Building and Environment 54 (2012) 86–99

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Environmental impacts of the UK residential sector: Life cycle assessment of houses

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ARTICLE INFO

Article history:
Received 3 November 2011
Received in revised form
12 January 2012
Accepted 6 February 2012

Keywords:
Housing sector
Life cycle assessment
Carbon footprint
Building materials

ABSTRACT

This paper presents for the first time the results of a full life cycle assessment (LCA)[1] study for the three most common types of house in the UK: detached, semi-detached and terraced. All life cycle stages are considered, including house construction, use and demolition after 50 years. The results indicate that the use stage has the largest contribution to most environmental impacts. For example, the global warming potential (GWP)[2] over the 50-year lifetime of the detached house is 455 t of CO_2 eq.; 374 t CO_2 eq. of the semi-detached; and 309 t CO_2 eq. of the terraced house. Around 90% of the GWP is from the use, 9% from construction (embodied carbon) and 1% from the end-of-life waste management. A similar trend is noticed for all other impacts. Recycling the building materials at the end of life leads to an overall reduction of the impacts. For instance, the GWP reduces by 3% for the detached and semi-detached houses (to 441 t of CO_2 eq. and 363 t CO_2 eq., respectively) and by 2% (to 302 t CO_2 eq.) for the terraced house. The main environmental benefit is from reusing the bricks and recycling the aggregates. At the housing sector level, the total GWP is 132 million tonnes of CO_2 eq. per year with the semi-detached houses contributing 40%, terraced 37% and detached houses 27%. Over the 50-year lifetime, the total GWP from the sector is nearly 6.6 billion tonnes of CO_2 eq. The results also highlight the importance of decisions made in the design and construction stages as they determine the impacts of the house in the use and end-of-life stages.

1. Introduction

The construction industry plays an important role in meeting different human needs, including provision of housing, hospitals and transport infrastructure. However, these needs are provided at the expense of intensive use of mineral resources and energy as well as waste generation. For example, in the UK over 200 million tonnes of minerals are extracted and consumed by the sector each year, representing 84% of the country's annual mineral extraction [1]. Furthermore, the residential housing sector consumes around 500 million MWh/yr of energy [2], contributing 158 million tonnes of CO_2 eq./yr or 28% of the UK annual carbon emissions [1,3]. In addition, the sector produces over 100 million tonnes or 33% of waste per year [4]. As a result, the construction industry contributes significantly to different environmental impacts including global warming and natural resource depletion [5].

A number of Life Cycle Assessment (LCA) studies have been conducted to estimate the environmental impacts from the construction sector. In Europe these include studies of office buildings [6,7], universities [8,9], apartment buildings [10,11] and houses [12–19]. As far as the authors are aware, only four LCA studies have been conducted in the UK housing sector; however, neither considered the full life cycle from 'cradle to grave' or the full range of impacts normally included in LCA. For example, Monahan and Powell [17] considered the construction stage only and estimated the embodied carbon of a three bedroom semi-detached low-energy house in England while Asif et al. [13] determined the embodied energy and the associated emissions of CO_2, NO*x*, and SO*x* of the construction materials used for a three bedroom semi-detached house in Scotland. Hammond and Jones [16] considered several houses and apartments across the UK but also estimated only the embodied energy and carbon. However, neither study considered the use and end-of-life stages. The fourth study [15] went further by considering carbon emissions from both the construction and use stages for a two bedroom semi-detached house in England; however, the end of life of the house was not considered.

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[1] Life cycle assessment.
[2] Global warming potential.

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doi:10.1016/j.buildenv.2012.02.005

Table 1
General information on the three types of house under study.

	Detached house	Semi-detached house	Terraced house	Data sources
Number of bedrooms	4 bedrooms	3 bedrooms	2 bedrooms	[27]
Number of floors	2	2	2	—II—
Construction type	Traditional build: brick and block	Traditional build: brick and block	Traditional build: brick and block	—II—
Typical usable floor area (m^2)	130	90	60	[26]
Household size (no. of people)	2.3	2.3	2.3	[21]
Indoor temperature (°C)	19	19	19	[21,26]
Air exchange rate (1/h)	1	1	1	[26]
Specific heat loss (W/K)	220	170	120	[21, 26]

This study aims to contribute towards a better understanding of the full LCA impacts of the housing sector[3] in the UK by focussing on the existing stock and the most common types of house. The bulk of the existing housing stock is brick-built and is quite old and energy inefficient [20] so the environmental impacts could be quite significant. The most common types of house are detached, semi-detached and terraced. Together, they represent 72% of the stock, housing 18 million households; semi-detached and terraced houses each account for 28% and detached houses for the remaining 16% of the residential sector [21].

The following sections present and compare the life cycle impacts of each type of the house from 'cradle to grave'. This is followed by a discussion of the environmental impacts of the UK housing sector as a whole. It is hoped that the results of this work will be useful for a range of stakeholders, including house designers, developers and owners as well as policy makers.

2. Life cycle assessment of UK houses

This LCA study follows the ISO 14040/44 methodology [22,23]. The LCA modelling has been carried out in GaBi V4.3 [24] and the CML 2001 method [25] has been used to estimate the environmental impacts.

2.1. Goal and scope of the study

The goal of the study is to estimate the life cycle environmental impacts of typical types of house in the UK: detached, semi-detached and terraced house. These results are then used to estimate the overall impacts from the UK housing sector with the aim of identifying the hot spots and improvement opportunities along the supply chain.

The functional unit is defined as the 'construction and occupation of a house over its lifetime'. The lifetime of a house depends on many factors, making it a difficult parameter to standardise. However, for research purposes, many authors (e.g. [10,12,14,18]) have assumed the life span of 50 years. Therefore, this lifetime has also been assumed in this study. The following typical usable floor areas are considered [26]:

- detached house: 130 m^2;
- semi-detached house: 90 m^2; and
- terraced house: 60 m^2.

It has also been assumed that each house is occupied by an average UK household size, consisting of 2.3 people [21]. Table 1 provides further information on the houses under study.

The life cycle of the three types of house is outlined in Fig. 1. As shown, it comprises three main stages: house construction, its use and end-of-life waste management. Construction involves extraction and manufacture of construction materials and fuels, transportation through the supply chain and construction of the house. The use stage includes water and energy consumption for space and water heating, cooking, lighting and domestic appliances. Maintenance activities such as replacement of windows, doors and floor covering are also considered. Finally, the end-of-life stage involves house demolition and waste management activities, such as reuse, recycling and landfilling of construction waste.

2.2. System description, assumptions and data

General information for each type of house considered in this study is summarised in Table 1 and the floor plans are provided in Fig. 2. All houses have two floors (ground and first floor) and the layout is similar: the kitchen and living area are on the ground floor with the bathroom and the bedrooms on the first floor. In addition, the three houses have a pitched roof with fink truss and traditional strip footing foundations. The following sections provide an overview of the assumptions made for each house and the data estimation.

2.2.1. Construction stage

The types and quantities of material for the construction of each house have been calculated using construction guides and specifications [26], material specifications [28,29], direct observations and expert consultation. As shown in Table 2, it is estimated that 177 t of materials are used in the construction of the detached house, 135 t for the semi-detached and 89 t for the terraced house. The energy data for the construction machinery have been sourced from [12]. The total energy used in the construction of each house is estimated at 31.2 GJ for the detached, 21.6 GJ for the semi-detached and 14.4 GJ for the terraced house, respectively (see Table 3).

2.2.2. Use stage

Total energy use in different life cycle stages of each house is summarised in Table 3. As can be seen, over the lifetime of 50

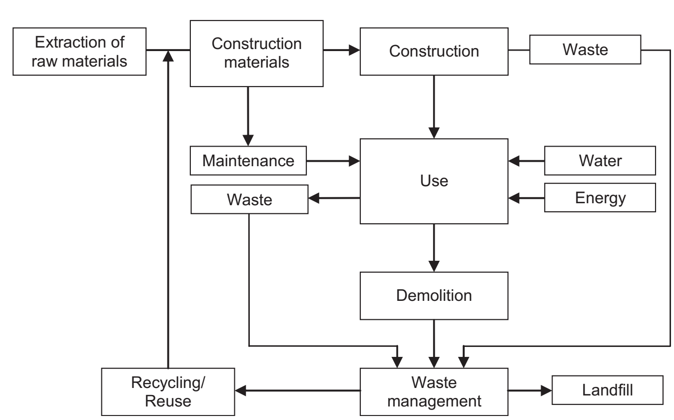

Fig. 1. System boundaries and life cycle stages considered for the three types of house (detached, semi-detached and terraced).

[3] For the purposes of this paper, the term 'housing sector' refers to houses only, excluding apartment buildings.

