Testing the Nexus between C&D Waste Management Strategies & GHG Emission Performances: The Case of UK Student Accommodation Refurbishment Projects

Eric C.W. Lou [1*], Angela Lee [2], Andrew J. Welfle[3], Aminu L. Abdullahi [4]

1. Department of Engineering, John Dalton Building, Manchester Metropolitan University, UK.
2. School of Science, Engineering & Environment, Maxwell Building, University of Salford, UK.
3. Tyndall Centre for Climate Change Research, Pariser Building, Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK.
4. Kano University of Science and Technology Wudil, Nigeria.

*e.lou@mmu.ac.uk, +44 (0) 161 247 1866

Highlights

- Buildings and C&D processes have a large environmental footprint for all countries.
- In the UK buildings provide 40% of all emissions and C&D generates 62% of all waste.
- Refurbishment projects are a core and growing element of the C&D sector.
- Management of key waste streams influences the emission performance of projects.
- High emission risk wastes sent to landfill will offset benefit of reuse and recycling.

Abstract

All governments, industry sectors and societies each have a pivotal role to play if we are to mitigate anthropogenic climate change. For the construction industry, limiting emissions and addressing issues of sustainability is not just important for reducing the environmental impacts of the sector, but is simply good practice. This research investigates the nexus between the generation and management of waste and greenhouse gas performance in the refurbishment sector, with specific focus on UK student accommodation projects. Performance data from three case study projects were analysed in order to: evaluate the types and extent of wastes and how they are managed; the greenhouse gas impacts of each project waste management strategy; and an assessment is undertaken to estimate the number of BREEAM waste credits that each project would have achieved. The research concludes that the overall greenhouse gas performance of a project's waste management strategy is highly dependent on how specific high emission impact factor waste streams are managed, and notably, there is a disconnect between waste targets, legislation and sustainability benchmarking schemes that measure success based on the levels of diverting waste from landfill, and the emission performance of waste management strategies. A key area of risk potentially overlooked relates to the scenarios where proportionally small quantities of high emission wastes (e.g. plastics) were sent to landfill alongside large quantities of low emission wastes (e.g. aggregates, bricks, etc.). To ensure the increased emission performance of the refurbishment sector, greater focus is needed on preventing specific categories of waste from the landfill pathway.

Keywords

Refurbishment; Waste management; Student Accommodation; greenhouse gas; Sustainability Management

1. Introduction

Scientific and political pressure has ensured climate change remains a key theme on the World agenda. International actions such as the Kyoto Protocol (UNFCCC, 1998) and the more recent Paris Agreement (UNFCCC, 2015), demonstrate the prominence of the climate change issue, and highlight the types and scales of action that will be required to limit increases in global temperature. For the construction industry (CI), limiting emissions and addressing issues of sustainability is not just important for reducing the environmental impacts of the sector, but is simply good practice (European Commission, 2012). Greenhouse gas (GHG) emissions from buildings will be a significant portion of the overall emission profile of any given country, for example the built environment contributes around 40% of the UK's total carbon footprint (UKGBC, 2020).

How buildings are constructed, materials used, energy consumed and building management and eventually demolished, ultimately determines the whole life cycle environmental footprint of any given building (Dixit, 2019). The choice of construction materials is highly significant as the embodied energy required to make or create different materials can vary highly, in addition to the available methods for managing the materials post-use. Kibert (2005) reported that 90% of all materials ever extracted may be residing in the CI, and many of these materials during a building's demolition are ultimately regarded as waste (Brandon and Lombardi, 2011). To reduce the impact of these 'waste' materials from refurbishment activities, legislation has been developed to both reduce the levels of waste generated and to ensure that different categories of waste are managed using 'waste management strategies' that to reduce environmental impact. For example, The European Commission (2008) Waste Framework Directive included targets for each EU country to achieve at least 70% recovery of materials from CI waste streams by 2020. Many EU countries met and exceeded this target achieving recycling rates >90%; subsequently the EU Construction and Demolition

Waste Protocol and Guidelines was produced to aid the the non-compliant EU Member States and to encourage the lesson learning from both leading EU and wider case sudies (European Commission, 2018).

In the UK, more recent (2016) statistics document that 62% of total UK waste (tonnes) is sourced from the Construction, Demolition and Excavation (C&D) sector. The equates to 66.2 Mt of non-hazardous waste materials, of which 91% was recovered/ reused and thus diverted from landfill (DEFRA, 2020). The UK's high C&D waste recovery levels were achieved through a combination of forty different regulations targeted at improving performance of waste management practices. Legislation specifically developed for CI include the Aggregates Levy (HMRC, 2016) and Site Waste Management Plan Regulation 2008 (SWMP), each intending to make individual construction operations responsible for the waste they generate and how these are managed. Despite highly targeted legislation, the UK Green Building Council highlighted the problem that almost 10% of UK CI waste materials have no further use and end up in landfill (UKGBC, 2017). To address this, current research is focusing heavily on single discipline analyses such as using building waste management reduction or prediction models (Llatas and Osmani, 2016).

