity used per t waste</td><td colspan="2">Carbon footprint
(kg CO_2e/ t waste)</td></tr>
<tr><td>**Sub-total**</td><td>**Total**</td></tr>
<tr><td colspan="2">**Direct emissions**</td><td>**N/A**</td><td>**332**</td><td rowspan="3">**337**</td></tr>
<tr><td rowspan="2">**Indirect emissions**</td><td>**Gas oil**</td><td>**1.34 kg**</td><td>**5**</td></tr>
<tr><td>**Water supply and treatment**</td><td>**0.29 m^3**</td><td>**0.29**</td></tr>
<tr><td colspan="2" rowspan="2">Output</td><td rowspan="2">Quantity generated per t waste</td><td colspan="2">Carbon footprint
(kg CO_2e/ t waste)</td></tr>
<tr><td>**Sub-total**</td><td>**Total**</td></tr>
<tr><td colspan="2">**Net electricity**</td><td>**482.34 kWh**</td><td>**-152**</td><td rowspan="2">**-170**</td></tr>
<tr><td colspan="2">**Slag metals recycled**</td><td>**12.10 kg**</td><td>**-18**</td></tr>
<tr><td colspan="3"></td><td>**Net**</td><td>**167**</td></tr>
<tr><td rowspan="5">**High temperature incineration**</td><td colspan="2" rowspan="2">Input</td><td rowspan="2">Quantity used per t waste</td><td colspan="2">Carbon footprint
(kg CO_2e/ t waste)</td></tr>
<tr><td>**Sub-total**</td><td>**Total**</td></tr>
<tr><td colspan="2">**Direct emissions**</td><td>**N/A**</td><td>**880**</td><td rowspan="3">**949**</td></tr>
<tr><td rowspan="2">**Indirect emissions**</td><td>**Electricity**</td><td>**195.56 kWh**</td><td>**62**</td></tr>
<tr><td>**Water supply and treatment**</td><td>**6.81 m^3**</td><td>**7**</td></tr>
</table>

CO_2e = carbon dioxide equivalents, kg = kilograms, kWh = kilowatt hours, m = metres, t = tonnes.

Table 5
Carbon footprint of disposing of hospital waste.

Waste stream		Carbon footprint (kg CO_2e/t waste)		
	Waste process		Transportation	Total
Recycling reusable surgical instruments	Recycling scrap metal	21	0[a]	21
Recycling reusable surgical linens	Recycling clothing	21	0[a]	21
Recycling batteries	Recycling batteries	65	0[a]	65
Dry mixed recyclable waste	Low temperature incineration with EfW	167	5	172
Domestic waste	Low temperature incineration with EfW	167	5	172
Non-infectious offensive waste	Low temperature incineration with EfW	167	82	249
Infectious waste	Autoclave decontamination	338	64	569
	Low temperature incineration with EfW	167		
Clinical waste, medicinal contaminated sharps, anatomical waste, medicinal waste	High temperature incineration	949	125	1074

CO_2e = carbon dioxide equivalents, EfW = energy from waste, kg = kilograms, t=tonnes.
[a] = included in waste process.

(37%), followed by incineration (25%), recycling (23%), and landfill (15%) (NHS Digital, 2018). A study of eight hospitals in Egypt found that two-thirds of waste was sent to landfill, with the remainder predominantly incinerated, and a small proportion autoclaved prior to landfill (Abd El-Salam, 2010). There is a lack of published data on the proportion of waste disposed of via the different waste streams, and this is likely to vary by country as well as by region. In terms of the financial cost of waste streams, NHS national data indicate that incineration holds the highest financial cost (£189/t waste), followed by landfill (£149/t), EfW (£129/t), and recycling (£100/t) (NHS Digital, 2018). There are reports of recycling schemes (including for plastics used in the operating theatre) where the recycling company will pay healthcare providers for waste materials, offsetting costs of waste removal and processing (McGain et al., 2008). Whereas the financial costs of different waste streams do not show the same magnitude of difference as the carbon intensity, the two measures closely mirror each other. Saving carbon also saves money.

The results demonstrate that on both carbon and financial grounds, hospital waste should be recycled where possible, and used to recover energy from waste at low temperatures of incineration where it is not, with decontamination prior to either of these options where necessary (such as for infectious waste and non-medicinally contaminated sharps) (Department of Health, 2013). High temperature incineration is the most carbon intensive and financially expensive waste stream and should be reserved for waste streams where it is mandated, such as for anatomical waste, infectious or sharps waste contaminated with chemicals (the former referring to ‘clinical waste’), medicinal waste, and items contaminated with cytotoxic or cytostatic medicines (Department of Health, 2013).