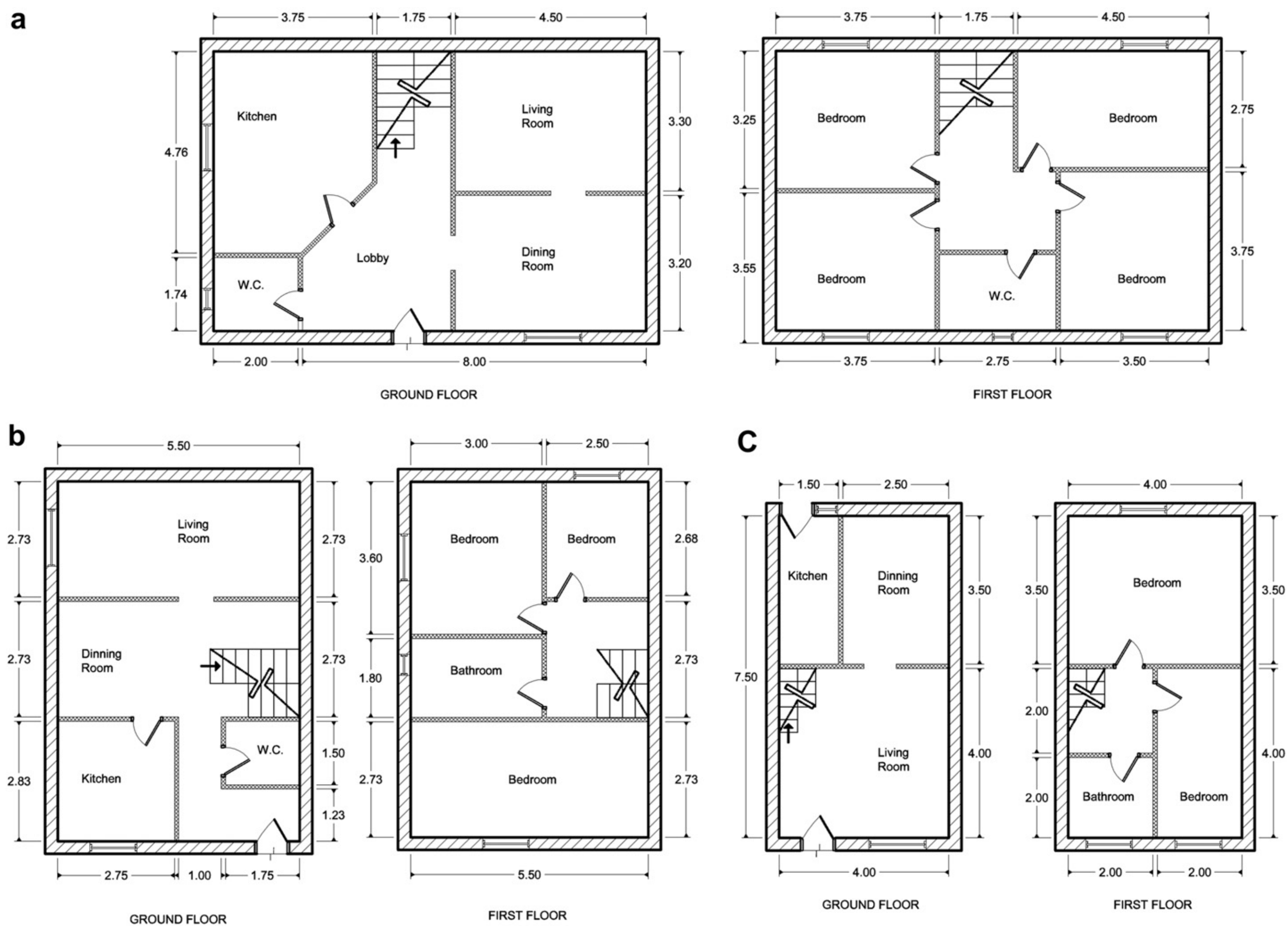

Fig. 2. Floor plans for the houses under study: (a) detached (b) semi-detached (c) terraced house.

years, the detached house consumes in total 4406 GJ of energy; semi-detached 3641 GJ and terraced 3026 GJ.

Energy consumption in the use stage has been calculated using the statistics for domestic energy use in the UK by fuel type (see Fig. 3 and Table 4) and own estimates of energy requirements for space and water heating, lighting, cooking and electrical appliances. The energy requirement for space heating has been calculated from the specific heat loss for each house (see Table 1), following the methodology suggested by Brinkley [26]. The data for water heating and cooking are based on the figures reported in Utley and Shorrock [21] and those for lighting and appliances are from Barker and Jenkins [30].

The average water use is assumed at 150 L per person per day [31] so that the total consumption over 50 years for each house is equivalent to 6280 m^3 of water. Table 5 gives the breakdown of water consumption by end use over the lifetime of the house.

The maintenance activities considered in the use stage involve replacing the windows, doors and floor coverings. The latter includes carpets in the bedrooms and the hallways, ceramic tiles in the bathrooms, toilets and kitchens, and laminated flooring in the living rooms. Table 6 shows the typical replacement intervals [28] which have been used in this study.

2.2.3. Demolition stage

End-of-life options have been analysed based on the destination of demolition waste in the UK (see Table 7). For the demolition activities, the data for the energy used by the demolition machinery have been sourced from Dewulf et al. [33], CRW [4] and Kohler and Davies [34]. System expansion has been used to credit the system for the burden avoided by the reuse and/or use of recycled materials. To avoid double counting, it is assumed that all the construction materials are manufactured from virgin raw materials.

As shown in Table 8, the following amounts of waste are generated by each house, including the waste generated from maintenance:

- detached: 181 t of waste, of which 43 t are reused, 124 t recycled and 14 t landfilled;
- semi-detached: 138 t of waste, of which 33 t are reused, 94 t recycled and 11 t are landfilled; and
- terraced: 91 t of waste, of which 21 t are reused, 62 t are recycled and 7 t are landfilled.

Note that the quantities of replacement components and materials used in the maintenance stage which are added to the total waste at the end of life are based on the inventory data in Table 2 and the replacement intervals in Table 6.

Table 2
Materials used for the construction of houses.

Element	Surface (m^2)			Components	Thickness (mm)	Amount (kg)		
	Detached	Semi-detached	Terraced			Detached	Semi-detached	Terraced
External wall	194	141	90	Brick (Imperial 9"), outer leaf	102.5	43,828	31,747	20,193
				Cement mortar	10	11,662	8447	5373
				Extruded polystyrene	75	510	292	96
				Concrete block (aerated), inner leaf	100	14,577	10,559	6716
				Plasterboard	12.5	1944	1408	895
				Gypsum plaster skimming	3	653	473	301
Internal wall	99	85	44	Brick (Imperial 9"), inner leaf	102.5	22,302	19,199	9809
				Cement mortar	10	5934	5108	2610
				Plasterboard	12.5	1978	1703	870
				Gypsum plaster skimming	3	665	572	292
Foundation	30	25	19	Brick (Imperial 9")	–	16,144	13,362	10,956
				Cement mortar	–	1044	870	726
				Concrete	–	19,615	16,157	13,094
First floor & ground-floor ceiling	62	43	28	Cement mortar	20	190	233	173
Bathroom	4.4	5.4	4	Timber floor boards	20	640	443	288
Bedrooms	58	39	24	Carpet (bedrooms)	–	30	21	12
				Ceramic floor tiles (bathroom)	–	70	86	64
				Mineral Wool	200	236	163	106
				Softwood timber (main beams and joists)	–	1104	767	504
				Plasterboard	12.5	621	430	280
				Gypsum plaster skimming	3	209	144	94
Ground floor	65	45	30	Ceramic floor tiles (kitchen/toilet)	–	303	162	84
Kitchen & toilet	25	10	5	Cement mortar	20	822	438	227
Living room	40	35	25	Laminated floor (living room)	–	264	227	161
				Concrete slab	100	15,600	10,824	7200
				Expanded Polystyrene	100	150	104	69
				Damp-proof membrane	–	16	11	8
				Sand and gravel	50	7280	5051	3360
Roof	75	52	35	Concrete tiles	–	3750	2602	1732
(timber structure)	81	54	38	Sarking felt	–	9	7	4
				Softwood timber (purlins, ridge and wall plates, rafter, battens and truss membranes)	–	2478	1668	1185
First floor ceiling	65	45	30	Softwood timber (joists)	–	78	54	38
				Mineral Wool	300	449	311	207
				Plasterboard	12.5	650	451	300
				Gypsum plaster skimming	3	218	152	101
Windows	13	10	8	U-PVC frame	–	254	207	167
				Double glazed panes	–	197	160	129
Interior doors	11	9	6	Hardwood timber	34	292	250	167
Exterior doors	3	3	3	Hardwood timber	44	121	121	121
				Total		**176,931**	**134,965**	**88,701**

2.2.4. Transport

All transport is assumed to be by road using 22 t trucks. The construction materials are assumed to be transported 50 km from the manufacturing gate to the construction site [18]. The materials used for maintenance are transported on average for 50 km to the house and the demolition waste for 30 km from the location of the house to its destination. Table 9 gives a breakdown of transport data for these three life cycle stages.

Table 3
Energy consumption for the three types of house over 50 years.

Activities	Amount (MJ)		
	Detached	Semi-detached	Terraced
Construction			
On-site construction	31,200	21,600	14,400
Use			
Space heating	2,820,000	2,160,000	1,602,000
Water heating	912,500	912,500	912,500
Cooking	103,500	103,500	103,500
Lighting	255,750	151,150	93,700
Appliances	314,360	314,360	314,360
Use total	4,406,110	3,641,510	3,026,060
End-of-life			
Demolition	14,500	10,000	6700
Total	4,451,810	3,673,110	3,047,160

2.2.5. Other data

The background life cycle inventory (LCI) data have been sourced from the Ecoinvent [35] and GaBi V4.3 [24] databases as well as various literature sources [2,12,14,18,21,26,28,31,33]. Where UK-specific LCI data have not been available, the data used from the databases have been adapted as far as possible to reflect the UK conditions, particularly with respect to the UK energy mix.

2.3. Impact assessment and interpretation of results

The results of impact assessment are shown in Figs. 4–6. These are discussed and compared for the three houses in the following sections.

2.3.1. Global warming potential

As shown in Figs. 4–7, the total GWP over the lifetime of the detached house is 455 t CO_2 eq.; for the semi-detached and terraced houses the equivalent values are 374 t CO_2 eq. and 309 t CO_2 eq., respectively. The large majority of the impact (90%) is from the use

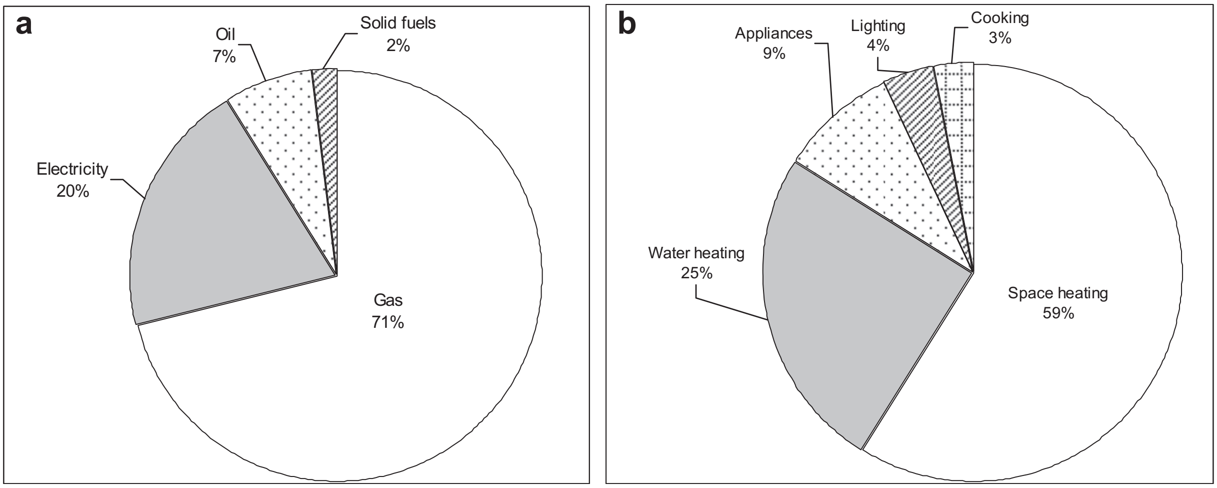

Fig. 3. UK energy consumption by fuel/energy type and end use [21,2]. (a) Energy consumption by fuel type (b) Energy consumption by end use.

