2009-01-01

Land use Planning in Ireland: a Life Cycle Energy Analysis of Recent Residential Development in the Greater Dublin Area

Aidan Duffy
Dublin Institute of Technology, aidan.duffy@dit.ie

Recommended Citation

Duffy, A.: Land use planning in Ireland:a life cycle energy analysis of recent residential development in the Greater Dublin area. International Journal of Life Cycle Assessment, Vol.14, 3, 2009, pp.257-267. doi:10.1007/s11367-009-0059-7

Int J Life Cycle Assess
DOI 10.1007/s11367-009-0059-7

LAND USE

Land use planning in Ireland—a life cycle energy analysis of recent residential development in the Greater Dublin Area

Aidan Duffy

Received: 26 August 2008 / Accepted: 6 February 2009

Abstract

Background, aim, and scope One third of the total housing stock in the Republic of Ireland has been built in 10 years up to and including 2006 and of this approximately 34% was built in the Greater Dublin Area (GDA). Much of the housing was low-density with poor public transport links leading to doubts over its sustainability—particularly in terms of energy use. Although the country is committed to reducing greenhouse gases to 13% above 1990 levels by the period 2008–2012, by 2005, emissions were already 25.4% higher than the baseline and current projections are that this figure will rise to 37% over the period. The residential sector is estimated to contribute to approximately 24.5% of energy-related CO_2 emissions. This paper estimates total emissions from residential developments in the GDA constructed between 1997 and 2006.

Materials and methods Carbon dioxide equivalent (CO_2) emissions are estimated using a life cycle assessment approach over a 100-year building lifespan and employing process, input–output and hybrid energy techniques. Life cycle stages include: construction, operation, transport, maintenance and demolition. The main data sources include: national population and industry census data, household travel survey data, residential energy performance surveys and national accounts. The GDA was split into four zones each encompassing development at increasing radii from Dublin's city centre, namely: city centre, suburbs, exurbs and commuter towns.

Results Per capita CO_2 life cycle emissions in the GDA were found to be approximately 50–55% greater in the exurbs and commuter towns than in the city centre. Of the five life cycle stages studied, operational energy requirements (predominantly space heating and hot water, but including power) contributed most significantly to emissions (68%), followed by transport (17%), construction (9%) and maintenance/renovation (6%).

Discussion Operating emissions from dwellings in the commuter town and extra-urban zones were almost twice those in the city centre both due to larger dwelling sizes and the predominance of detached and semi-detached dwellings (with large amounts of exposed walls) in the former and the prevalence of smaller apartments in the latter. Car use was most pronounced in the zones furthest from the city centre where per capita emissions were almost twice those of residents in the city centre. Despite their smaller size, the per capita construction CO_2 emissions of apartments were approximately one third greater than for low-rise dwellings due to the greater energy intensity of the structure. However, this difference was more than compensated for by the significantly lower operational emissions referred to above.

Conclusions In 2006, recurrent CO_2 emissions (operational, transport and maintenance) from dwellings built in the GDA over the ten preceding years were 2,108 kt while construction-related emissions in that year were 1,325 kt giving a total contribution from the residential sector of 3,434 kt CO_2/annum—representing 4.9% of national emissions for that year. Had the development policy prescribed 'city centre'-type development and transport modes, then emissions for the year 2006 would have been 2,892 kt CO_2—a reduction of almost 16% over the actual figure. However, in this scenario recurrent emissions would have

Responsible editor: Llorenç Milà i Canals

A. Duffy (✉)
School of Civil and Building Services Engineering,
Dublin Institute of Technology,
Bolton Street,
Dublin 1, Ireland
e-mail: aidan.duffy@dit.ie

been reduced to 1,417 kt CO_2—a reduction of 33% over actual levels.

Recommendations and perspectives This study supports Irish and international governments' policies aimed at curbing CO_2 emissions from the domestic sector which focus primarily on reducing operational emissions from new and existing housing through design and construction improvements. However, it demonstrates that significant reductions in operational emissions are associated with high-density residential development with modest floor areas. Furthermore, it highlights the scope for transport emissions' reductions through better spatial planning leading to reduced car travel.

Keywords Carbon dioxide equivalent · CO_2 · Domestic dwellings · Embodied energy · Energy · Greenhouse gas emissions · Life cycle assessment · Spatial planning

1 Background, aim, and scope

At the end of 2006 there were 1,835,515 domestic dwellings in the Republic of Ireland (CSO 2007a). Of these, 607,961—representing one third of the total housing stock—were built in the 10 years up to and including that year (Fig. 1). Approximately 34% of this new housing was built in Dublin and the greater Dublin region, much of which was low-density with poor public transport links. Indeed, much of the housing development in Ireland can be characterised as 'once-off' or low-density located outside urban centres: over one third of the development comprised detached houses, 44% were semi-detached or terraced housing units and only one fifth were apartments. In contrast, multi-family dwellings account for almost half of Europe's housing stock (Netherlands Ministry of Housing, Spatial Planning and the Environment 2004). The adoption in Ireland of such low density suburban and extra-urban development policies may have resulted in increased greenhouse gas emissions when compared with higher density urban developments.