The importance of low carbon refurbishment, maintenance and improvements of buildings were also reported by Ferreira *et al.* (2013), de Larriva *et al.* (2014), and Schwartz *et al.* (2018), among others. Refurbishments provide an opportunity to improve poor energy performing buildings by replacing old items with new energy efficient materials and technologies (Palacios-Munoz *et al*., 2019). New sustainable materials and lifecycle costs were taken into considerations by Biolek and Hanak (2019). Innovation of new products, practices and processes were considered by Streicher *et al.* (2020). There were also an increasing trend in the uptake of building sustainability schemes (Buyle *et al.*, 2019), such as the Building Research Establishment Environmental Assessment Methodology (BREEAM, 2020) in the UK, Haute Qualité Environnementale (HQE, 2020) in France, Leadership in Energy and Environmental Design (LEED) (USGBC, 2020) in the USA, Comprehensive Assessment System for Built Environment Efficiency (CASBEE, 2020) in Japan, Building Environmental Assessment Method (BEAM) Plus (HKGBC, 2020) in Hong Kong, amongst many others. These schemes were widely used and considered to be the best method forward to drive sustainability and lower the environmental impact by buildings. However, GHG emissions, waste elements and sustainability schemes are not considered in parallel.

This research introduces the nature of waste from refurbishment projects and the environmental impact of how waste is managed through varying strategies. It evaluates the types of waste generated by three (3) refurbishment case study projects from the UK, focusing on the student accommodation sector. This sector has emerged as the best-performing asset in the UK and US property markets (Hammond, 2013) and demand continues to accelerate (KnightFrank and UCAS, 2018). The three case studies were specifically chosen in order to demonstrate the diversity of waste streams that may be generated in refurbishment projects, and how environmental performance may vary widely depending on how different waste streams are managed. Each case study focuses on: (i) evaluating the types and scales of waste generated, and how these waste are managed within each case study; (ii) undertaking calculations to estimate the GHG emission performance of the adopted waste management strategies, and; (iii) comparing how the waste management performance of each case study benchmarks the criteria of the UK's BREEAM environmental performance assessment scheme. These analyses allow this research to assess and conclude on the how waste management strategies may be developed to improve GHG emission performance for the refurbishment industry; to evaluate the success of environmental benchmarking schemes (eg. BREEAM), through comparing each case study project's waste BREEAM Credit Scores against calculated waste management GHG emission performance.

2. Research Methodology

2.1. Case Study UK Refurbishment Construction Projects

This research focuses on three Case Study Projects that were managed by a privately-owned construction management company from the north of England with expertise in student accommodation. The projects were higher education student accommodation refurbishment projects: low rise apartment blocks comprising of individual student flats with en-suite shower/bath rooms, shared kitchens and lounge areas in the cities of Liverpool and Leeds, England. The booming student population in both cities presented an ideal case study for potential impact on future refurbishment projects in the UK. Waste data was collected for each case study, the data characterising the types of waste materials generated and how these materials were managed. The projects varied in size, duration, cost and activities, as shown in Table 1, providing further opportunities for analysis focusing on how project characteristics may influence waste generations and the environmental performance of waste management strategies.

Insert Table 1 here

All case studies were low-rise apartment blocks of less than 5 floors, with no lift access. This research analysed the environmental performance of refurbishment waste management practices, which provided invaluable insights of the environmental performance attributed to different types of waste stream generated and ways they are managed.

2.2. Assessing Waste Generation & Waste Management Performance

The first analysis focused on calculating the amount (tonnes) of the different types of waste categories generated by each case study. This is achieved through analysing the waste data sourced directly from each project's site waste management record sheets. A waste profile of each project is generated - recording the extent that different waste that was generated and how they were managed. The key performance metric of interest in this analysis was to establish the extent that different categories of waste were diverted from landfill – these values were compared against benchmark levels for 'Standard', 'Good' and 'Best Practice' as recommended by the Waste and Resources Action Programme (WRAP, 2007). This allowed a first assessment of the environmental performance of each project's waste management strategy by benchmarking against that of the wider refurbishment sector.

2.3. Calculating the GHG Emission Performance of Waste Management Strategies

This research used waste generation and waste management performance data to calculate levels of GHG emission performance. The emission performance of each project's waste management strategy was calculated as a function of the extent that different categories of waste are generated (QW), the extent that different proportions of these waste were managed through different pathways (WMP), and the emissions factors (EF) attributed to different the pathways (Welfle *et al.*, 2017), as shown in Equation 1. Quantities of different categories of waste (QW) and how these are managed (WMP) within each project were taken directly from the site waste management record sheets. The emission factor (EF) data is sourced from the United States Environmental Protection Agency (EPA, 2006) and the UK's National Atmospheric Emissions Inventory (NAEI, 2016). This analysis was applied to evaluate the overall GHG performance of each project's waste management strategy and to highlight differences between the potential GHG impact of specific waste categories and their management practices.

Insert Equation 1 here

2.4. Waste Environmental Performance Benchmarking

The environmental performance of each project's waste strategy was evaluated using the criteria of an environmental performance-benchmarking tool. Given the location of the projects and the characteristics of the refurbishment activities undertaken, waste performances were assessed against the Building Research Establishment's 'BREEAM UK Refurbishment and Fit-out 2014' assessment scheme for non-domestic buildings (BRE, 2014). Within BREEAM, the environmental performance was measured across a series of categories and factors and number of 'credits' may be awarded. The level of performance achieved was determined by the extent that a project's design, operation and management complied with a list of performance criteria (Welfle, 2009). Each project's waste performance was evaluated against the criteria of the most relevant 'BREEAM Credit' for waste management – 'Wst 01 Project Waste Management'. This tests performance against how much waste was actually generated and how much was diverted from landfill. This assessment was used within this research to compare how the projects perform against the BREEAM scheme related to the calculated GHG performance of each project's waste management strategy. This provided valuable information and insight into the extent that the current BREEAM environmental assessment scheme effectively awards increased waste management strategy GHG performance.