Table 4
Domestic energy consumption by fuel and end use in the UK [21,2].

	Gas (%)	Oil (%)	Solid fuels (%)	Electricity (%)	*Total* (%)
Space heating	84	9	2	5	*100*
Water heating	80	7	1	12	*100*
Cooking	53.5	0.3	0.2	46	*100*
Lighting	0.1	–	–	99.9	*100*
Appliances	0.1	–	–	99.9	*100*

Table 5
Water consumption in the use stage over 50 years [31,32].

Activities	End use (%)	Volume (m^3)[a]
Personal hygiene	30	1890
W.C.	30	1890
Washing machine/dishwasher	21	1300
Housekeeping	8	500
Personal consumption	4	250
Gardening	4	250
Others	3	200
Total	**100**	**6280**

[a] Water consumption for all three types of house is the same due to the same size of household.

stage, with the construction contributing 9% and the end-of-life stage the remaining 1%. When the system is credited for the avoided burden due to the reuse and recycling of wastes, the total GWP reduces by 3% for the detached and terraced houses (to 440 t and 363 t CO_2 eq.), and by 2% for the terraced house (to 302 t CO_2 eq.). In that case, the average percentage contribution from each life cycle stage changes to 92% and 7% for the use and constructions stage respectively; the contribution of the end-of-life stage remains at 1%.

The detached house emits 47 t CO_2 eq. during the construction stage, while the semi-detached generates 36 t CO_2 eq. and the terraced house 23 t CO_2 eq. Figs. 8 and 9 show that the main contributors in the construction stage are the construction materials with bricks having the highest impact: 19 t CO_2 eq. for the detached, 15 t CO_2 eq. for the semi-detached and 9 t CO_2 eq. for the terraced house. However, when the system is credited for the

Table 6
Typical intervals for the main maintenance activities over 50 years [28].

Element/Material	Typical replacement interval (years)	Number of replacements over 50 years
Windows	25	1
Interior doors	20	2
Exterior doors	20	2
Carpet	5	9
Ceramic floor tiles	20	2
Laminated floor	20	2

Table 7
Destination of demolition waste in the UK [4,34].

Waste type	Reused (%)	Recycled (%)	Landfill (%)	*Total*
Concrete, binders and aggregates	–	100	–	*100*
Brick	51	36	13	*100*
Gypsum	–	100	–	*100*
Ceramic tiles	57	7	36	*100*
Insulation	18	–	82	*100*
Inert	15	15	70	*100*
Timber	2	79	19	*100*
U-PVC	–	50	50	*100*

Table 8
End-of-life waste management for the three types of house.

Waste category	Amount (kg)		
	Detached	Semi-detached	Terraced
Concrete, binders and aggregates	81,995	61,292	41,809
Bricks	82,281	64,295	40,950
Gypsum	6939	5331	3133
Ceramic tiles	934	619	369
Insulation	1360	882	485
Inert	704	533	388
Timber	6079	4428	3137
U-PVC	507	413	333
Total	**180,799**	**137,793**	**90,604**

Table 9
Transportation in the life cycle of the three types of house.

Life cycle stage	Transport (t km)		
	Detached	Semi-detached	Terraced
Construction	8400	6350	4000
Use (maintenance)	200	120	80
End of life	8500	6500	4200
Total	**17,100**	**12,970**	**8,280**

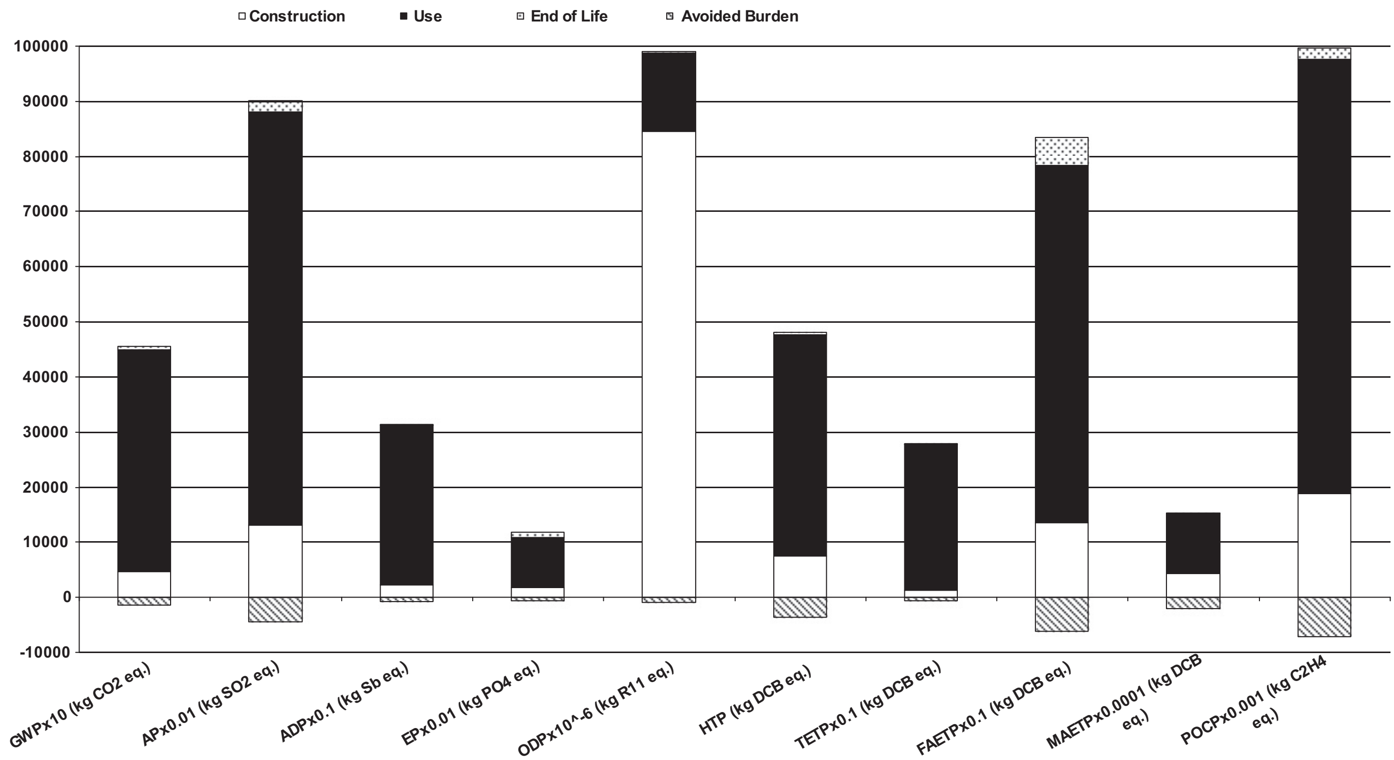

Fig. 4. Life cycle impacts of the detached house over the lifetime of 50 years showing the contribution of the life cycle stages. [The values for some impacts have been scaled to fit on the scale. The original (un-scaled) values can be obtained by multiplying the value shown on the *y*-axis by the scaling factor given in brackets for each impact. Impact categories: GWP: Global warming potential; AP: Acidification potential; ADP: Abiotic depletion potential; EP: Eutrophication potential; ODP: Ozone layer depletion potential, HTP: Human toxicity potential; TETP: Terrestrial ecotoxicity potential; FAETP: Freshwater aquatic ecotoxicity potential; MAETP: Marine aquatic ecotoxicity potential; POCP: Photochemical ozone creation potential].