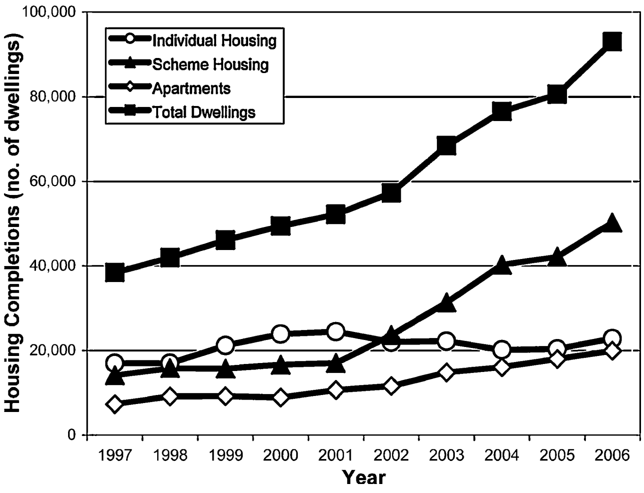

Fig. 1 Annual housing completions in Ireland 1997–2006

Ireland's energy emissions' performance is poor by international standards: in 2004, energy use per capita was 3,870 kg of oil equivalent (kgoe) and associated greenhouse gas emissions were 10,589 kg. This compares unfavourably with EU27 figures of 3,689 kgoe and 8,180 kg, respectively (Eurostat 2007). Although the country has committed to reducing greenhouse gases to 13% above 1990 levels by the period 2008–2012, by 2005, emissions were already 25.4% higher than the baseline (EPA 2007) and current projections are that this figure will rise to 37% over the period. Residential energy use accounted for almost one quarter of total national fuel consumption in 2005 of which almost 75% is used for space heating and hot water (Howley et al. 2006).

The impact of a domestic development on greenhouse gas emissions is related to the quantity and carbon content of the energy required over its lifetime. For example, two similar buildings with different passive thermal performances will consume different amounts of energy: one will emit more greenhouse gases than the other. Identical buildings powered by fuels with different carbon contents (for example, biomass- versus oil-fuelled boilers) will also have differing impacts. The energy impact of a domestic development over its entire life cycle can be viewed as the sum of this operational energy use together with the energy needed to produce and maintain it, demolish it as well as the energy required to travel to and from it. Similarly, the CO_2 impact is the global warming potential-weighted sum of greenhouses gases (predominantly carbon dioxide, nitrous oxide and methane) emitted by this energy use.

Australian literature suggests that the average energy required to produce a house in that country is approximately 5 GJ/m^2 producing some 0.49 tonnes/m^2 floor area of carbon dioxide (CSIRO 2007) based on Australian emissions' intensities. This is referred to as 'embodied energy' and theoretically includes all direct and indirect production energy inputs such as construction, material production, raw material extraction and associated services. The average floor area of a domestic dwelling in Ireland in 2004 was 112 m^2 (SEI 2005) and applying the Australian data, this gives a per-dwelling embodied energy of 560 GJ and emissions of 55 tonnes of carbon dioxide (CO_2). Assuming a 100-year building lifespan, this is equal to annualised emissions of 0.55 tonnes of CO_2 and 5.6 GJ of energy use. Although these figures are rough estimates—since the Australian embodied energies are likely to differ from those in Ireland (no Irish data are available at the time of writing)—when used with the operational and travel data below, they indicate the relative importance of embodied energy in the life cycle of a domestic building and will assist in the development of the life cycle assessment (LCA) methodology described in this paper.

In 2004, the mean energy use per Irish dwelling was 88 GJ resulting in the emission of 8.2 tonnes of CO_2 per annum. Some 79% of energy use was in the form of direct fossil fuel consumption, the remainder was electricity (SEI 2005).

In 2006, the Irish transport sector consumed 213,000 TJ of energy and emitted 15,273 kt of CO_2 (SEI 2006) of which 40% was attributable to private cars (SEI 2004). In the same year, there were 1,469,521 households in Ireland (CSO 2007b) giving average annual transport-related CO_2 and energy use figures of 4.2 tonnes and 58 GJ per dwelling, respectively. This approximation overestimates the direct energy inputs associated with moving to and from a domestic dwelling since many private car trips would be used for other purposes, although it ignores indirect energy inputs such as product development and manufacturing.

Little data are available on the maintenance-related energy requirements of domestic dwellings and associated emissions. Figures for the refurbishment and repair of office buildings are reported to lie in the range of 0.17 to 0.34 GJ/m^2 (Yohanis and Norton 2002). Taking the lower figure—since office refurbishment is likely to be more energy-intensive than domestic refurbishment—and assuming an interval between refurbishments of 7 years, the annual maintenance-related energy intensity for an average Irish house is 2.72 GJ/m^2 with associated emissions of 0.23 t CO_2. However, even the use of the lower office refurbishment energy intensity figure may overestimate domestic emissions.

Based on these data, the total approximate annualised life cycle energy requirement for an average domestic Irish dwelling is 154.3 GJ emitting 13.2 tonnes of CO_2. Transport and operation dominate life cycle energy requirements (38% and 56% respectively) and CO_2 emissions (32% and 62% respectively). Based on these preliminary results, the methodology outlined in this paper focuses therefore to a greater extent on operational and transport energy use and emissions than on construction, maintenance and demolition.

The objectives of this study are to: determine the whole-life energy and CO_2 intensities of dwellings built in the Greater Dublin Area (GDA) between 1997 and 2006; assess the relative impact of different life cycle stages on energy use and CO_2 emissions; and quantify and compare the impact of urban, suburban and extra-urban residential developments in and around Dublin on national energy-related greenhouse gas emissions.

2 Materials and methods

Life cycle assessment (LCA) was used to determine energy use and carbon dioxide emissions for all stages of a residential development including:

- construction;
- operation including heating, hot water, lighting and small power loads;
- travel to and from the development;
- maintenance; and
- demolition

The study only considered the greenhouse gas impacts associated with energy use and ignored wider environmental impacts such as resource depletion, groundwater pollution and habitat loss. CO_2 emissions only were calculated since these data are easily available. However, since CO_2 accounts for only 93% of non-agricultural greenhouse gas (GHG) emissions in Ireland by global warming potential (CSO, 2007c), resulting figures were divided by 0.93 to correct for unaccounted energy-related GHG emissions (such as N_2O and CH4) to estimate total emissions in CO_2 equivalent (referred to hereafter simply as CO_2).