3. Results

3.1. Waste Generation and Waste Management

Table 2 presents the varying types and scales of waste generated by each project and how it was managed. A myriad of waste streams was presented across the three projects. Project A generated the largest overall quantities of waste followed by Project C and Project B. Project A's overall waste tonnage was dominated by furniture, floor coverings, timber, packaging, aggregates and other waste categories; Project B's dominant waste category was furniture; furniture and aggregate formed the greatest contributions within Project C. The greatest proportion of waste in Project A was managed through a recycling pathway, a smaller proportion of the materials were reused and the remaining were disposed to landfill. Project B's waste management strategy was an even balance between reuse, recycle and landfill pathways. The waste management strategy for Project C stands out because the overwhelming proportion of waste generated was sent to landfill, with only limited proportions of waste being reused.

Insert Table 2 here

Table 3 provided analysis of each project's performance in relation to the extent that each category of waste is diverted from landfill. Colour coding in Table 3 highlights the performances of each project as shown against the industry benchmark levels as prescribed by WRAP (2007). This table clearly highlights some major contrasts in level of performance between the projects. Project A's waste management performance is predominantly achieved 'Standard Practice' performance for many of its waste categories; it achieved 'Best Practice' performance managing furniture and metal waste; 'Good Practice' for other waste and below standard practice for insulation/ fabric waste materials. Project B is shown to achieved 'Best Practice' for managing all categories of waste aside from 'other' waste where is achieves 'Good Practice'. In contrast Project C is calculated to achieve 'Standard Practice' when managing canteen/ office/adhoc waste, all other categories of waste falling below this standard.

Insert Table 3 here

3.2. GHG Emission Performance of Waste Management Strategies

Analyses of the GHG emission performance of each project's waste management strategies are presented within Figures 1 and 2. Figure 1 provides two levels of analysis: the blue columns for each project documents the GHG impact of the implemented waste management strategy, as calculated using Equation 1; the purple, red and green columns for each project provide an estimate of the potential GHG performance each project met with the minimum waste diversion from landfill requirements to achieve WRAP's benchmarks. Comparison of the blue column for each project against the subsequent columns provides an indication of the level of performance against benchmark standards for the sector.

Insert Figure 1 here

Insert Figure 2 here

Figure 1 demonstrates Project A's waste management strategy generated the most emissions overall, followed by Project C and B. Project A and B were shown to achieve GHG performance levels below expected levels by diverting 'Best Practice' levels of waste from landfill. Project C is shown to generate the least overall emissions, but proportionally the scale of calculated emissions were higher than would be expected by projects diverting 'Standard Practice' levels of waste from landfill.

These dynamics are analysed further in Figure 2 where the data from Table 5 was normalised to reflect performance indexed to each project's gross internal floor area (GIFA), allowing clear comparisons of the performances between the projects. Project GIFA has been shown to provide an accurate metric to compare environmental performance between projects of different scales (Lou *et al*., 2017). The first stacked columns for each project within Figure 2 provide a breakdown of the total quantity (tonnes/GIFA) of different categories of waste generated. The second stacked columns for each project document the overall GHG impact associated with managing each category of waste (tCO_2/GIFA), as calculated using Equation 1. For each waste category this calculation takes account of any emissions generated through disposal, recovery and recycling processes, minus any emission savings that may be generated through reusing resources. The third stacked columns for each project documents the overall calculated GHG impact (tCO_2/GIFA) of different waste management pathways taking account of all disposal, recovery, recycling and reuse processes.

Figure 1 highlighted that Project B's overall waste management performance was far above industry 'Best Practice'. This may be explained by evaluating the analysis in both Figure 2 and Table 4 – furniture forms the largest waste category in terms of tonnage, 100% of Project B's furniture is reused resulting in significant emissions being prevented.

Insert Table 4 here

Figure 2 shows that the greatest contribution of emissions in Project A is attributed to managing floor coverings, plastic and packaging waste. The emissions from packaging and plastics are shown to contribute particularly large proportions to the overall emission profile in relation to the proportion that these wastes make up the overall waste tonnage – indicating that that these categories of waste may pose particular GHG impact risks. Column three for Project A demonstrates that the overall GHG impact of the project is largely linked to its landfill and recycling waste management activities, although emissions are also prevented through the waste reuse management activities.

Figure 2 also demonstrates that Project C generates the greatest levels of waste in relation to the GIFA. This performance is shown to be a direct consequence of Project C's emphasis on using a landfill as the predominant waste management pathway (Table 4). Calculated emissions generated through diverting furniture, timber and metals to landfill are shown to have large GHG impacts. There were no calculated emission savings generated by Project C as a consequence of there being no waste reuse activities.

3.3. Environmental Performance Benchmarking

Table 5 presents results where each Project's performances are evaluated against the criteria of the relevant BREEAM Credit, 'Wst 01 Project Waste Management'. Up to four credits may be awarded for minimising the levels of waste generated, and a further two credits are potentially available for diverting waste from landfill (BRE, 2014). Table 5 documents the specific performance criteria needed to achieve each credit, the levels of performance calculated for each project and finally the number of credits that would have been awarded.

Insert Table 5 here

Project A would achieve one of the four available credits for waste generation and zero credits for diversion to landfill; Project B would achieve two credits in both assessment themes; Project C would achieve just one credit for minimising the levels of waste generated. Project B's four overall credits made it the best performing project, which reflected its leading performance in the GHG analysis. Project A and B scored one credit each, which does not accurately reflect the discrepancy in GHG performance calculated between the projects – Project A's waste management strategy generating almost half the comparative emissions compared to project C.