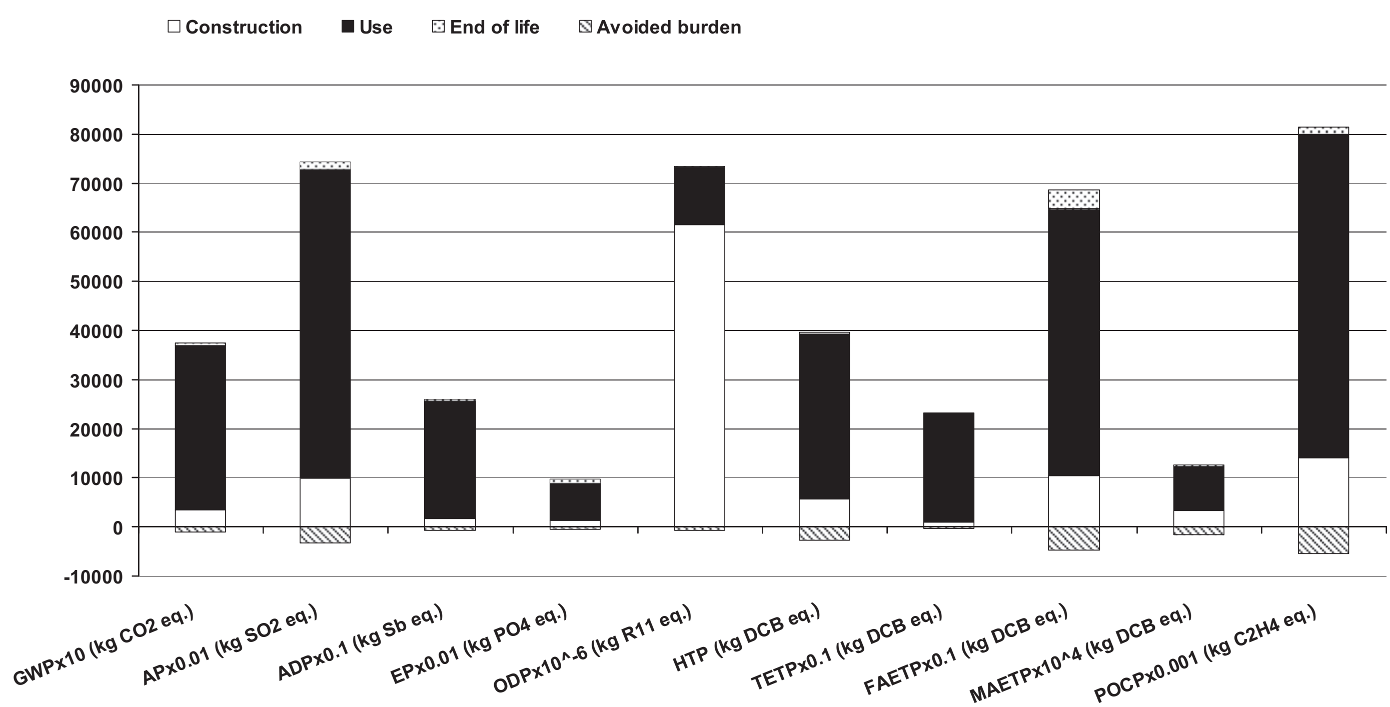

Fig. 5. Life cycle impacts of the semi-detached house over the lifetime of 50 years showing the contribution of the life cycle stages. [The values for some impacts have been scaled to fit on the scale. The original (un-scaled) values can be obtained by multiplying the value shown on the *y*-axis by the scaling factor given in brackets for each impact. For description of impact categories, see Fig. 4].

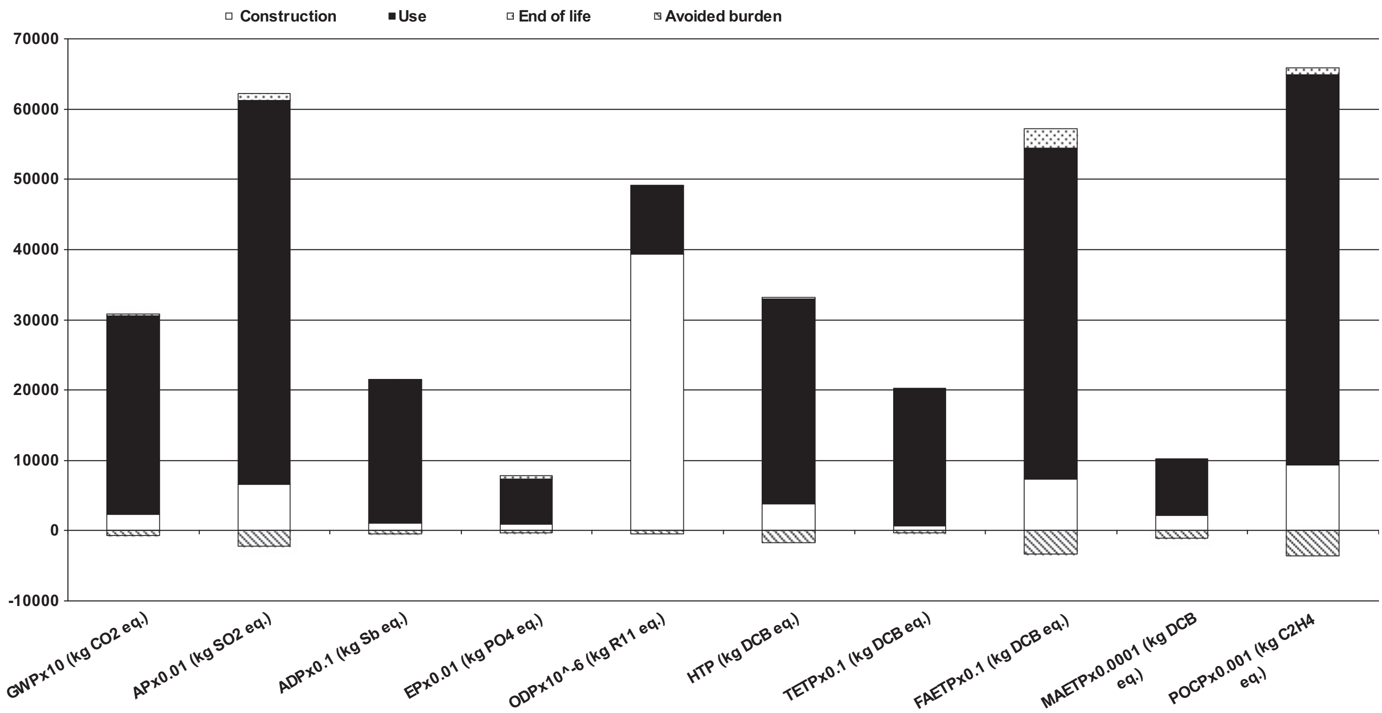

Fig. 6. Life cycle impacts of the terraced house over the lifetime of 50 years showing the contribution of the life cycle stages. [The values for some impacts have been scaled to fit on the scale. The original (un-scaled) values can be obtained by multiplying the value shown on the *y*-axis by the scaling factor given in brackets for each impact. For description of impact categories, see Fig. 4].

avoided burden, the GWP from the construction stage reduces on average by about 28% to 34 t, 25 t and 17 t CO_2 eq., for the three houses respectively.

As mentioned before, the use stage is by far the highest contributor to the total GWP (see Fig. 7): the detached house generates 403 t CO_2 eq. over 50 years, while the semi-detached produces 334 t CO_2 eq. and the terraced house 174 t CO_2 eq. Fig. 10 shows that space and water heating and domestic appliances are the main contributors from this stage, contributing between 83% (detached) and 88% (terraced house) of the total. The results

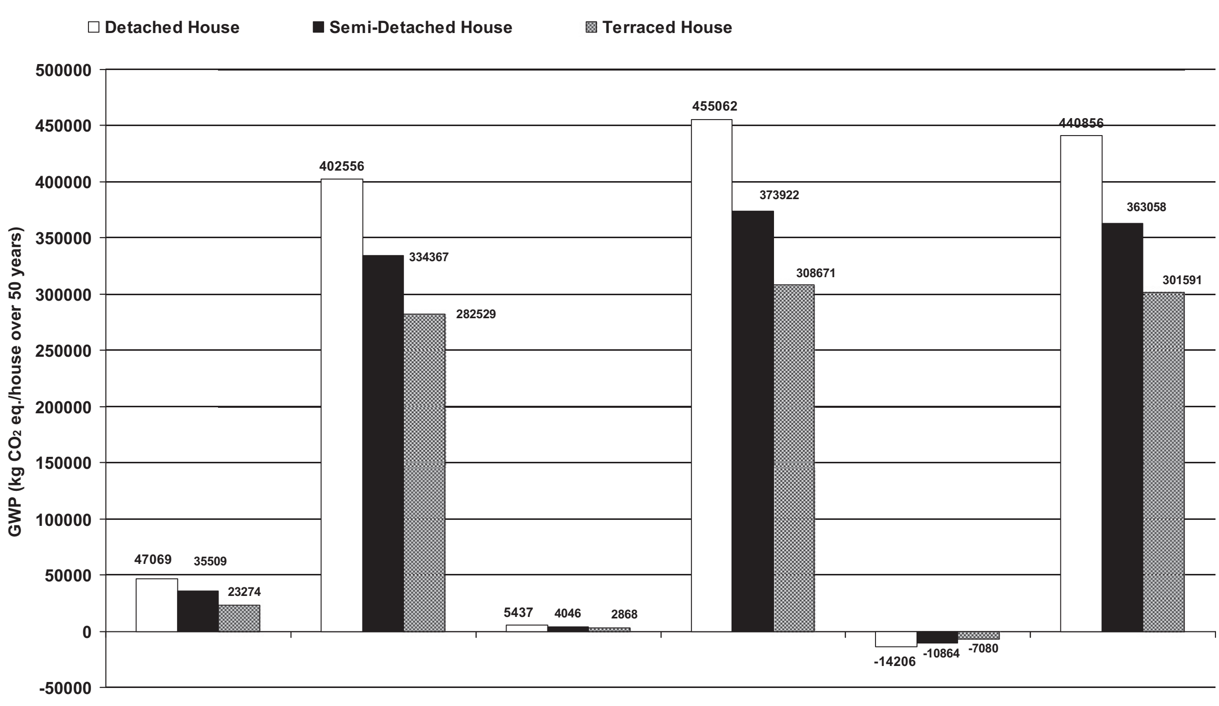

Fig. 7. GWP for the detached, semi-detached and terraced house over the lifetime of 50 years, showing the contribution of the life cycle stages.