Energy requirements and emissions for each of the life stages of the residential development were determined using process, input–output or hybrid process analysis depending on data availability. These methodologies are described by inter alia Crawford (2007) and Bullard et al. (1978).

2.1 Developments

Two developments were selected to represent typical recent residential developments in the Greater Dublin Area (a term which is used to describe the city and county of Dublin as well as the adjacent counties of Kildare, Meath and Wicklow) which are described below.

A high density mixed-use urban development in the city of Dublin comprising 300 apartments of one, two and three bedrooms with a total gross floor area of 22,500 m^2. The scheme also contains retail and office units.

A development of 118 two-storey detached, semi-detached and terraced houses on a 5.7 ha site outside the city comprising detached, semi-detached and terraced houses ranging in size from three to five bedrooms.

2.2 Construction

The energy embodied in the above developments was determined using hybrid process analysis up to the point of completion of the construction process by the contractor and hand over to the new resident. This required material-specific energy intensities (Hammond and Jones 2006) which were used in conjunction with national input–output tables (CSO 2006a) to quantify the total upstream and direct energy requirements for the building. Upstream energy requirements might include raw materials' extraction and building materials' manufacturing; direct energy relates to energy expended during the construction process itself.

Bills of quantities detailing material quantities and prices were obtained from the contractor who built the schemes. Where possible, materials were identified, characterised and process energy intensities applied. Energy intensities of unidentified expenditure were estimated using Irish construction sector energy intensities derived from national input–output tables, mean national energy tariffs, primary energy factors and disaggregation coefficients (Acquaye et al. 2008). An integral part of this methodology involved calculating a carbon dioxide equivalent intensity based on the mix of fuels used.

2.3 Transport

Transport emissions for all trips to and from dwellings were calculated based on data from the Dublin Transportation Office's 2006 Household Survey (DTO 2006) of approximately 2,500 households in the Greater Dublin Area. The survey was carried out over a 1-week period where participants kept a detailed log of all movements to and from their dwellings. Relevant variables were extracted from the database which included:

- mode of transport (for example train, rapid rail, tram, bus, truck, van, car, taxi, motorbike, running, walking);
- number of trips made;
- trip distances; and
- trip duration

It is accepted that development density and land-use mix are inversely related to household-related travel distances and vehicle emissions (Frank et al. 2000; Næss 2006; Newman and Kenworthy 1999). Moreover, the distance of a residence from concentrated employment and recreational areas (typically a city centre) affects both transport mode (DTO 2006) and travel distance and, therefore, fuel consumption and CO_2 emissions. In order to capture the effects of density and distance to urban centres, the Greater Dublin Area Household Survey data were therefore divided into four zones of increasing distance from the city centre (Fig. 2). These are:

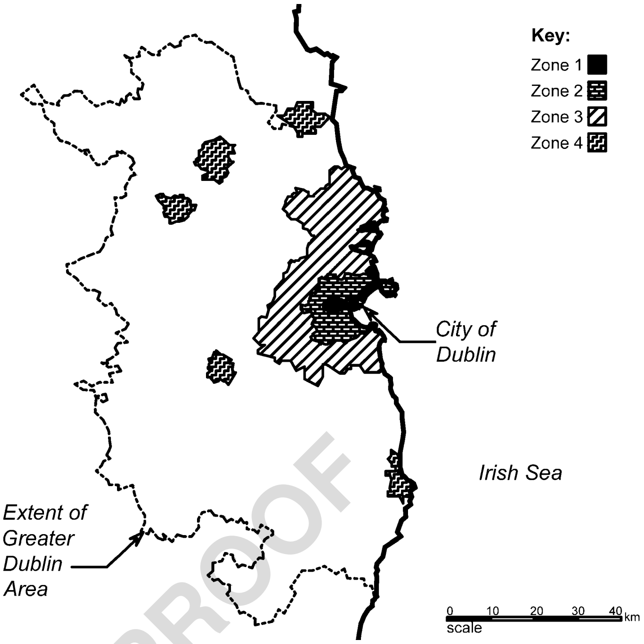

Fig. 2 Map of the Greater Dublin Area (GDA) showing the zones analysed

Zone 1 City Centre which is roughly bounded by two canals and the inner ring roads to the north and south giving a radius of up to 3.0 km around the city;
Zone 2 Suburbs which are located between the City Centre and the M50 motorway ring road at a radius of approximately 9.0 km around the city;
Zone 3 Exurbs covering the low density urban areas in the remainder of county Dublin located outside the M50 incorporating many of the closer commuter towns at a radius of 15 to 30 km from the centre; and
Zone 4 Commuter towns of Drogheda (42 km from the centre), Navan (45 km), Enfield (40 km), Naas (31 km) and Wicklow (43 km).

Data were then analysed by zone to determine the total number of trips by mode of transport and total annualised modal distances travelled. Mean data were then calculated on a per household and per capita basis.

Fuel consumption and CO_2 emissions data were calculated in the following ways:

no carbon dioxide emissions or fuel consumption was attributed to walking, running or cycling. This assumes that the energy and CO_2 embodied in equipment such as footwear, bicycles, special clothing and helmets is negligible compared to that embodied in other forms of transport. The food requirements of individuals are outside the LCA boundary in all cases.

aeroplane, train, rapid rail transit, tram, bus, mini-bus, truck and motorbike energy uses and emissions were calculated using published average emissions per person kilometre (Cox and Hickman 1998; Davies and Diegel 2007). Trains, buses, mini-buses and trucks were assumed to be diesel-fuelled while DART (a rapid rail system) and LUAS (a tram system) use electricity only. The average fuel consumption and carbon dioxide emissions data used in the analysis is presented in Table 1.