4. GHG Emission Lessons for Waste Management Strategies

4.1. The Waste Hierarchy & its Influences on Environmental Performance

The environmental and emission performance of each project's waste management strategies were used to evaluate the success of the 'waste management hierarchy', testing the notion that the more waste reused ensured less waste to be diverted to landfill, and improved environmental and emission performance. To add greater context to the performance of the case study projects, waste recovery from UK refurbishment projects were reported to be 89.9% (DEFRA, 2018). Table 4 documented that the case studies achieved the overall recovery from landfill rates of 72.4% in Project A, 99.2% in Project B and only 1.8% in Project C. The success of the waste management hierarchy may initially be promoted using the example of Project C, where reliance on landfill as the primary waste management pathway resulted in calculated emission and environmental performances being far below levels that may be expected for 'Standard Practice'.

4.2. Varying Emission Risks from Different Waste Streams

Figure 2 and Table 5 depicts the differentiation that exists between the potential emissions risks associated with different categories of wastes. For example, plastics were relatively minor waste streams within each project in relation to the overall tonnage of waste generated, yet the emissions generated through the management of plastic waste were proportionally large given the extent of the waste being managed. Inversely, aggregates and bricks wastes provided significant contributions to the overall tonnage of waste generated, yet the waste management of these waste results in proportionally insignificant levels of emissions. This trend is supported across literature, for example, the US Environment Protection Agency highlighted that the emission factor associated with sending certain plastics to landfill may generate over 3,000 times more emissions in terms of kg CO_2 released compared to sending a tonne of aggregate to landfill (EPA, 2006). Such discrepancies and increased emission risks associated with certain categories of waste means there is great scope for variations in waste management emission performance between projects - potential risks where the landfilling of high emission impact categories of waste may offset any benefits gained through reusing and recycling other categories of waste. This dynamic is clearly highlighted in Figure 2 by the analysis for Project C. The largest waste category for Project C is aggregate/hardcore/inert and the data presented shows that all the waste was sent to landfill. However, the GHG calculations showed that almost zero of GHG emissions came from the landfilled aggregate, the emissions coming from the far less abundant materials landfilled alongside the aggregate waste category.

4.3. Questions for Legislation and Environmental Benchmarking Schemes

This poses potential problems and questions for legislation (eg. EC Waste Directive) and sustainability benchmarking schemes (eg. BREEAM), where success is awarded for 'blanket success' of diverting waste from landfill. There is a need for a greater focus to prevent specific categories of waste from the landfill pathway to increase emission performances. The research results can be used to highlight this problem – Table 5 demonstrated that Project B would have scored the most BREEAM credits and with the least emission impact. However, Project A and C scored the same in terms of BREEAM credits despite Project A performing much better in terms of calculated emission performance. This poses doubts if environmental assessment and benchmarking schemes, such as BREEAM, may not be sufficient for assessing multiple factors such as the levels of waste generated, the waste diverted from landfill and the subsequent emission performances of the waste management strategy.

5 Conclusion

This research presented analysis of waste management performances of three case studies of higher education student accommodation refurbishment projects in the UK. The projects were evaluated in terms of types and scales of waste generated, how the wastes were managed, and how waste performances compare to the refurbishment industry standards for 'standard', 'good' and 'best' practice. Analysis was undertaken to calculate the emission performance of each project's adopted waste management strategies through applying emission factors, and each project was assessed against the relevant criteria of the BREEAM environmental assessment and benchmarking methodology. A number of lessons may be drawn from the research conclusions in order to reduce the GHG impact of refurbishment waste management strategies:

- There is a disconnect between waste targets, legislation and sustainability benchmarking schemes that measure success based on the levels of diverting waste from landfill, and the emission performance of waste management strategies. For example, this research highlights that achieving high levels of performance against targets such as those defined by the EC's Waste Directive or the criteria of BREEAM credits does not guarantee a low emission waste management strategy.
- Due to the varying emission factors associated with the management of different categories of waste, it is more important to ensure that specific wastes are diverted from landfill. Sending high emission risk categories of waste to landfill such as plastics may offset any benefits gained through reusing and recycling other categories of waste.

Acknowledgements

This research is supported by InnovateUK (Technology Strategy Board) Knowledge Transfer Partnership (KTP008158); and the EPSRC, BBSRC and UK Supergen Bioenergy Hub (EP/S000771/1).

References

Biolek, V. and Hanak, T. 2019. LCC estimation model: A construction material perspective. *Buildings*. 9(8), 182

BREEAM (2020), *BREEAM Technical Standards*, Build Research Establishment. https://www.breeam.com/discover/technical-standards/ [Date accessed 11/1/2020]

Brandon, P. and Lombardi, P., 2011. *Evaluating Sustainable Development in the Built Environment*, 2nd Edition. New Jersey: Wiley-Blackwell.

BRE, 2014. *BREEAM UK Refurbishment and Fit-out 2014 - Non-Domestic Buildings*. Watford: Building Research Establishment.