There will be differences in the carbon footprint of alternative methods of decontaminating infectious waste (allowing it to be processed as non-hazardous waste) and these should also be taken into account when determining national policy and guidance. A life cycle assessment study by Hong et al. (2017) found that the carbon

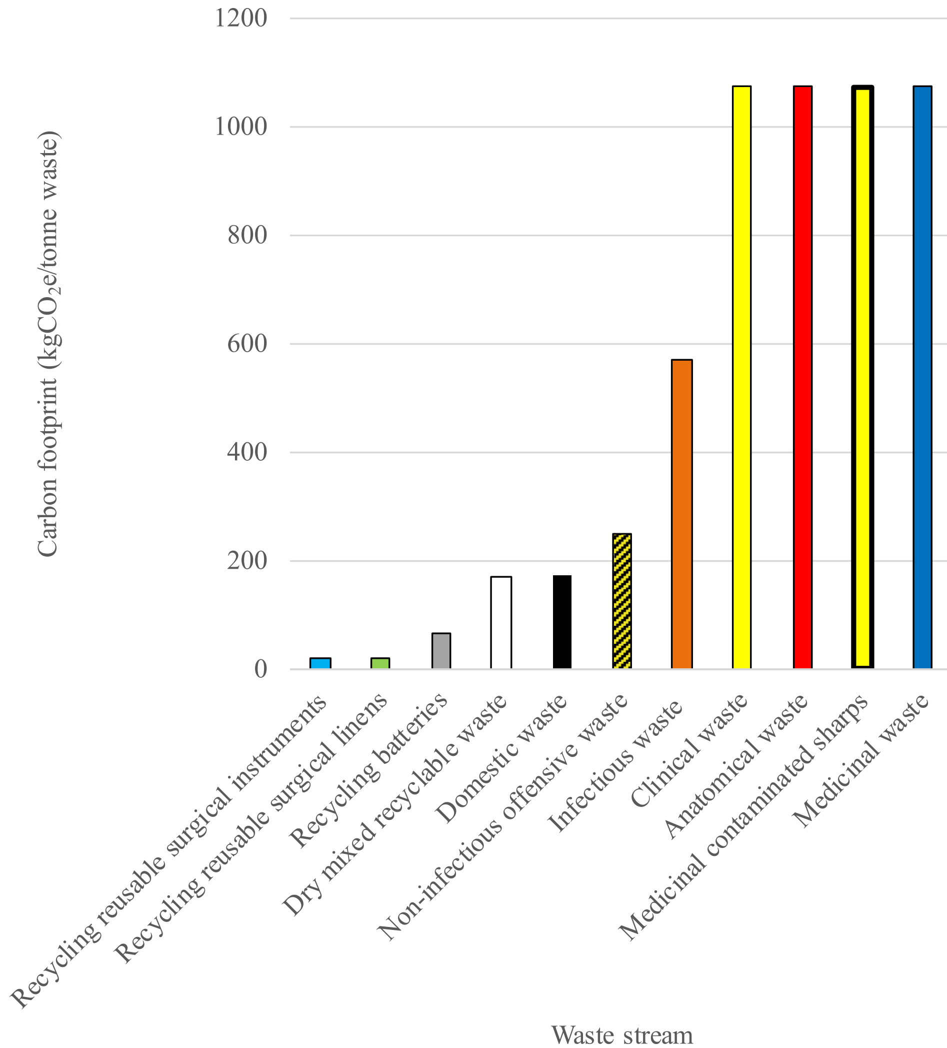

Fig. 3. Bar Graph comparing carbon footprint of hospital waste streams
The colour of bars reflects the colour of the waste stream receptacle where relevant. The waste processes with the largest carbon footprints were those using high temperature incineration, followed by autoclaving prior to low temperature incineration with energy from waste, followed by low temperature incineration with energy from waste alone, and finally recycling had the smallest carbon footprint. CO_2e = carbon dioxide equivalents. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

footprint of steam sterilisation of infectious waste in China was five times greater, and more expensive, than chemical disinfection (although the authors included hazardous waste incineration of both waste streams following decontamination within the study system boundary). Whilst low temperature incineration (potentially with energy from waste) would be sufficient to decontaminate infectious waste (without the need for autoclave sterilisation or alternative decontamination), this would require the incinerator operator to adopt hazardous waste handling procedures, which may affect efficiency and the carbon footprint. More should be done to explore this, saving the cost and carbon associated with additional decontamination.

Whilst this paper provides evidence for the optimum hospital waste stream hierarchy (on both financial and carbon grounds), there are a number of measures which could be taken to shift the disposal of hospital waste towards more desirable routes. Where there are multiple safe options for a given waste category, national bodies should provide clear guidance on which disposal route has the lowest carbon footprint and seek to restrict use of less preferable options. Correct use of waste receptacles could be improved through centralised simplification of waste terminology using intuitive language designed to improve appropriate waste segregation. For example, the waste stream for infectious waste contaminated with chemicals is commonly confusingly labelled ‘clinical waste’, and in our experience, this waste stream is often available in clinical areas where an infectious or offensive waste stream would be more appropriate in accordance with guidelines (Department of Health, 2013), whilst reducing the carbon footprint and cost of disposal. There is much variability in the waste streams available in comparable clinical settings, even within a given hospital, and these could be standardised at a national level. Healthcare facilities should ensure that waste management contracts are awarded to companies using minimally impactful processes for each category of waste. For example, instead of using high temperature incineration for infectious waste, this should be decontaminated via an autoclave before disposal via an alternative low carbon footprint waste stream, which could include recycling. Whilst the study case site for high temperature incineration did not use any energy recovery, these facilities do exist and should be used in preference.

