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Modelling the impact of urban form on household energy demand and related CO_2 emissions in the Greater Dublin Region

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ABSTRACT

This study aims to investigate the relationship between household space heating energy use and urban form (land use characteristics) for the Greater Dublin Region. The geographical distributions of household energy use are evaluated at the Enumeration Districts (ED) level based on the building thermal balance model. Moreover, it estimates the impact of possible factors on the household space heating consumption. Results illustrate that the distribution profile of dwellings is a significant factor related to overall heating energy demand and individual dwelling energy consumption for space heating. Residents living in compact dwellings with small floor areas consume less energy for space heating than residents living in dwellings with big floor areas. Moreover, domestic heating energy demand per household was also estimated for two extreme urban development scenarios: the compact city scenario and the dispersed scenario. The results illustrate that the compact city scenario is likely to decrease the domestic heating energy consumption per household by 16.2% compared with the dispersed city scenario. Correspondingly, the energy-related CO_2 emissions could be significantly decreased by compact city scenario compared with the dispersed city scenario.

1. Introduction

Urban areas throughout the world have increased in size over the past few decades. With increasing urbanization, cities are growing in number, population and complexity, and making a major contribution to global climate change (IPCC, 2007). In Ireland, the government has set a target of reducing greenhouse gas emissions by 3% per year based principally on achieving targets for sustainable energy development (DOEHLG, 2007). To meet these targets, policy makers concerned with sustainable development are required to focus on urban planning. One of the main objectives is to develop residential settlement forms in a manner which encourages energy-efficient housing layouts and minimises transport-related energy consumption.

Research about effect of urban form on residential energy demand is a new field which has just emerged in this decade, while the relationship between urban form and transport energy use is currently a topic under active studies. Some research supports the contention that urban form can affect energy consumption per household and resulting greenhouse gas emissions from land use patterns (Ewing and Rong, 2008; Holden and Norland, 2005). There are some factors of urban form (land use characteristics) that significantly influence domestic energy demand (energy use for heating and cooling): population density, size and age and type of housing, in addition to local climate conditions (Holden and Norland, 2005). A dispersed residential land use pattern is characterised by larger houses and more detached units, which consume more energy than the smaller houses and attached units typical of more compact communities (Ewing and Rong, 2008). Compact residential built environments might be expected to reduce heating loads in winter. Moreover, dwellings and their servicing infrastructure, which form an integral part of the future built environment, can affect national and regional energy demand and resource consumption over a long time period (Ghosh and Vale, 2006).

Holden and Norland (2005) claimed that the implications of a compact urban form on residential energy use are likely to depend on the type of housing and grouping of housing, which are two major land use characteristics that influence energy consumption for space heating and cooling with local climate. Their study also shows that single-family housing is less efficient than multifamily housing, while residents of larger and older houses use more energy than that of smaller and newer units due to the advance in modern building. Consequently, upgrading existing buildings in energy-efficiency and improving the insulation regulations could be one of the important ways to decrease energy demand for space heating (CODEMA, 2007; Randolph, 2008).

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Previous work on energy efficiency of urban form considers that compact urban form is more important to save energy use on transport. Moreover, increasing the compactness of cities has been being recognised by researchers as an effective way to reduce CO_2 emissions by reducing energy use for space heating or facilities (Hamin and Gurran, 2008). However, a study by Kahn (2000) based on the 1993 U.S. Residential Energy Use Survey indicates no significant difference of the residential energy consumption between suburbanites and their counterparts in the central cities within the same metropolitan areas. Further studies on the effect of urban form on residential energy use are required for more conclusive judgements.

This study focuses on an investigation of the relationship between urban form (land use characteristics) and household energy demand for space heating. Projected land-use changes by MOLAND Model are employed to estimate future household heating energy demand. The theory of compact city is also discussed in terms of energy-efficiency for pace heating.

In this study, the Greater Dublin Region (GDR), shown in Fig. 1, is chosen as the case study area including Dublin City, Dun Laoghaire, Fingal, South Dublin, Kildare, Meath, Louth and Wicklow. In 2006, the population of the GDR was 1772,079 which accounted for nearly 42% of the total population (4234,925) of Ireland. Additionally, over one million citizens, approximately 30% of the national population, live in the Dublin Metropolitan Area (Dublin city, Dun Laoghaire, Fingal, and South Dublin) which extends over only 922 km^2, 1.3% of total state's area. The GDR has naturally become one of the most important metropolises in Ireland and in Europe. With rapidly increasing population, energy for domestic and transport use is likely to rise significantly in the GDR in the next decades. Consequently, it is essential to control the GDR's increasing energy consumption to reduce the overall increasing national energy demand.