Buyle, M., Galle, W., Debacker, W. and Audenaert, A. 2019. Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*, 218, 141-156.
CASBEE, 2020. *CASBEE Homepage*. Comprehensive Assessment System for Built Environment Efficiency http://www.ibec.or.jp/CASBEE/english/ [Date accessed 11/1/2020]
de Larriva, R.A., Rodríguez, G.C., López, J.M.C., Raugei, M. and Palmer, P.F. 2014. A decision-making LCA for energy refurbishment of buildings: Conditions of comfort. *Energy and Buildings*, 70, 333-342.
DEFRA, 2018. *UK Statistics on Waste*. London: Department for Environment, Food & Rural Affairs.
DEFRA, 2020. *UK Statistics on Waste*. London: Department for Environment, Farming and Rural Affairs.
Dixit, M.K. 2019. Life cycle recurrent embodied energy calculation of buildings: A review. *Journal of Cleaner Production*. 209, 731-754.
EPA, 2006. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks Report*. Washington: United States Environmental Protection Agency.
European Commission, 2008. *Directive on Waste*. Brussels: European Union.
European Commission, 2012. *Best Environmental Management Practice for the Building and Construction Sector*. Brussels: European Union.
European Commission. 2018. EU Construction and Demolition Waste Protocol and Guidelines. Brussels: European Union.
Ferreira, J., Pinheiro, M.D. and de Brito, J. 2013. Refurbishment decision support tools review. Energy and life cycle as key aspects to sustainable refurbishment projects. *Energy*, 62, 1453-1460.
Hammond, E. 2013. *Student Housing is Top Property Asset*, Financial Times. http://www.ft.com/cms/s/0/8c28a348-2691-11e2-9295-00144feabdc0.html [Data accessed 15/3/2017]
HMRC, 2016. *Excise notice AGL1: Aggregates Levy*. London: HM Revenue & Customs.
HQE. 2020. *HQE Homepage*, Haute Qualité Environnementale (HQE) http://www.behqe.com/cerway/essentials [Data accessed 11/1/2020]
HKGBC. 2020. *Building Environmental Assessment Method (BEAM) Plus*, Hong Kong Green Building Council. https://www.hkgbc.org.hk/eng/beam-plus/beam-plus-new-buildings/ [Data accessed 11/1/2020]
Kibert, C., 2005. *Sustainable Construction: Green Building Design and Delivery*. New Jersey: John Wiley & Sons.
KnightFrank and UCAS. 2018. *Student Accommodation Survey 2018/2019*, London.
Llatas, C. and Osmani, M. 2016. Development and validation of a building design waste reduction model. *Waste Management*, 56, 318-336.
Lou, E.C.W., Lee, A. and Welfle, A., 2017. Greenhouse gases (GHG) performance of refurbishment projects - Lessons from UK higher education

student accommodation case studies. *Journal of Cleaner Production,* 154, 309-317.
NAEI, 2016. *Emissions Factors Database*. London: National Atmospheric Emissions Inventory.
Palacios-Munoz, B., Peuportier, B., Gracia-Villa, L. and Lopez-Mesa, B. 2019. Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach. *Building and Environment*. 160, 106203.
Schwartz, Y., Raslan, R. and Mumovic, D. 2018. The life cycle carbon footprint of refurbished and new buildings - A systematic review of case studies. *Renewable and Sustainable Energy Reviews*. 81(1), 231-241.
Streicher, K.N., Mennel, S., Chambers, J., Parra, D. and Patel, M.K. 2020. Energy and Buildings Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. *Energy and Buildings*. 109870.
UKGBC, 2017. *Resource Use*. London: UK Green Building Council.
UKGBC, 2020. *Climate Change.* London: UK Green Building Council. https://www.ukgbc.org/climate-change/ [Data accessed 10/1/2020]
UNFCCC, 1998. *Kyoto Protocol to the United Nations Framework Convention on Climate Change.* Kyoto: United Nations.
UNFCCC, 2015. *Paris Agreement*. Bonn: United Nations.
USGBC, 2020. *USGBC Homepage*, United States Green Building Council http://www.usgbc.org/ [Data accessed 11/1/2020]
Welfle, A., Gilbert, P., Thornley, P. and Stephenson, A. 2017. Generating low-carbon heat from biomass: Life cycle assessment of bioenergy scenarios. *Journal Cleaner Production*. 149, 448-460.
Welfle, A.J. 2009. Introducing BREEAM for Healthcare. *Health Estate,* 63, 57-59.
WRAP, 2007. *Waste Recovery Quick Wins*. Banbury: Waste and Resources Action Plan.

Table 1: Basic Characteristics of the Case Study Projects

Details	Case Study Project A	Case Study Project B	Case Study Project C
Project Location	Liverpool, UK	Leeds, UK	Leeds, UK
Project Brief	Developing 495 flats into contemporary accommodation with en-suite shower rooms, kitchen and lounge areas with new fit-out.	Phase 1 (Case Study B) and Phase 2 (Case Study C) refurbishment works of existing accommodation including; study rooms, kitchen areas, bathrooms/en-suites and block entrances.	
Building type	Low rise apartment blocks of 5 stories high. No lifts installed.		
Distance from Site to Head Office (km)	168	264	264
Project Duration (weeks)	57	10	9
Gross Internal Floor Area (GIFA) (m^2)	17,805	5,100	5,850
Rooms	495	210	258
Project Value	£4,100,000	£1,160,000	£1,170,000
Total Waste (t)	258.6	30.1	124.8

Table 2: Waste Generation and Waste Management Performance of each Case Study Project