Since emissions from cars were expected to predominate, these were calculated in the more detailed manner described below.

Engine size and fuel type (diesel/petrol) distributions were determined using 2005 local government car registration data and a weighted mean engine size was calculated for both fuel types.

Mean fuel consumption was calculated for this engine size based on published data and speed-related efficiencies (Davies and Diegel 2007) were combined to give an equation for fuel consumptions for the weighted mean engine size (calculated above) at different speeds.

Average speeds for all car trips were calculated and fuel consumption determined using the fuel consumption to speed relationship.

This represents the fuel consumed only and does not consider the full life-cycle energy use of the car. Research by Castro et al. (2003) suggests that direct fuel consumption represents approximately 95% of the total life cycle energy requirements of a car and the results were adjusted accordingly. In the absence of equivalent life cycle assessment literature for other modes of transport, this figure was also applied to buses, trains, vans, trucks and motorbikes.

2.4 Operation

Operational energy requirements were quantified using the Energy Performance Survey of Irish Housing undertaken jointly by Sustainable Energy Ireland and CODEMA between 2004 and 2005. This study involved a detailed survey of the energy use characteristics of dwellings in Ireland and covered a range of construction types, ages and occupancy patterns. Relevant survey data were selected to be representative of the development types chosen here, in particular:

Data in the fields 'Detached', 'Semi-Detached', 'Terraced' and 'Purpose-Built Apartment' were incorporated whereas, 'Converted Apartment' and 'Other' were ignored and

Developments built since 1997 were included since different Building Regulations and energy performance standards pertained prior to this date and would not have been representative of the 1997–2006 housing stock. However, a lack of data for apartments necessitated the use of pre-1997 data which would have overestimated energy use and emissions to some extent.

Mean annualised energy use and carbon dioxide emissions data were calculated for the reduced sample of 59 dwellings based on recorded fuel mixes and quantities and these were validated against Scottish data. Data were converted from per-dwelling to per capita by dividing by the average number of persons per private household for the county or city as listed in the 2006 national census (CSO 2007a).

2.5 Maintenance and demolition

Maintenance requirements were determined using input–output analysis. Total expenditure for Irish housing repair, maintenance and improvements for the year 2004 were used (CSO 2006b) together with the energy intensity for the construction sector and total existing housing units for the period to determine the average annual domestic dwelling maintenance energy use.

Demolition costs were calculated using input–output analysis employing data from the 2004 Census of Building Construction (CSO 2006c). Turnover and input figures for Nace 45.1 'Site preparation, demolition and wrecking of buildings, earth moving, test drilling and boring' were used to determine energy intensities and these were used with 2004 published demolition costs (Davis Langdon and Everest 2004) to determine demolition energy requirements.

3 Results and discussion

3.1 Construction

Figure 3 shows the embodied CO_2 emissions per dwelling. It can be seen that detached dwellings were found to have

Table 1 Average fuel consumptions and CO_2 emissions for various modes of transport excluding cars (source: EEA 2003)

Mode	Fuel consumption (grams oil equivalent/passenger km)	CO_2 emissions (g/passenger km)
Bus	23	73
Truck	97	216
Motorbike	36	104
Rail	20	44

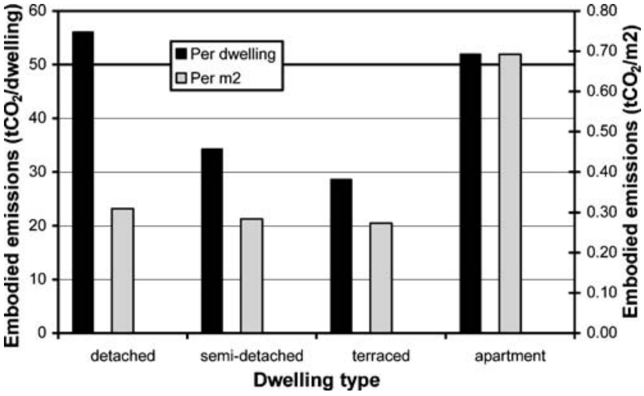

Fig. 3 Embodied CO_2 for each dwelling type studied expressed both on a per dwelling and a per m^2 of gross floor area basis

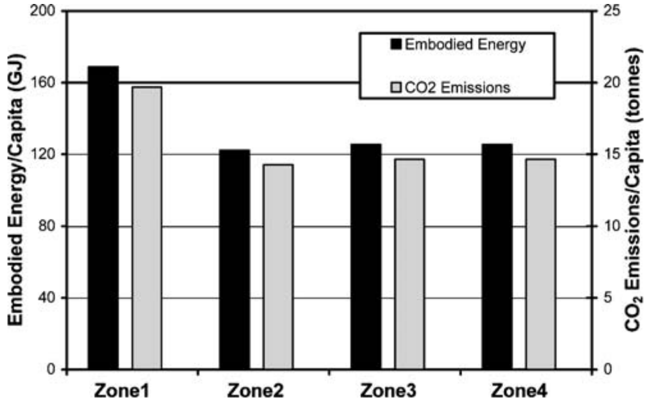

Fig. 5 Per capita embodied energy and construction-related CO_2 emissions for each zone

the highest embodied emissions due to their large size and construction characteristics. For example, the mean size of a detached house in the sample was 181.2 m^2 whereas semi-detached houses, terraced houses and apartments were 120.6, 104.6 and 75.0 m^2, respectively. Detached houses have greater construction materials' requirements since they have no shared walls, unlike other dwelling types. Apartments have the second highest embodied energy due to the need for more structural elements and, consequently, greater quantities of steel and concrete—both materials which have relatively high energy intensities. The use of these materials results in apartments producing the most CO_2 emissions per constructed dwelling. Terraced houses were found to have the lowest embodied energy and CO_2 emissions due to their relatively small size and use of shared structure (such as party walls). When compared on a per square metre of constructed gross floor area, it can be seen that due to their relatively small size and large structural requirements, apartments have almost two and a half times more embodied energy and CO_2 emissions than other forms of residential construction.