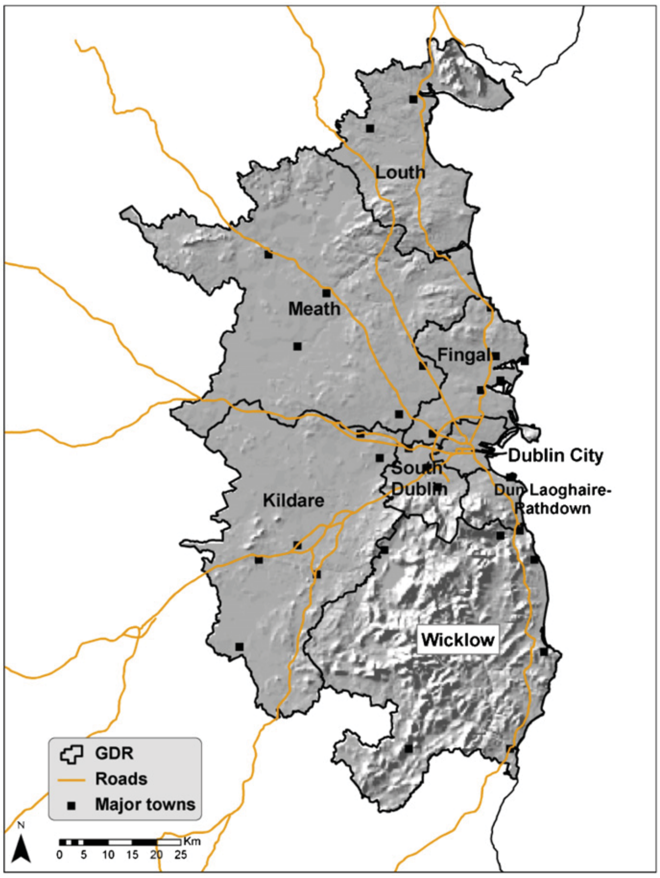

Fig. 1. Case study area: the Greater Dublin Region (GDR).

2. Methodology and data

This investigation employed a two-step analysis. First, the heating energy demands were calculated for different residential dwellings based on a thermal balance model. Based on this analysis, average heating energy demand for Enumeration Districts (ED) was estimated for the GDR according to housing census data (2006), which were obtained from the Central Statistics Office and contains information about accommodation type, age and number of rooms. Additionally, the historical data of electricity energy consumption per capita and natural gas sales per capita in 2006 was used to adjust the estimated heating energy demand per household at ED level.

The second step evaluated the spatial distribution of energy demand. Heating energy demand for different residential settlement patterns specified by the MOLAND model was statistically analysed. The impact of urban from on heating energy demand per household was also studied. Future domestic energy demand for space heating was projected based on future residential settlements changes which are estimated by the MOLAND model integrated with the future climate scenario data. The CO_2 emissions from dwellings associated with energy consumption were also estimated for the GDR.

The simulation model for analyzing heating energy consumption was based on the Heat Energy Rating (HER) Calculation described in Appendix C of the Building Regulations (Conservation of Fuel and Energy Dwellings) (DOEHLG, 2002a). The Heat Energy Rating is a measure of the annual energy requirements of a dwelling for space heating and domestic hot water for standardized conditions. Generally, the heating of a building is essentially an energy balance. To maintain the internal space at a constant temperature the heat inputs into the building must balance heat losses. Heat inputs include input from the heating system (Q_h), solar gains (Q_{g_solar}) and input from occupancy ($Q_{g\_opccupancy}$). Heat losses include losses through the fabric ($Q_{l\_fabric}Q_{l\_fabric}$), thermal bridging (Q_{g_bridge}) and as a result of ventilation ($Q_{g\_ventilation}$).

As this is an energy balance, the sum of the losses and gains (ΣQ) must equal to zero.

$$\sum Q = \sum Q_g - \sum Q_l = 0 \quad (1)$$

ΣQ is sum of the energy gains and losses, ΣQ_g is the total heat gains, and ΣQ_l is the total loss through fabric and ventilation. By aggregating all the losses and gains associated with the building, the heating load can be specified. Once the heating load had been determined, the heating energy consumption Q_h can be calculated from:

$$Q_h = (Q_{l\_fabric} + Q_{l\_ventilation} + Q_{l\_bridge}) - (Q_{g\_solar} + Q_{g\_occupancy}) \quad (2)$$

The detailed procedures of calculation for heat gains and heat losses are presented in Appendix C of the Building Regulations (Conservation of Fuel and Energy Dwellings) (DOEHLG, 2002a).