Waste Resource	Case Study Project A					Case Study Project B					Case Study Project C				
	Waste (t)	Waste Management Strategy				Waste (t)	Waste Management Strategy				Waste (t)	Waste Management Strategy			
		RU	RC	RR	D		RU	RC	RR	D		RU	RC	RR	D
Bricks	1.2	-	0.84	-	0.16	3.3	-	1.0	-	-	-	-	-	-	-
Tiles & Ceramics	1.9	-	0.77	-	0.23	-	-	-	-	-	2.9	-	-	-	1.0
Glass	-	-	-	-	-	-	-	-	-	-	0.3	-	-	-	1.0
Aggregates/Hardcore/Inert	21.4	-	0.82	-	0.18	1.8	-	1.0	-	-	49.6	-	-	-	1.0
Insulation/Fabrics	7.3	-	-	-	1.0		-	-	-	-	0.4	-	-	-	-
Metal	1.7	-	0.84	-	0.16	0.9	-	1.0	-	-	6.1	-	-	-	1.0
Packaging	34.1	-	0.83	-	0.17	0.9	-	1.0	-	-	0.8	-	-	-	1.0
Gypsum/Plasterboard	-	-		-		0.5	-	1.0	-	-	2.3	-	-	-	1.0
Plastic	9.9	-	0.65	-	0.35	1.0	-	1.0	-	-	1.1	-	-	-	1.0
Timber	26.4	-	0.76	-	0.24	0.01	-	1.0	-	-	11.0	-	-	-	1.0
Floor Coverings (soft)	51.7	-	0.38	-	0.62	-	-	-	-	-	-	-	-	-	-
Electrical & Electronic Equipment	-	-	-	-	-	2.0	-	1.0	-	-	5.0	-	-	-	1.0
Furniture	61.5	0.41	0.59	-	-	19.0	0.47	0.53	-	-	40.0	-	-	-	1.0
Canteen/Office/Adhoc Waste	-	-	-	-	-	-	-	-	-	-	2.9	-	0.78	-	0.22
Other	41.6	-	0.72	-	0.28	0.8	-	0.58	-	0.42	2.3	-	-	-	1.0
Total Waste (t)	258.6	25.9	160.3	-	72.4	30.1	9.0	11.1	-	0.3	124.8	-	2.5	-	122.3

Waste - Total waste (t) generated by project.
RU - Proportion (%) waste reused.
RC - Proportion (%) waste recycled
RR - Proportion (%) waste recovered.
D - Proportion (%) waste disposed through a landfill waste management strategy.

Table 3: Comparing Waste Management Performance Against Industry Benchmarks for Standard, Good and Best Practice

	Diversion of Waste from Landfill (%)					
Waste Resource	**Case Study Project A**	**Case Study Project B**	**Case Study Project C**	**Standard Practice**	**Good Practice**	**Best Practice**
	Project Data	Project Data	Project Data	(WRAP, 2007)	(WRAP, 2007)	(WRAP, 2007)
Bricks	0.84	1	-	0.75	0.85	1
Tiles & Ceramics	0.77	-	0.00	0.75	0.85	1
Glass	-	-	0.00	0.75	0.95	1
Aggregates/Hardcore/Inert	0.82	1	0.00	0.75	0.85	1
Insulation/Fabrics	0.00	-	0.00	0.12	0.5	0.75
Metal	0.84	1	0.00	0.95	1	1
Packaging	0.83	1	0.00	0.6	0.85	0.95
Gypsum/Plasterboard	-	1	0.00	0.3	0.9	0.95
Plastic	0.65	1	0.00	0.6	0.8	0.95
Timber	0.76	1	0.00	0.57	0.9	0.95
Floor Coverings (soft)	0.38	-	-	0.12	0.5	0.75
Electrical & Electronic Equipment	-	1	0.00	0.5	0.7	0.95
Furniture	1	1	0.00	0.1	0.25	0.5
Canteen/Office/Adhoc Waste	-	-	0.78	0.12	0.5	0.75
Other	0.72	0.58	0.00	0.12	0.5	0.75

Proportion of waste diverted to landfill below the WRAP levels for 'standard practice'.

Proportion of waste diverted to landfill achieving WRAP levels for 'standard practice'.

Proportion of waste diverted to landfill achieving WRAP levels for 'good practice'.

Proportion of waste diverted to landfill achieving WRAP levels for 'best practice'.

Table 4: Breakdown of Emissions Attributed to the Different Categories of Waste & Project Waste Management Pathways

Waste Resource	Emission Breakdown Attributed to Waste Management Pathways (tCO_2)											
	Case Study Project A				Case Study Project B				Case Study Project C			
	Reuse	Recycle	Recover	Dispose	Reuse	Recycle	Recover	Dispose	Reuse	Recycle	Recover	Dispose
Bricks	-	0.003	-	0.041	-	0.009	-	-	-	-	-	-
Tiles & Ceramics	-	0.004	-	0.089	-	-	-	-	-	-	-	0.603
Glass	-	-	-	-	-	-	-	-	-	-	-	0.306
Aggregates/Hardcore/Inert	-	0.025	-	0.007	-	0.003	-	-	-	-	-	0.088
Insulation/Fabrics	-	-	-	13.591	-	-	-	-	-	-	-	-
Metal	-	1.595	-	0.897	-	0.981	-	-	-	-	-	20.625
Packaging	-	31.028	-	11.999	-	0.954	-	-	-	-	-	1.757
Gypsum/Plasterboard	-	-	-	-	-	0.078	-	-	-	-	-	0.446
Plastic	-	17.056	-	11.505	-	2.687	-	-	-	-	-	3.675
Timber	-	3.812	-	10.239	-	0.001	-	-	-	-	-	17.743
Floor Coverings (soft)	-	11.227	-	39.246	-	-	-	-	-	-	-	-
Electrical & Electronic Equipment	-	-	-	-	-	1.143	-	-	-	-	-	6.123
Furniture	-27.599	20.748	-	-	-9.771	5.756	-	-	-	-	-	48.985
Canteen/Office/Adhoc Waste	-	0.000	-	-	-	0.000	-	-	-	1.295	-	0.782
Other	-	17.121	-	14.265	-	0.249	-	0.386	-	-	-	2.841
Totals	-27.599	102.620	-	101.878	-9.771	11.860	-	0.386	-	1.295	-	103.976