Figure 4 shows the percentage of house type completed in 2006 by zone where it can be seen that areas closest to urban centres had the highest concentration of apartment completions: almost four fifths of dwellings completed in the city centre were apartments while this figure fell to 16% in Zones 3 and 4 where the development of 'scheme houses' comprising mixed housing units dominated.

Based on the mix of dwellings completed in the 10-year period between 1997 and 2006 and on the average number of persons per household (CSO 2007a), average embodied energies and CO_2 emissions were calculated for each zone and are shown in Fig. 5. It can be seen that both embodied energy requirements and CO_2 emissions are highest in Zone 1 due to its high proportion of energy-intensive apartments and relatively low occupancy figures (2.5 persons per household compared to 3.0 for Zone 4).

3.2 Transport

It was found that the further a development is from the city centre, the greater the reliance on the private car while less trips are made using public transport. In Zone 1 some 31% of trips are made by car compared to 49%, 58% and 63% for Zones 2, 3 and 4, respectively. The percentage of trips made by walking or cycling decreases with increasing distance from the city centre: for Zones 1, 2 and 3 the

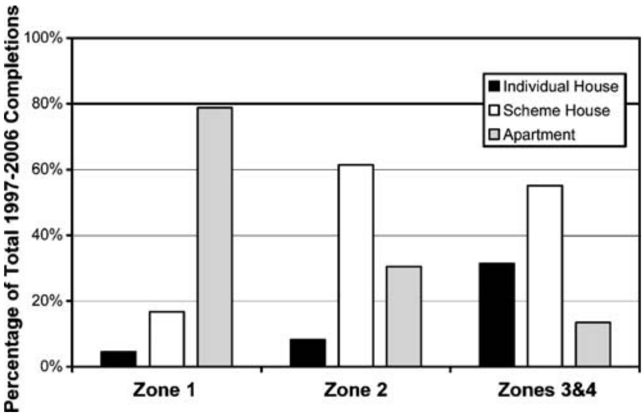

Fig. 4 Percentage of housing completions by type for each zone

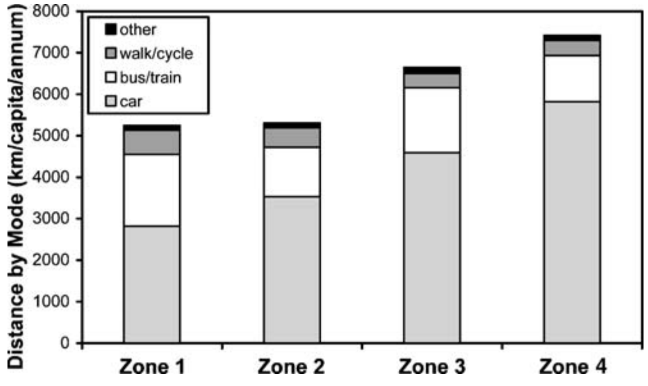

Fig. 6 Annual per capita distance travelled by mode for each zone

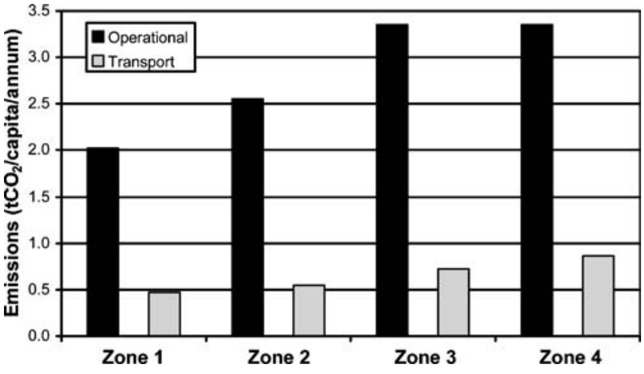

Fig. 7 Annual per-capita operational and transport-related CO_2 emissions for each zone

percentages of trips made using these modes are 40%, 29% and 22%, respectively. However, for Zone 4—commuter towns—the figure increases to 28% suggesting that local employment centres and amenities situated close to residential areas create greater opportunities for walking or cycling than in the Exurbs (Zone 3).

Figure 6 shows the annual modal distances travelled per capita for each zone. There is a clear positive relationship between distance from the centre of Dublin and distance travelled by car. The per capita distances travelled by public transport (bus and train) were highest for Zones 1 and 3 at 1,735 km and 1,566 km, respectively and lowest for Zones 2 and 4 at 1,196 km and 1,119 km, respectively.

Not surprisingly, transport-related fuel consumption and CO_2 emissions also increase the further a residential development is located from the city centre. Figure 7 shows the annual transport-related CO_2 emissions per capita for each zone. It can be seen that annual transport emissions in Zone 4 were highest where the average person consumed 14.2 GJ of energy (equivalent to 449 l of petrol) and emitted 866 kg of CO_2 in meeting their 2006 transport needs. These figures decrease with increased proximity to the city centre and reach a minimum of 8.3 GJ and 472 kg CO_2 for Zone 1. Transport-related CO_2 emissions are therefore almost 85% higher for residential developments in the commuter towns than in the city centre and approximately 16% and 54% higher for suburban (Zone 2) and extra-urban (Zone 3) areas, respectively.