We are aware of innovative services which decontaminate stainless steel surgical instruments prior to using the steel within the construction industry, and the potential to expand this to other healthcare waste materials and applications should be explored. A study of operating theatre waste found that 13% of infectious waste was potentially recyclable, accounting for non-contaminated paper/cardboard, plastics, aluminium, and glass only (i.e. items incorrectly placed into the infectious waste stream), and the recycling potential of infectious waste would be higher if items were decontaminated before recycling (McGain et al., 2015). The recycling potential, and carbon footprint of recycling healthcare waste will vary by hospital department, and will depend on the volumes generated alongside the content of the waste.

Surveys from a variety of geographical and clinical settings indicate that clinicians are concerned about the environment and are keen to improve the sustainability of their clinical practice, including surveys of ophthalmologists in New Zealand (Chandra et al., 2020), nephrologists in the UK (Connor and Mortimer, 2010), and anaesthetists in Australia (McGain et al., 2012). A survey of UK and Australian anaesthetists found that the major perceived barriers to recycling theatre waste were inadequate facilities (49%), staff attitudes (17%), and inadequate information (16%) (McGain et al., 2012). It is important that healthcare staff have access to appropriate waste disposal routes, alongside better education on how to use these appropriately. The carbon footprint of waste is lowest when it is recycled, and more should be done to facilitate recycling, given estimates that two-thirds of operating theatre plastics are potentially recyclable (McGain et al., 2015). Whilst there are isolated pioneering examples of this it is not common-practice, and research and enterprise to promote this should be encouraged. We hope that manufacturers will look to modify their products in conjunction with the development of recycling streams, to make it easier for healthcare staff to correctly segregate recyclable waste (Rizan et al., 2020). Whilst the strategy outlined would maximise disposal through low carbon intensity methods, this must be done in parallel with efforts to reduce resource consumption and to shift our reliance on single-use items towards reusables where possible, minimising the generation of waste.

The current study did not include landfill of hospital waste, as the study sites included here have a zero to landfill policy, but a number of sources have estimated the carbon footprint of sending waste to landfill. Emission factors within the DEFRA/BEIS (2019) database incorporate both direct and indirect emissions from the production, and combustion of, methane and biogas generated during decomposition of organic waste, but do not include transportation, or energy and materials required at landfill sites (which are included in our study system boundary for other waste streams). Zhao and Zang (2009) undertook an LCA and found that high temperature incineration of hospital waste generated 1190 kg CO_2e per t (a figure in agreement with our estimate of 1074 kg CO_2e), and that sending healthcare waste to landfill following autoclaving generated 461 kg CO_2e per t, (with minimal contribution from the decontamination process). When they modelled 30% energy recovery from waste, high temperature incineration became preferable to landfill (Zhao and Zhang, 2009). However this study did not include transportation and referenced activity data sources which were not specific to healthcare. Further work is needed to determine where landfill sits in the healthcare waste carbon footprint hierarchy, and is likely to be highly dependent on the composition of healthcare waste.

There are some limitations to our study. As with all carbon footprinting studies, the findings are limited by the system boundaries and assumptions. The extent to which results can be generalised to other healthcare settings may be limited as the activity data was modelled on waste processes found at one organisation, and emission factors applied were country specific where possible (e.g. based on UK energy supply). Determining the carbon footprint of healthcare waste in other countries is an important area of future research. Nevertheless, the data presented here should prove useful for future studies looking to include waste in carbon footprint estimations within a healthcare context, and are likely generalisable to other healthcare settings such as primary care which use the same waste streams. There are wider factors beyond GHG emissions which also need to be taken into account when comparing the environmental impact of different waste streams, and the preferable option may differ between impact categories examined. In order to consider broader environmental impacts beyond carbon dioxide equivalents, a full LCA is required, comparing healthcare waste across all waste streams.

5. Conclusion

Healthcare waste constitutes a small proportion of the overall carbon footprint of healthcare services (30,000 t CO_2e/year in England), equating to an estimated 0.1% of the total carbon footprint of the NHS in England (Sustainable Development Unit, 2018) and 3% of healthcare's carbon footprint globally (Healthcare Without Harm, 2019). However, the choice of waste stream has an up to 50-fold impact on the carbon footprint, and it is important that we optimise our handling of waste. Healthcare waste policies should encourage processes with lowest impact such as recycling (21–65 kg CO_2e/t) or energy from waste (172–249 kg CO_2e), and to explore the option of decontaminating infectious waste prior to disposal via low carbon methods, rather than sending such waste for high temperature incineration (which has the highest associated carbon footprint: 1074 kg CO_2e). This approach should confer both carbon and financial savings. Alongside this, further research and enterprise is required, focusing on designing products and systems enabling recycling of medical products.

CRediT authorship contribution statement

Chantelle Rizan: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Mahmood F. Bhutta:** Supervision, Funding acquisition, Writing - review & editing. **Malcom Reed:** Supervision, Writing - review & editing. **Rob Lillywhite:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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