Table 5: *Calculated Project Performance for BREEAM Credit Wst 01 – Project Waste Management*

<table>
<tr><th colspan="8">Generation of Waste</th></tr>
<tr><td rowspan="3">BREEAM Credits</td><td rowspan="2">Required Performance *</td><td colspan="6">Project Performance</td></tr>
<tr><td>Case Study A</td><td>Case Study B</td><td>Case Study C</td><td>Case Study A</td><td>Case Study B</td><td>Case Study C</td></tr>
<tr><td colspan="4">Total Waste Generated (t / 100m² GIFA)</td><td colspan="3">Potential BREEAM Credits Achieved</td></tr>
<tr><td>1</td><td>≤ 3.5</td><td rowspan="4">1.45</td><td rowspan="4">0.59</td><td rowspan="4">2.13</td><td rowspan="4">1</td><td rowspan="4">2</td><td rowspan="4">1</td></tr>
<tr><td>2</td><td>≤ 1.2</td></tr>
<tr><td>3</td><td>≤ 0.4</td></tr>
<tr><td>4</td><td>≤ 0.3</td></tr>
<tr><th colspan="8">Diversion of Waste from Landfill</th></tr>
<tr><td rowspan="3">BREEAM Credits</td><td rowspan="2">Required Performance **</td><td colspan="6">Project Performance</td></tr>
<tr><td>Case Study A</td><td>Case Study B</td><td>Case Study C</td><td>Case Study A</td><td>Case Study B</td><td>Case Study C</td></tr>
<tr><td colspan="4">Proportion of Waste Diverted from Landfill (%)</td><td colspan="3">Potential BREEAM Credits Achieved</td></tr>
<tr><td>1</td><td>90%</td><td rowspan="2">28%</td><td rowspan="2">1%</td><td rowspan="2">98%</td><td rowspan="2">0</td><td rowspan="2">2</td><td rowspan="2">0</td></tr>
<tr><td>2</td><td>97%</td></tr>
<tr><td>*</td><td colspan="7">Criteria detailed in Table 61 of the BREEAM 2014 Manual (BRE, 2014)</td></tr>
<tr><td>**</td><td colspan="7">Criteria detailed in Table 63 of the BREEAM 2014 Manual (BRE, 2014)</td></tr>
</table>

Equation 1: Calculating the GHG Impact of Refurbishment Waste Management Practices

$$\text{GHG Impact of Waste Management Pathways} = \underset{(t)}{QW} \times \underset{(\%)}{WMP} \times \underset{(tCO_{2eqv.}/t\ waste)}{EF}$$