3.3 Operation

Results for the annual operational (heating, hot water and small power) energy requirements and associated CO_2 emissions for four different dwelling types are shown in Table 2 both on a per square metre and per dwelling basis. Detached houses were found to emit 88 kg CO_2/m^2/annum of floor area; the corresponding figures for semi-detached houses, terraced houses and apartments were 67, 55 and 48 kg/m^2, respectively. Detached houses consume the greatest amounts of energy due to their higher floor areas and completely exposed external envelopes. Conversely, apartments have the lowest per dwelling consumption due to both their smaller size and reduced area of external envelope. Results were compared to emissions statistics for Scotland due to its similar weather and demographics; these are presented in Fig. 8. It can be seen that Scottish emissions compare favourably but are lower for detached and, to a lesser extent, semi-detached houses and are similar for terraced houses and apartments. These differences may be accounted for by the lower CO_2-intensity of electricity production in Scotland and the relatively large sizes of detached and semi-detached houses constructed in the GDA over the period being analysed.

Figure 7 shows annual operational CO_2 emissions per capita in each zone, taking account of the mix of house types and average occupancies for each zone. On average, each person in Zones 3 and 4 consumes approximately 85% more energy than in Zone 1 and 30% more than in Zone 2 in order to heat and power their home. This is due to the dominance of detached houses in the exurbs and commuter towns and the greater concentration of apartments in the city centre and suburbs. This effect of housing type distribution on increasing per capita operational energy use in Zones 3 and 4 is offset to some degree by higher dwelling occupancy rates in these areas (3.0 per dwelling versus 2.5 for urban).

3.4 Maintenance and demolition

The average energy requirements associated with maintaining and improving a domestic dwelling were estimated

Table 2 Annual operational energy requirements and associated CO_2 emissions for different dwelling types

Dwelling type	Energy requirements		CO_2 output		Average size (m^2)
	(GJ/dwelling/year)	(MJ/m^2/year)	(t/dwelling/year)	(kg/m^2/year)	
Apartments	32	400	3.8	48	75
Terraced	65	623	5.8	55	105
Semi-Detached	92	763	8.1	67	121
Detached	161	886	15.9	88	181

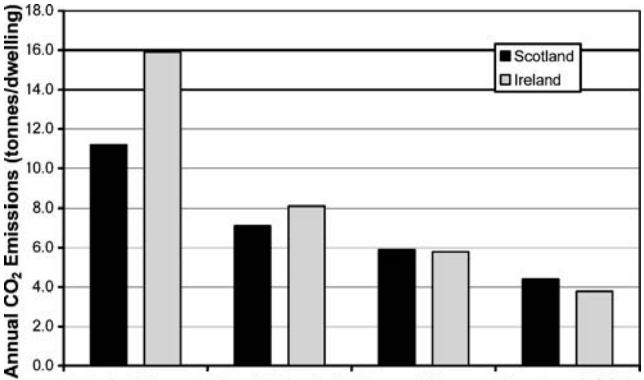

Fig. 8 CO_2 emissions per dwelling for Scottish housing stock and GDA sample (source: Hinchliffe 2005)

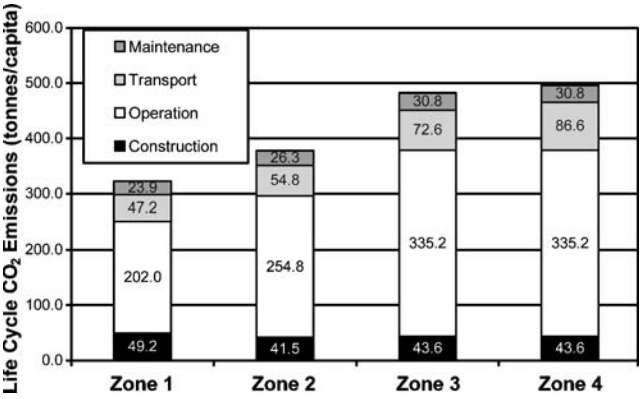

Fig. 9 Life cycle component CO_2 emissions for each zone (demolition has been excluded since emissions are negligible compared to other life cycle stages)

using input–output analysis (as described in Section 2.5) to be 0.046 GJ/m^2/annum producing 6.8 kg CO_2/m^2/annum. Due to a lack of data it was not possible to differentiate between maintenance requirements for different dwelling types. It is likely that this aggregation problem underestimates maintenance energy requirements for detached and semi-detached houses given the greater opportunities for the major refurbishment and extension of such properties over apartments and—to a lesser extent—terraced houses. Therefore, in the absence of more disaggregated data, the same per square metre energy and CO_2 emissions intensities were applied to the average house size for each zone.

The cost of demolishing a typical 120 m^2 domestic dwelling (brick, block and timber floor construction) was estimated at € 17,500 in 2004 and the energy intensity for Nace 45.1 was calculated to be 2.25 MJ/€ of demolition expenditure. Combining these figures gives a housing demolition energy requirement of approximately 0.33 GJ/m^2 with associated emissions of 8.3 kg CO_2/m^2. The additional cost of demolishing the concrete or steel structure in an apartment is estimated to be approximately € 14,300, resulting in an apartment demolition energy intensity of 0.60 GJ/m^2 with associated emissions of 15.1 kg CO_2/m^2. These figures do not allow for recycling.