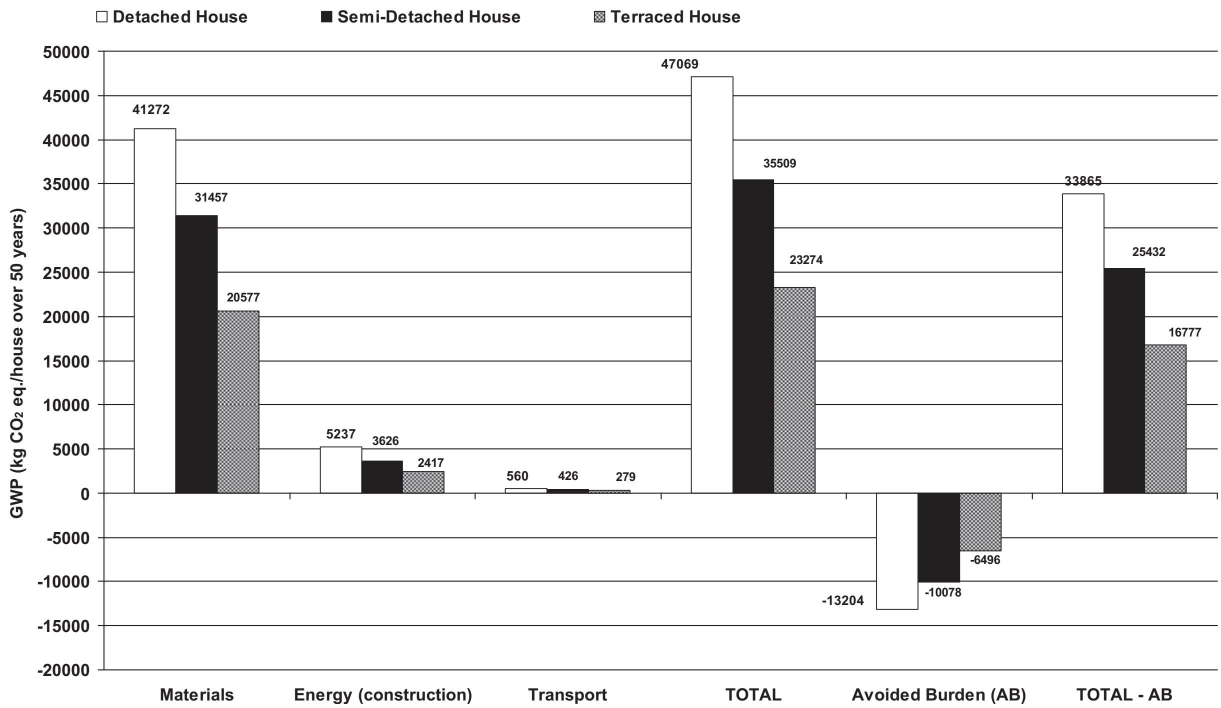

Fig. 8. GWP for the construction stage for the detached, semi-detached and terraced houses.

also indicate that the emissions arising from cooking, the appliances and water heating depend on the number of people residing in the house while emissions from space heating and lighting mainly depend on the physical properties of the house, e.g. size, type, materials, etc.

Finally, at the end of its useful life each house generates 5 t, 4 t and 3 t CO_2 eq., respectively, mainly due to the demolition activities and landfilling of construction waste (see Fig. 11). These contributions are thus negligible compared to the use and even the construction stage. Contribution of transport in the life cycle of the houses is also negligible; see Figs. 8, 10 and 11.

2.3.2. Other environmental impacts

A pattern similar to global warming can be observed for the other impact categories, with the use stage contributing most to all the impacts due to the energy consumption (Figs. 4–6). The

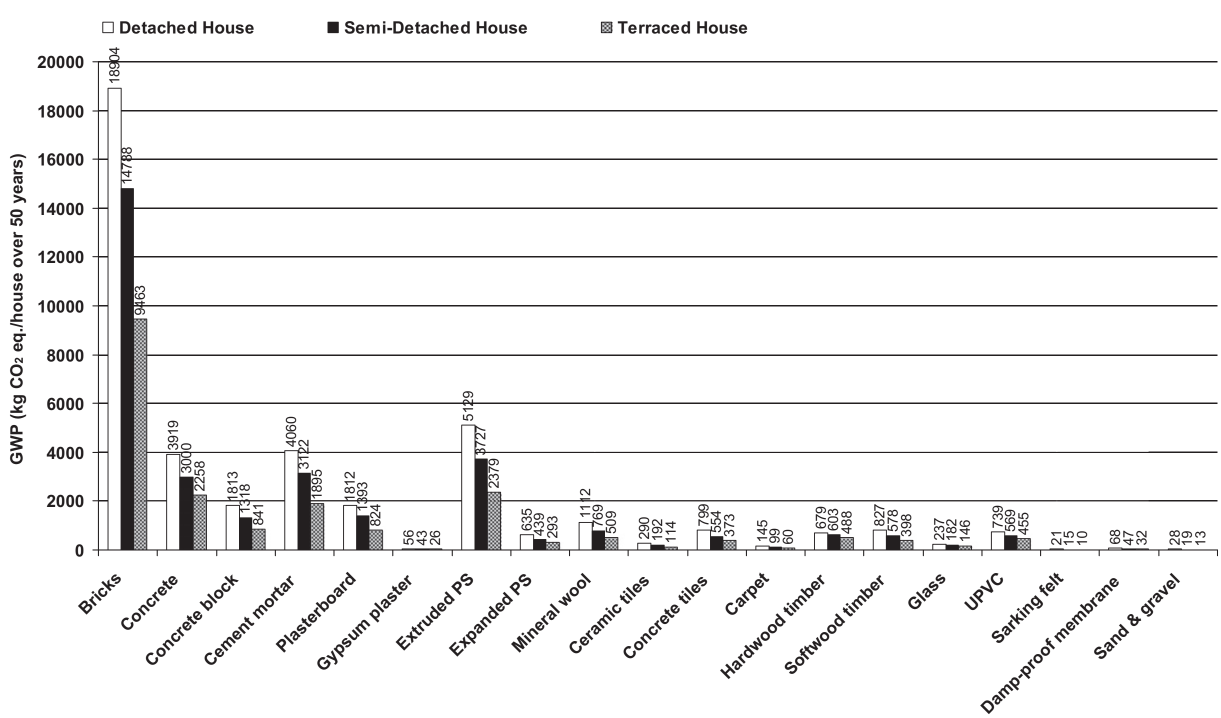

Fig. 9. GWP of the construction materials used for the houses.

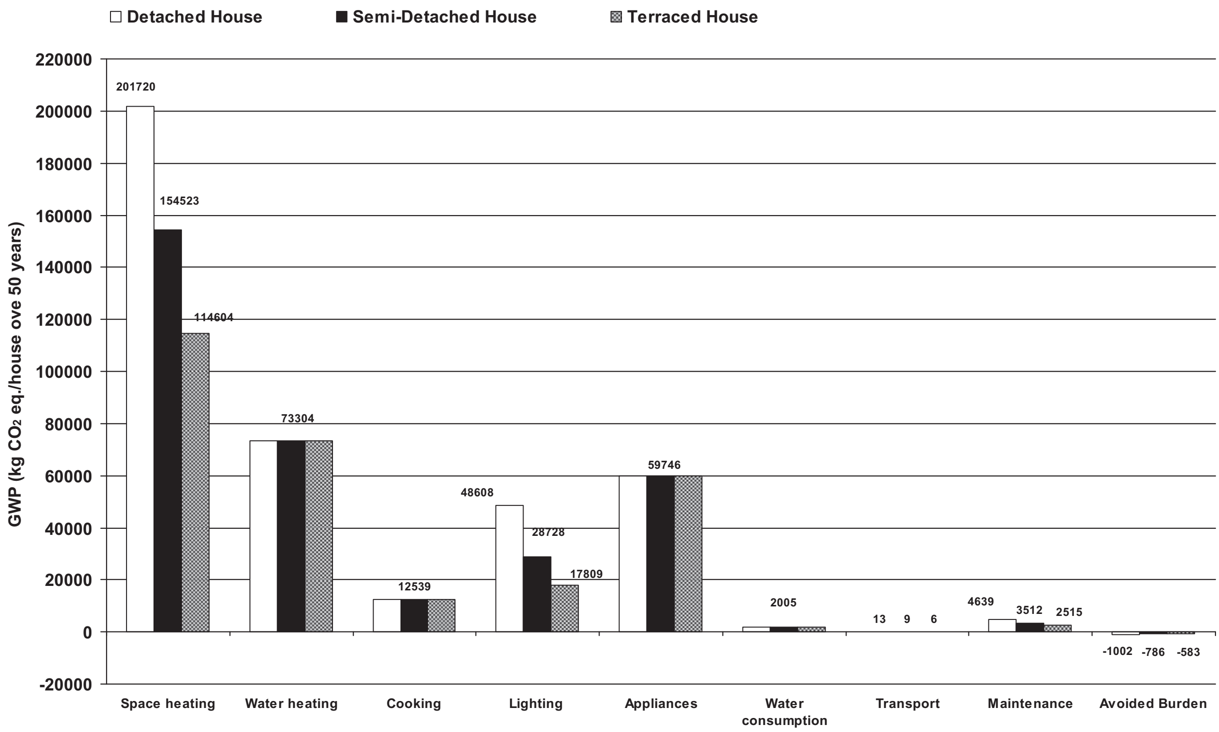

Fig. 10. GWP for the use stage for the detached, semi-detached and terraced houses over 50 years with an average occupancy of 2.3 people (The avoided burden is from recycling of flooring, windows and doors).

exception to this is ODP where the main contributor is the construction stage due to the use for insulation of expanded polystyrene, produced using ozone depleting blowing agents such as HCFCs. In the construction stage, bricks, lime mortar, windows and the insulation materials are the main contributors to all impacts. The overall benefits of recycling of the construction materials are more pronounced for the detached and semi-detached houses (Figs. 4 and 5) than for the terraced house (Fig. 6), and particularly for marine ecotoxicity (MAETP), saving 14% of this impact, followed by human and freshwater toxicity (HTP and FAETP) and photochemical smog (POCP), each being reduced by 7%.