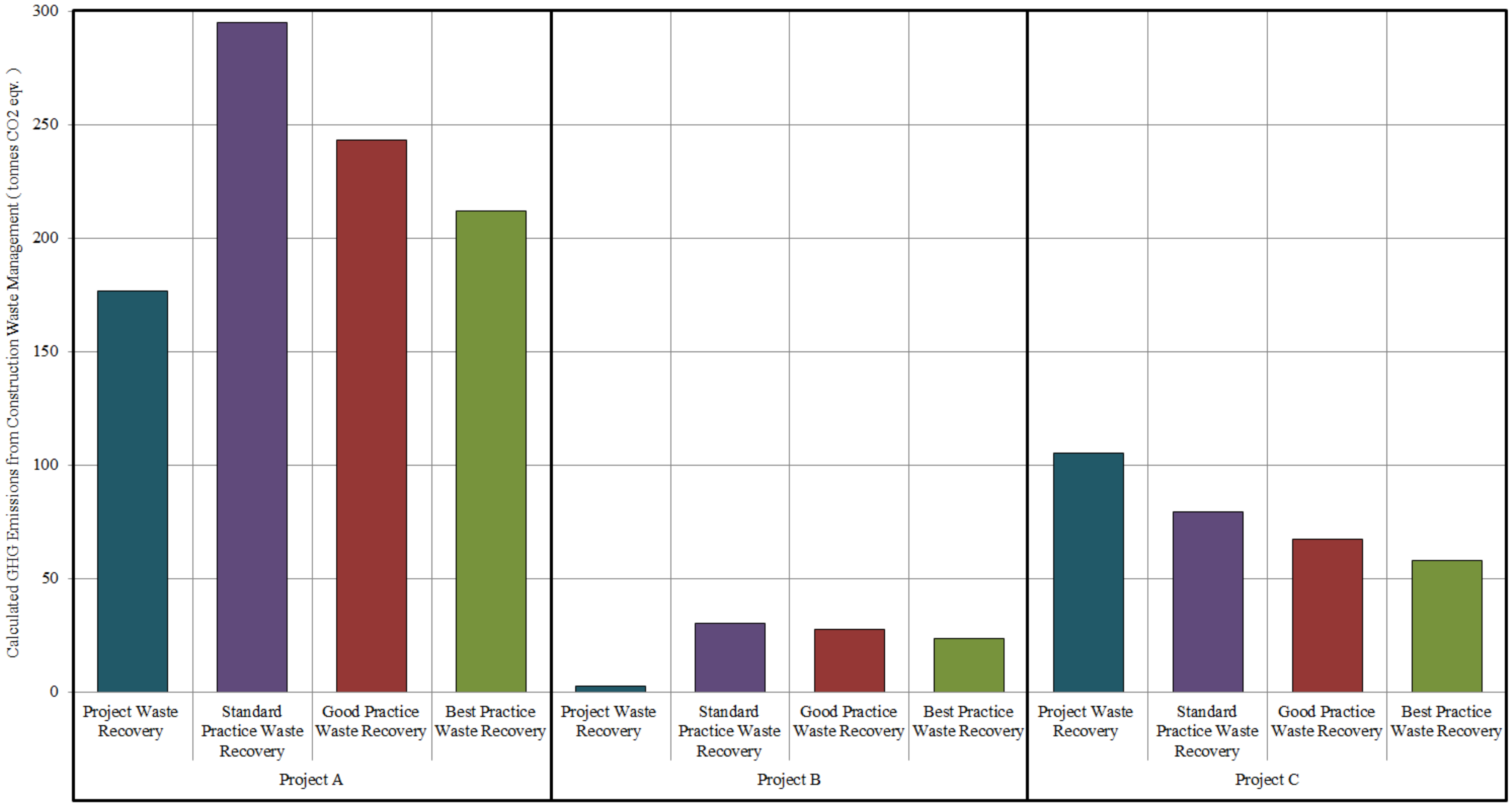

Figure 1: *GHG performance of the Case Study Project's waste management strategies, compared to calculated industry benchmarks for standard, good and best practice*

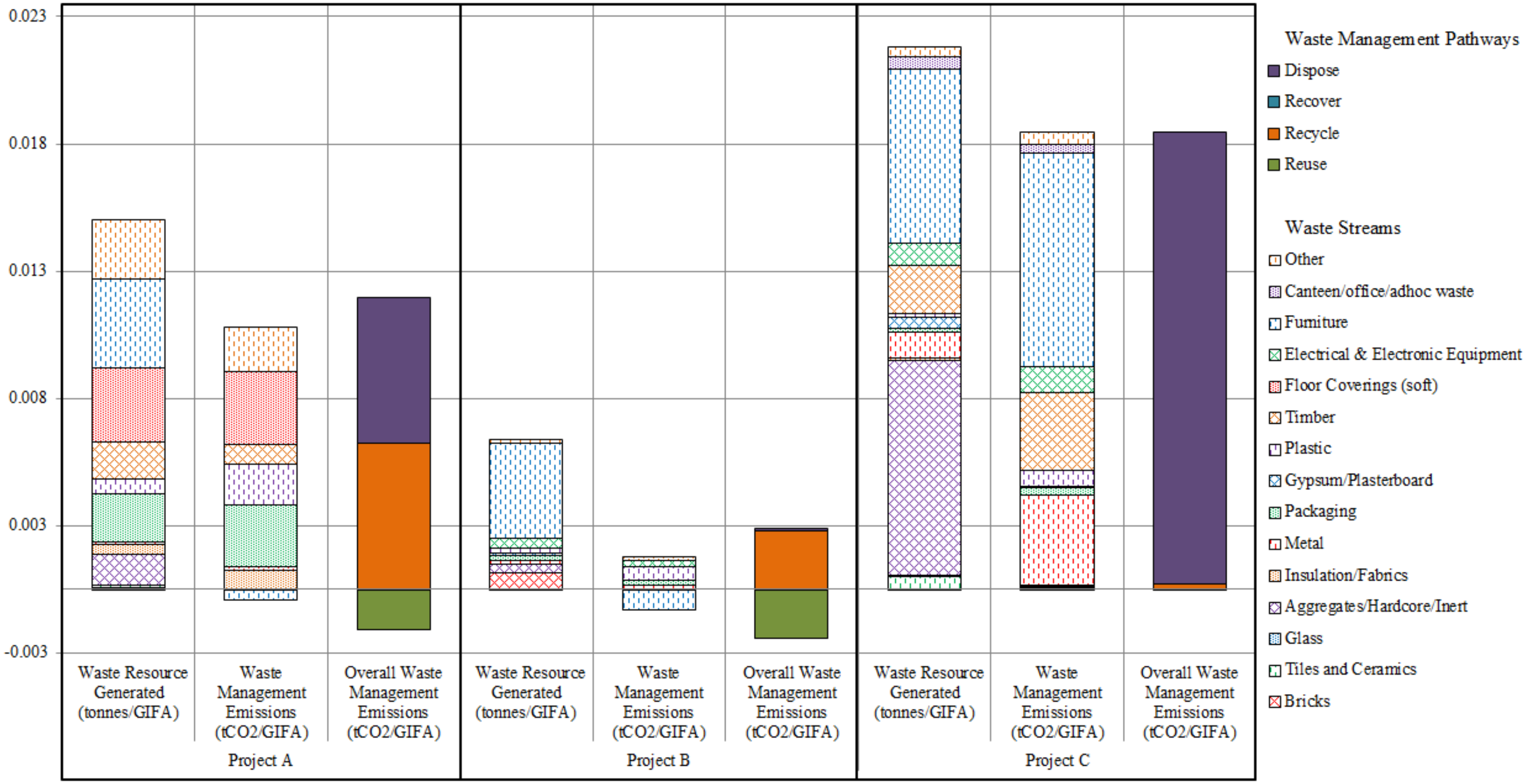

Figure 2: *Comparison of the types and scales of waste generated, the calculated GHG impact of managing these wastes and the overall GHG impact attributed to waste management pathways*