3.5 Life cycle

Figure 9 shows the CO_2 emissions for a residence built in the last 10 years in each of the four zones in the GDA. This assumes a building lifespan of 100 years. On average Zone 3 and 4 occupants consumed 92–98% more energy than those in Zone 1 and approximately one third more than Zone 2. Per capita CO_2 emissions in Zones 3 and 4 were approximately 50–55% greater than Zone 1 and almost 33% greater than Zone 2. The higher CO_2/energy ratio in Zone 1 can be accounted for by the high incidence of CO_2-intensive electrical storage heating in Zone 1 apartments.

Figure 10 shows CO_2 emissions for each dwelling type excluding transport but including the construction, operation and maintenance life cycle stages (demolition has been excluded since these emissions are negligible). It can be seen that operational emissions dominate and that total emissions over 100 years are significantly higher for detached houses (1,773 t) than for semi-detached (929 t), terraced (680 t) and apartments (482 t). This is due to the greater electrical and space heating requirement associated with the large floor areas of detached houses in Ireland and their relatively greater exposed-envelope/volume ratios. These figures demonstrate significant benefits in promoting high-density spatial planning policies.

When the data for all zones are aggregated, operational requirements dominate accounting for 68% of all CO_2 emissions followed by transport at 17%, construction at 9% and maintenance at 6%. Demolition contributes to less than 0.5% of life cycle emissions.

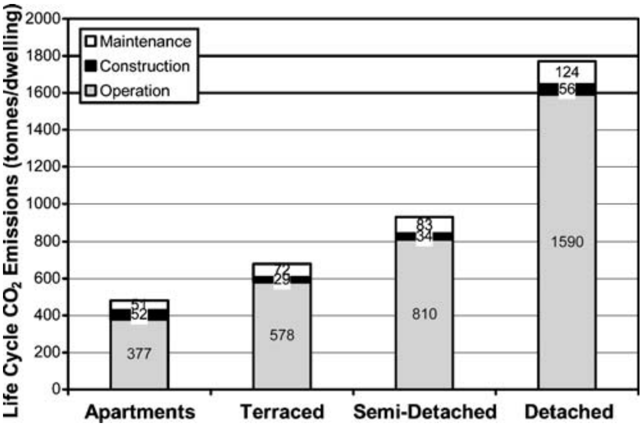

Fig. 10 CO_2 emissions for each dwelling type excluding transport (demolition has been excluded since emissions are negligible compared to other life cycle stages)

4 Conclusions

The life cycle per capita CO_2 emissions in the GDA are approximately 50–55% greater in the exurbs and commuter towns than in the city centre; corresponding energy intensities vary by almost 100%. Per capita residential emissions over a 100-year life span taking into account construction, operational, transport, maintenance and demolition energy requirements were 323, 378, 482 and 496 tonnes, respectively for the urban, suburban, extra-urban and commuter town zones studied.

Of the five life cycle stages studied, operational energy requirements (predominantly space heating and hot water, but including power) contributed most significantly to emissions (68%), followed by transport (17%), construction (9%) and maintenance/renovation (6%); demolition was found to have a negligible effect. Annual per-capita operational emissions in Zones 3 and 4 were almost twice as great as those in Zone 1 both due to larger dwelling sizes and the predominance of detached and semi-detached dwellings (with large amounts of exposed walls) in the former and the predominance of smaller apartments in the latter. The car dominated as the preferred mode of transport in all zones; however, this was most pronounced in the zones furthest from the city centre (zones 3 and 4) where per capita emissions were almost twice those of residents in the city centre. It is interesting to note that despite their smaller size, the per capita construction energy intensities of apartments were approximately one third greater than for traditional detached, semi-detached and terraced residences due to the greater energy intensity of the structure. However, this difference was more than compensated for by the significantly lower operational emissions referred to above.

By 2006 residential development in the GDA completed over the 10 years up to and including that year was contributing 3,434 kt CO_2/annum—representing 4.9% of national emissions for that year; this comprised 2,108 tonnes of recurrent emissions (operational, transport, maintenance) and 1,325 kt of once off construction-related emissions. Had the development policy required Zone 1-type development and transport modes, then emissions for the year 2006 would have been 2,892 kt CO_2—a reduction of almost 16% over the actual figure and representing approximately 4.1% of national emissions. However, in this scenario recurrent emissions would have been reduced to 1,417 kt CO_2—a reduction of 33% over actual levels.

5 Recommendations and perspectives

Irish and other governments' residential sector energy policies tend to focus on minimising operational energy use and emissions. This approach is broadly supported by the findings of this paper that approximately two thirds of emissions arise from heating and powering dwellings in the GDA. However, although operational CO_2 emissions dominate those from transport, maintenance and construction, assessing only operational emissions would underestimate 100-year emissions by approximately one third. This demonstrates the benefits of LCA in evidence-based policy-making and highlights the need for policy measures targeted at mitigating non-operational emissions. Indeed, the relative importance of these emissions will increase as existing energy policies further reduce operational emissions.

An additional weakness of existing policies is the emphasis placed on reducing unit area emissions through energy efficiency measures. In Ireland, this policy has run concurrently with the development of large detached dwellings in the area studied. However, the results above clearly indicate that large, detached dwellings achieve national emissions policy objectives despite having a significantly higher environmental impact than smaller 'attached' dwellings such as apartments. Although other social and functional considerations must be taken into account, a policy favouring high-density residential development with more modest floor areas would reduce emissions. Such a 'high density' planning approach would have the added benefit of reducing car dependency since residences could be constructed closer to urban centres and public transport infrastructure with relatively low emissions intensities. The operational and transport emissions from the worst performing zones could be reduced by approximately 40% with suitable policies.

Acknowledgement The author wishes to thank for the support of those who assisted in providing data for this work: the Pierse Group, Dublin Transportation Office, CODEMA, and Sustainable Energy Ireland. Funding for this work was provided by the Dublin Institute of Technology's Research Support Unit.