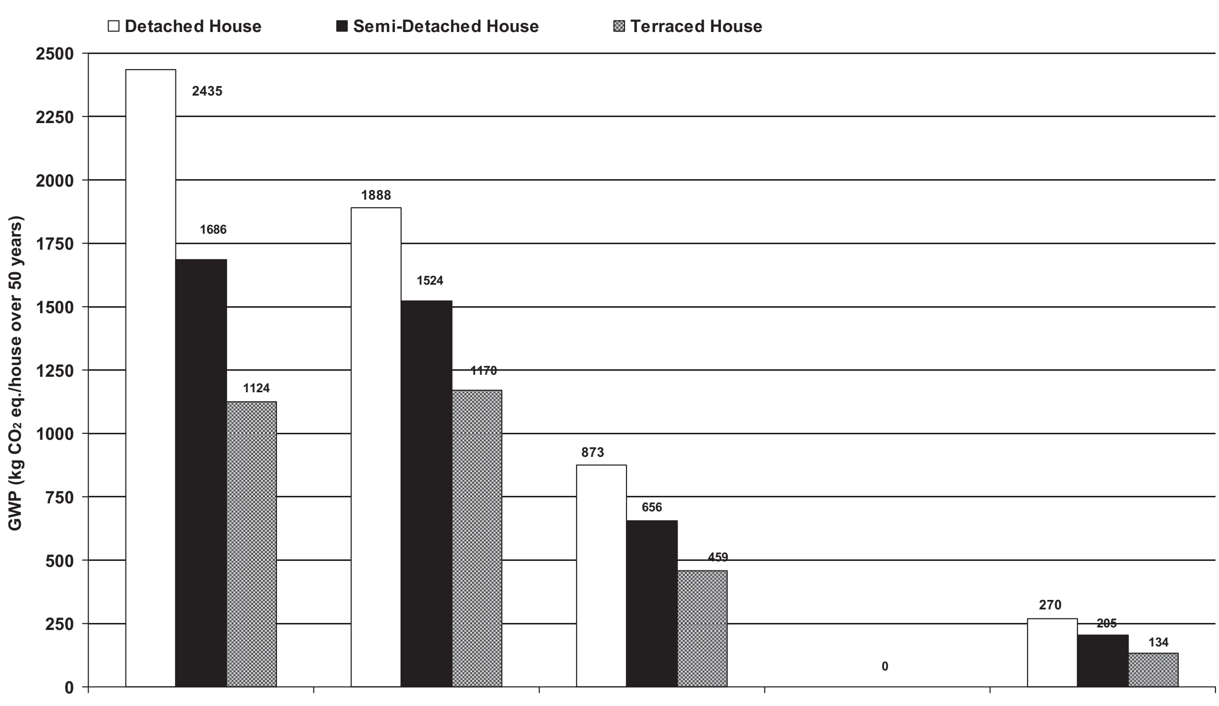

Fig. 11. GWP of the end-of-life stage for the detached, semi-detached and terraced houses, including the waste from maintenance over the lifetime of 50 years.

2.3.3. Impacts per unit floor area

This section compares the impacts of the three houses over their service life per unit floor area. As can be observed from Figs. 12 and 13, the detached house has the lowest impacts per unit of floor area, while the semi-detached and terraced houses are less environmentally efficient. This at first appears to be at odds with the results discussed so far, which indicate that smaller houses are environmentally more sustainable (see Figs. 4–6). The reason for this is that most environmental impacts are highly influenced by the energy use which is dependent on either the type and size of the house or the size of the household (note that residents' behaviour is not considered here). For example, space heating and lighting are a function of the size and type of house whereas cooking, use of domestic appliances and water heating are dependent on the household size. Therefore, given the same household size assumed for all three types of house and the fact that the energy used for water heating and appliances is the same for all three sizes of the house (see Table 3), it is not surprising that the larger floor area (e.g. detached house) will have a smaller impact per unit of area than a smaller one (e.g. terraced). An exception to this is ozone layer depletion (ODP), which varies little between the three types of house. This is because this impact is not dependent on energy used but, as mentioned previously, on the construction materials, the amount of which is roughly proportional to the size of the house.

2.3.4. Comparison with other studies

As mentioned in the introduction, no other full LCA studies exist for the housing sector in UK, so that a full comparison of the results is not possible. Instead, we first compare the results of the current work with an LCA study of a detached Spanish house. This is followed by a comparison of GWP with some other studies, more limited in scope.

Fig. 14 shows a comparison with the Spanish detached house with an area of 160 m^2 housing four people over 50 years [18]. This study considered only the construction and use stages, excluding the end-of-life activities. As can be seen, there is a relatively good agreement between the results. Overall, both studies show a similar contribution to the environmental impacts from different life cycle stages per unit floor area, with the use stage contributing around 90% of the total impacts. The exception to this is ozone depletion which in the present study is mainly from the construction stage. This is due to the different insulation material used in the UK house compared to the Spanish study: the former uses expanded polystyrene while the latter considered polyethylene, which has lower ozone depletion potential [35]. However, ODP from the use stage is comparable in both studies.

The total GWP reported by Ortiz et al. [18] is 2340 kg CO_2 eq./m^2 while in this study the GWP is estimated at 3500 kg CO_2 eq./m^2. A similar difference is also noticed for abiotic resource depletion (ADP). This is largely due to the different energy consumption assumed: 44 GJ in the Ortiz and 88 GJ in the current study. The former is lower even though the Spanish house is bigger and has four inhabitants mainly because of the lower heating requirements in Spain. This is exemplified by the fact that out of 88 GJ estimated in the current study, 56 GJ is used for space heating.

Furthermore, Ortiz et al. [18] assumed electricity as the only type of energy used in the house while this research considers all the different fuels used in the residential sector in the UK (see Fig. 3 and Table 4). This is reflected in the higher acidification (AP) and human toxicity potentials (HTP) in the Ortiz study since these two impacts are higher for electricity than for natural gas [36,37] which is included in this study in addition to electricity. Further differences in the results are due to the different electricity mix in the UK and Spain.

However, the difference for terrestrial ecotoxicity (TETP) between the two studies is much larger, with this impact being by a factor of 30 higher in the present study. In the absence of further details on the reasons for a low estimate in Ortiz et al. [18], it is difficult to explain this discrepancy apart from speculating that this

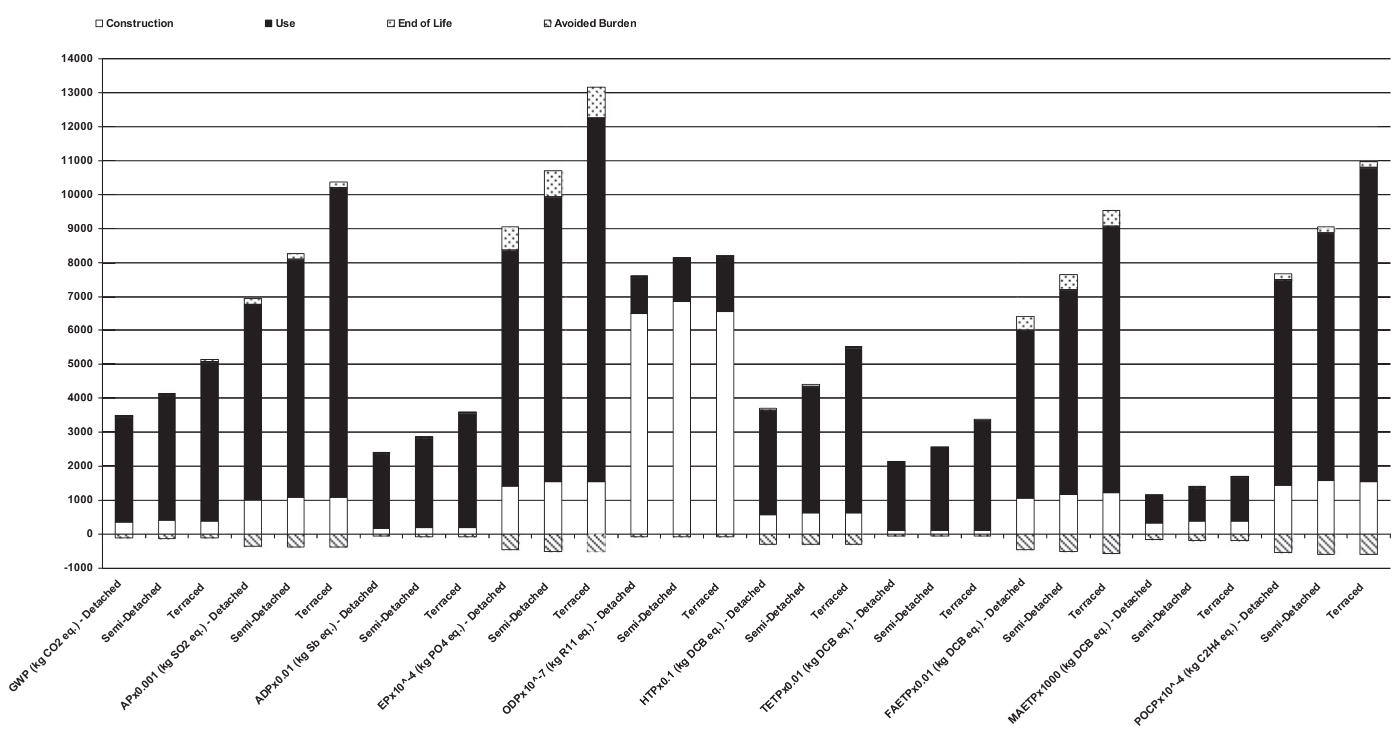

Fig. 12. Comparison of environmental impacts of the detached, semi-detached and terraced house per unit floor area over 50 years. For description of impact categories, see Fig. 4].