References

Acquaye A, Duffy A, Basu B (2008) Development of a construction sub-sector embodied energy hybrid analysis. Faculty of Engineering, Dublin Institute of Technology. Working Paper 1. http://arrow.dit.ie/dubenart/1

Bullard C, Penner P, Pilati D (1978) Net energy analysis—handbook for combining process and input–output analysis. Resour Energ 1:267–313

Castro M, Remmerswaal J, Reuter M (2003) Life cycle impact assessment of the average passenger vehicle in the Netherlands. Int J Life Cycle Assess 8(5):297–304

Cox J, Hickman A (1998) Aggregated emission factors for road and rail transport, report for MEET project: methodologies for estimating air pollutant emissions from transport. TRL, Berkshire

Crawford RH (2007) Validation of a hybrid life-cycle inventory analysis method. J Environ Manage (in press), Corrected Proof, viewed 7

May 2007 from <http://www.sciencedirect.com/science/article/B6WJ7-4NNPH93-1/2/93e3f688ca69d69d7aa89c2a0cdde130>

CSIRO (2007) Embodied Energy. Viewed 26 May 2008, http://www.cmmt.csiro.au/brochures/tech/embodied/index.cfm

CSO (Central Statistics Office) (2006a) 2000 Supply and use and input–output tables. Stationary Office, Dublin, Ireland

CSO (Central Statistics Office) (2006b) Construction and housing in Ireland. Stationary Office, Dublin, Ireland

CSO (Central Statistics Office) (2006c) 2004 Census of Building Construction, Central Statistics Office, Dublin. Viewed 16 August 2008, http://www.cso.ie

CSO (Central Statistics Office) (2007a) Census 2006 Reports—Volume 6 Housing. Viewed 13 February 2008, http://www.cso.ie

CSO (Central Statistics Office) (2007b) Statistics: housing and households. Viewed 16 August 2007, http://www.cso.ie

CSO (Central Statistics Office) (2007c) Environmental accounts for Ireland 1997–2005. Stationery Office, Dublin

Davies S, Diegel S (2007) Transportation energy data book. Edition 26. Oak Ridge National Laboratory, Tennessee

Davis Langdon and Everest(2004) Spon's Architects and Builders Price Book 2004. Spon, London

DTO (Dublin Transportation Office) (2006) Greater Dublin Area Travel Demand Management Study—Dublin 2004, DTO. Viewed 13 November 2007, http://www.dto.ie/web2006/TDMS.pdf

EEA (2003) European Environment Agency Indicator Factsheet TERM 2003 27 EEA 31—overall energy efficiency and specific CO2 emissions for passenger and freight transport. Viewed 10 February 2009, www.eukn.org/eukn/themes/Urban_Policy/Housing/Housing_quality/Sustainable-Refurbishment-of-High-Rise-Residential-Buildings_1001.html

EPA (2007) Ireland's greenhouse gas emissions—provisional estimate for 2005, Environmental Protection Agency. Viewed online 14th February 2008, http://www.epa.ie

Eurostat (2007) Ireland—energy mix factsheet. Viewed online 14th February 2008, http://ec.europa.eu/energy/energy_policy/doc/factsheets/mix/mix_ie_en.pdf

Frank LD, Stone B, Bachman W (2000) Linking land use with household vehicle emissions in the central Puget sound: methodological framework and findings. Transport Res Part D. 5(3):173–196

Hammond G, Jones C (2006) Inventory of Carbon and Energy—Version 1.5 Beta, University of Bath, UK. Accessed 26 August 2008, http://people.bath.ac.uk/cj219/

Hinchliffe S (2005) Scottish housing condition survey: energy efficiency and estimated emissions from the Scottish Housing Stock 2003/04, Scottish Executive. Viewed 3 October 2008, http://www.scotland.gov.uk/Resource/Doc/161328/0043785.pdf

Howley M, O'Leary F, Ó Gallachóir B (2006) Energy in Ireland 1990–2005. Sustainability Energy Ireland, Dublin, pp 67–73

Næss P (2006) Accessibility, activity participation and location of activities: exploring the links between residential location and travel behaviour. Urban Stud 43(3):627–652

Netherlands Ministry of Housing, Spatial Planning and the Environment (2004) Sustainable refurbishment of high-rise residential buildings and restructuring of surrounding areas. Report for European Housing Ministers' Conference held in Prague, Czech Republic 14–15 March 2005. Viewed 22 January 2008, www.eukn.org/eukn/themes/Urban_Policy/Housing/Housing_quality/Sustainable-Refurbishment-of-High-Rise-Residential-Buildings_1001.html

Newman P, Kenworthy J (1999) Sustainability and cities: overcoming automobile dependence. Island, Washington, pp 31–36

SEI (2004) Strategies to reduce greenhouse gases from Irish transportation. SEI, Dublin. Viewed 18 May 2007, http://www.sei.ie/uploadedfiles/InfoCentre/GHGtransportFNLformattedcover04.pdf

SEI (2005) Energy consumption and CO_2 emissions in the residential sector 1990–2004. Viewed 22 May 2007, www.sei.ie/index.asp?locID=70&docID=-1

SEI (2006) Energy in transport: trends and influencing factors. SEI, Dublin

Yohanis YG, Norton B (2002) Life-cycle and embodied energy for a generic single-storey office building in the UK. Energy 27:77–92

ID: 11367/59.

AUTHOR QUERY FORM

Dear Author,

During the preparation of your manuscript for typesetting, some questions have arisen. These are listed below. Please check your typeset proof carefully and mark any corrections in the margin of the proof or compile them as a separate list.

Queries and/or remarks

Location in Article	Query/Remark
	No queries.

Thank you for your assistance.