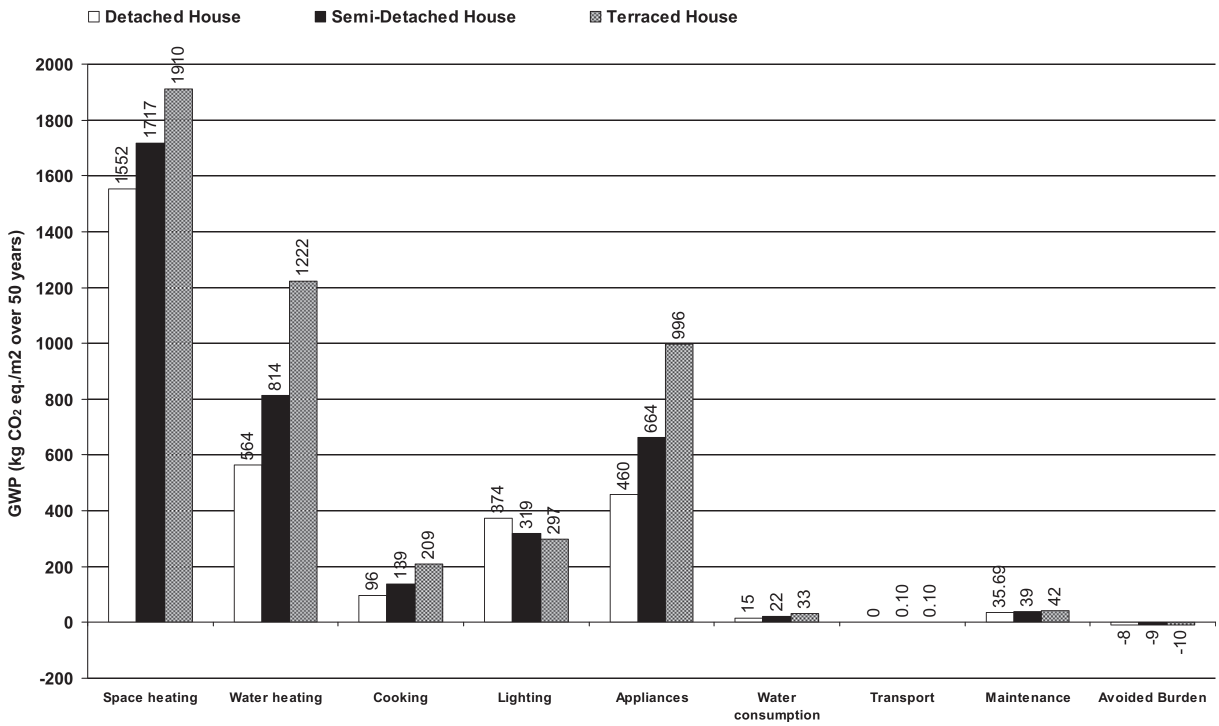

Fig. 13. GWP for the use stage of the detached, semi-detached and terraced houses per unit floor area over 50 years.

impact might be underestimated, particularly as all the energy is from electricity, which has a relatively high TETP.

Peuportier [19] also assessed GWP from the construction and operation stages but considered a typical French detached house with a living area of 112 m^2. As can be observed in Fig. 15, the total GWP in the current study is around 60% higher than for the French house. This could be due to two main factors: the French study assumed 68% lower energy consumption for heating than in the current study and the French electricity mix has a much lower GWP than the UK grid due to a high contribution from nuclear power.

Fig. 15 also compares the GWP of a UK semi-detached house carried out by Hacker et al. [15], which also only considered construction and use. The GWP results are 53% higher in the current study. The reason for this could be due to the fact that the authors considered the use of passive techniques for cooling and heating.

Finally, the current results are compared in Fig. 16 to the remaining UK studies mentioned in Introduction [14,16,17] but only

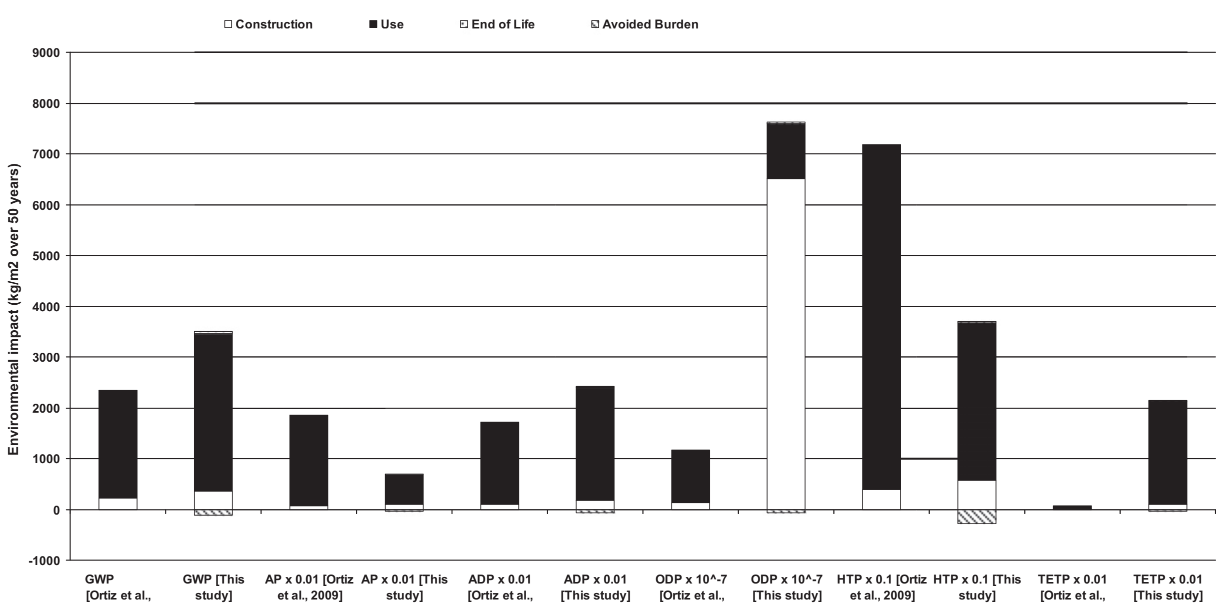

Fig. 14. Comparison of life cycle impacts of a detached Spanish house [18] and the current study for the detached house. [Current study: floor area of 130 m^2 occupied by 2.3 people. Ortiz et al. (2009): 160 m^2 occupied by 4 people. For description of impact categories, see Fig. 4].

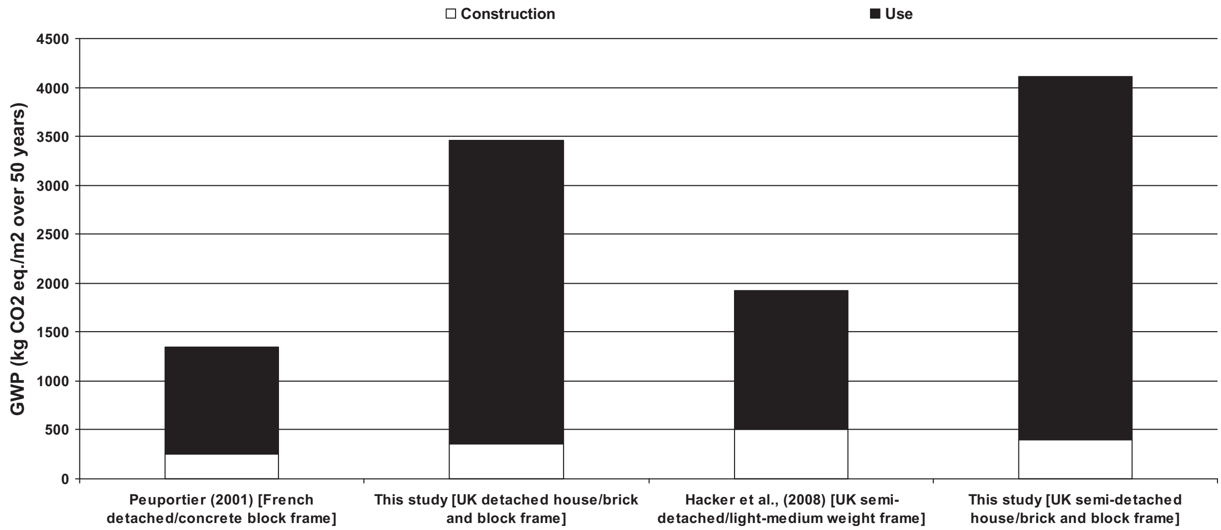

Fig. 15. Comparison of GWP for the construction and use stages between this and other studies.

with respect to the embodied carbon since those studies only considered GWP of the construction stage. Monahan and Powell [17] studied semi-detached UK houses with a living area of 80 m^2 and with different types of frame: timber only, timber with brick claddings and masonry frame. The embodied carbon of all three types was found to be higher than the results obtained in this study, despite using timber in two of the three houses. The reason is mainly due to the use of steel reinforcement for the foundations and the inclusion of end-of-life waste management. On the other hand, the results obtained by Hammond and Jones [16] for the twelve case studies that considered both houses and apartment show consistency with the results obtained here.

3. Environmental impacts of the housing sector

This section looks at the life cycle impacts from the whole housing sector in the UK. These have been estimated using the LCA results for the three types of house presented in this paper, the housing stock distribution and the annual energy consumption in the residential sector [21]. In 2006, there were over 7 million each of semi-detached and terraced and 4 million of detached houses in the UK. Collectively, they represented 72% of the residential sector comprising over 25 million of residencies.

3.1. Global warming potential

As shown in Fig. 17, with 51 million tonnes CO_2 eq. per year, semi-detached houses have the highest GWP, followed by terraced houses with 45 million; GWP from detached houses is 36 million tonnes per year. Over the 50 years lifetime of the houses, this would add to a total of 6.6 billion tonnes of CO_2 eq. from all three types of the house. To put these figures in perspective, the total UK GHG emissions in 2010 were 582.4 million tonnes CO_2 eq. [1]. Therefore, the emissions from the housing sector over 50 years are 11 times

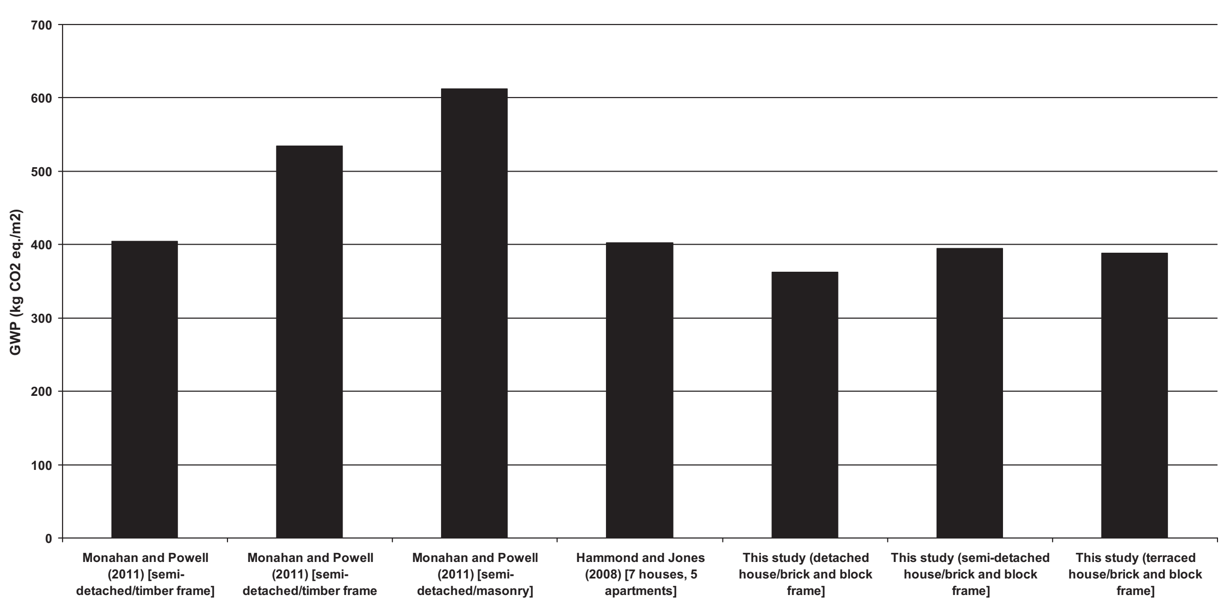

Fig. 16. Comparison of GWP for the construction stage (embodied carbon) between this and other UK studies.

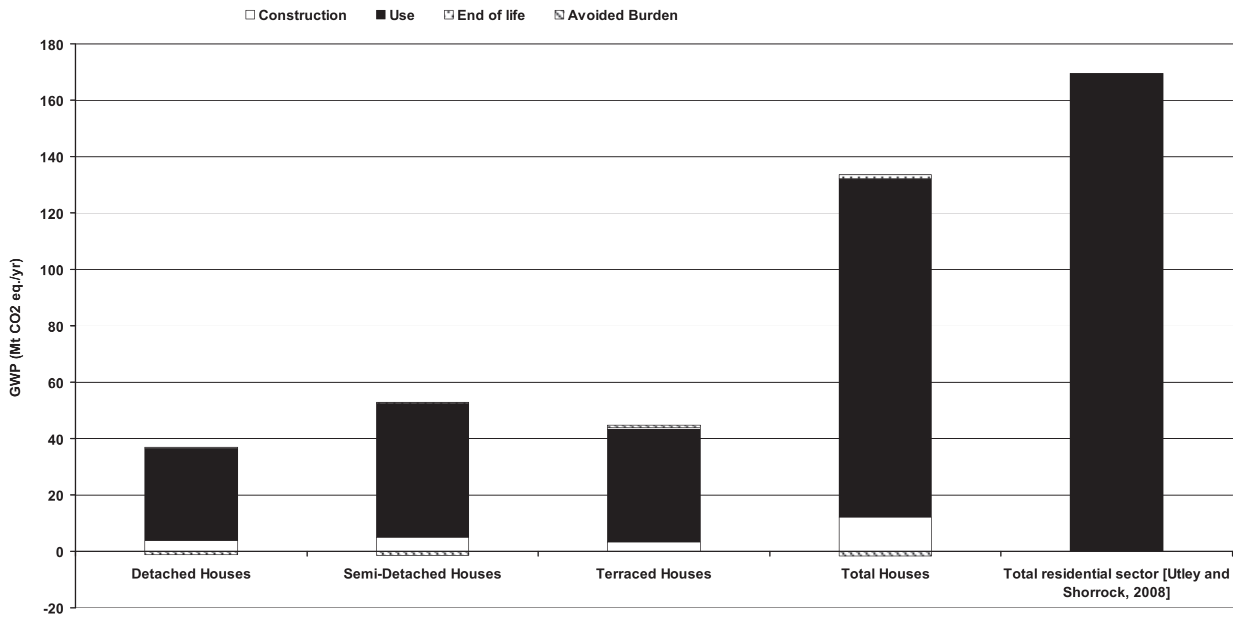

Fig. 17. GWP of the UK housing sector showing contributions from the life cycle stages.

higher than the current emissions from the whole of the UK. As indicated in the figure, the vast majority of this impact is from the use stage.

For validation of the results, Fig. 17 shows GWP from the total UK residential sector reported in Utley and Shorrock [21]. The value of 170 million tonnes of CO_2 eq. per year refers to the use stage only but is for the whole residential sector. This is comparable to the total value of 132 million tonnes of CO_2 eq. for all types of houses estimated in this study, representing 78% of 170 million tonnes. Given that this study considers houses only which represent 72% of the residential market and that the contribution of the other life cycle stages is around 9%, the two values estimated independently are very close.

3.2. Other environmental impacts

The other life cycle impacts from the housing sector are shown in Fig. 18. Whilst it is difficult to put these results in context as there

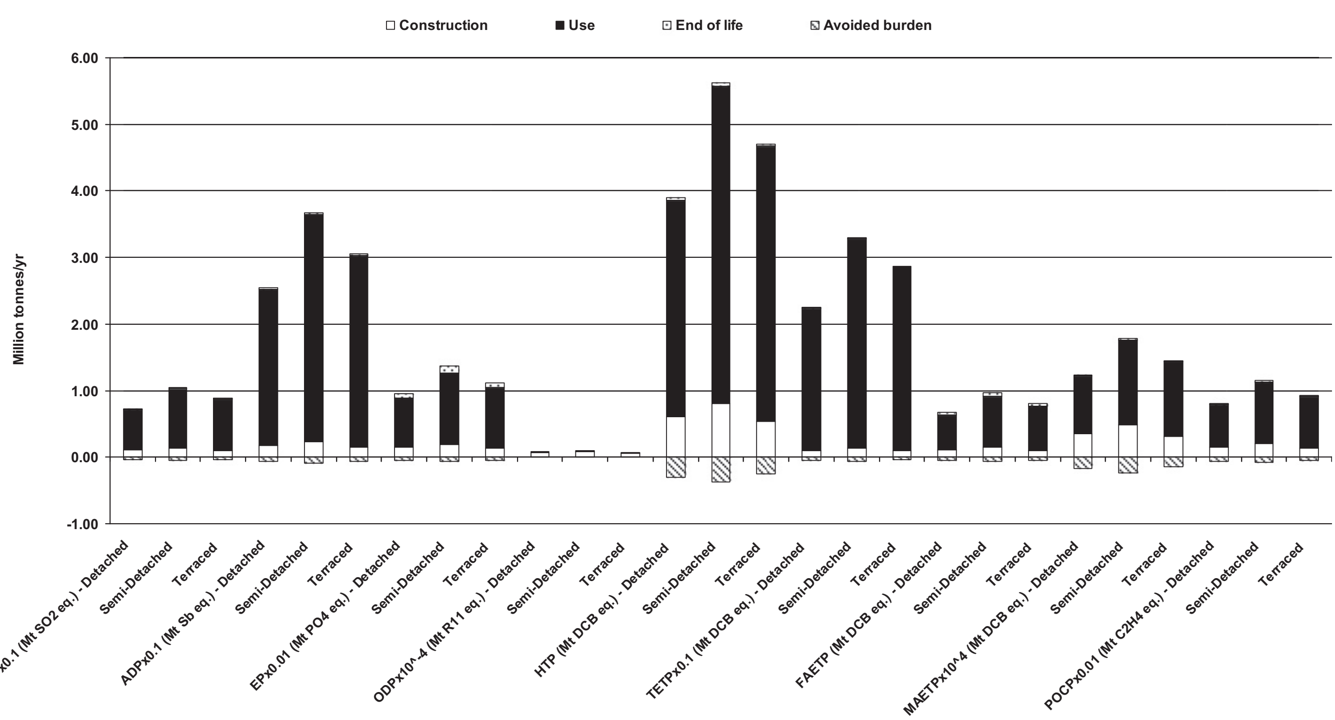

Fig. 18. Environmental impacts (other than GWP) from the UK housing sector showing contribution of the life cycle stages. [The values for some impacts have been scaled to fit on the scale. The original (un-scaled) values can be obtained by multiplying the value shown on the *y*-axis by the scaling factor given in brackets for each impact. For description of impact categories, see Fig. 4].

are no other comparable results, it is again indicative that the use of energy in houses is the most important hot spot. Due to their total share in the housing sector, semi-detached houses contribute on average 40% to the total impacts, terraced houses 33% and detached houses 28%.

4. Conclusions

The total GWP over the lifetime of 50 years for a typical UK detached house is 455 t CO_2 eq., 374 t CO_2 eq. for a semi-detached house and 309 t CO_2 eq. for a terraced house. For all three types of house, the use stage contributes to 90% of GWP, followed by the construction stage (9%), and the end-of-life stage (1%). The contribution of transport is negligible. When the system is credited with the avoided burden from recycling the construction waste, the total GWP over the lifetime of each house reduces to 440 t CO_2 eq. for the detached house, 363 t CO_2 eq. for the semi-detached house, and 302 t CO_2 eq. for the terraced house. The total annual GWP from the whole housing sector amounts to 132 million tonnes of CO_2 eq. with the semi-detached houses contributing almost 40%, terraced 37% and detached houses 27%. Over the 50-year lifetime, the total GWP from the sector is nearly 6.6 billion tonnes of CO_2 eq. or 11 times the current total UK emissions of CO_2 eq.

The results indicate that the use stage is also the main contributor to all other environmental impacts which are mainly related to energy use. The exception to this is ozone layer depletion which is due to the construction stage and in particular from the use of insulating materials.

Therefore, on a life cycle basis, the main improvement opportunities in the housing sector lie in the reduction of the impacts in the use stage of the house. Whilst people behaviour plays a big role, the greatest improvement opportunities are in the design stage of the house as decisions taken at this stage determine the impacts of a house for the rest of its life cycle. Therefore, this study reinforces the importance of sustainable home design, including a more energy efficient house envelope. Coupled with building smaller properties such as terraced houses, energy efficient appliances and renewable energy sources, this could help to deliver a more sustainable housing stock in the UK.

Acknowledgements

The authors would like to thank Dr. Yasantha Abeysundara U.G. for technical advice, the architects at Bernard Taylor Partnership Ltd. for providing data, Fernanda Cuéllar-Franca for creating the floor plans and CONACYT for their financial support.

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