3. The profile of housing stock in the GDR

In order to study the energy consumption pattern, the profile of housing stock in the GDR needs to be specified. The energy demand for space heating is influenced by two major factors: housing characteristics and household density. Household density has been recognised as one of the significant characteristics associated with domestic energy demand. In the GDR, the

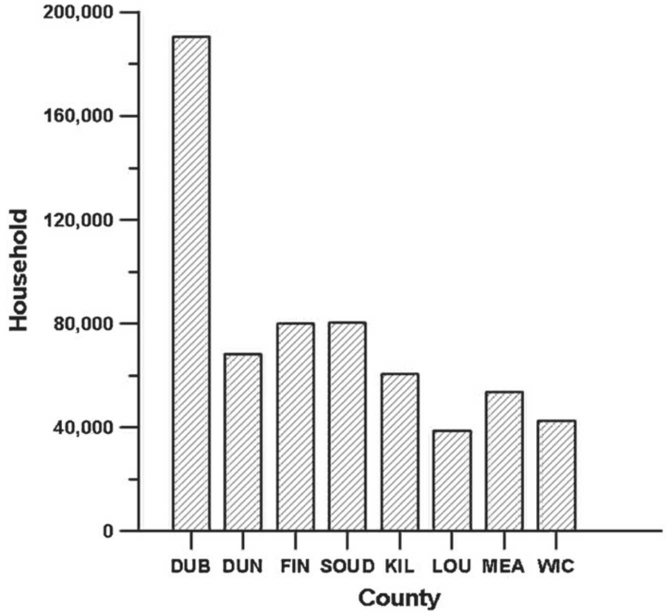

Fig. 2. Number of households by county in 2006 (DUB: Dublin City; DUN: Dun laoghaire; FIN: Fingal; SOUD: South Dublin; KIL: Kildare; LOU: Louth; MEA: Meath; WIC: Wicklow).

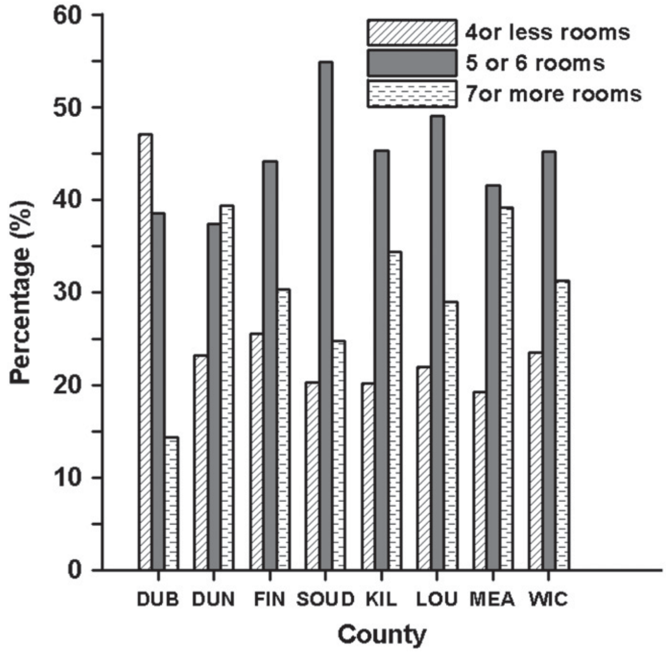

Fig. 3. Percentage of households by floor area by county in 2006 (DUB: Dublin City; DUN: Dun laoghaire; FIN: Fingal; SOUD: South Dublin; KIL: Kildare; LOU: Louth; MEA: Meath; WIC: Wicklow).

distribution of household in 2006 is characterized by a highly uneven distribution reflecting settlement history and variations in the geography of more recent development. In 2006, the number of overall households in the GDR was 616,857. Fig. 2 shows that over 190,000 households were resident in the Dublin City (DUB) region, nearly equivalent to combined number of households in Kildare (KIL), Louth (LOU), Meath (MEA) and Wicklow (WIC). County Louth (LOU) has the minimum number of households compared with that of other fringe counties in the GDR.

Fig. 3 shows the households as percentage of total households by floor area in 2006. It illustrates that the higher percentages of households living in small houses (with four or less rooms) were in Dublin City, while lower percentage are found in fringe counties. Overall, average 45% of total households were living in medium houses (with five or six rooms), while about 30% in large houses (with seven or more rooms).

The geographical distribution of households in 2006 is illustrated in Fig. 4. The dominance of Dublin and its impact on settlements throughout the Greater Dublin Region is also evident in Fig. 4. The northwest and southwest of the GDR are characterised by weak urbanisation with lower household density of less than 50 households/km^2. By contrast, parts of the midlands have a number of competing urban centres with high population density of over 1000/km^2 at the edge of Dublin commuter hinterland. However, throughout the urban fringe areas, ED population densities are generally very low, less than 50 household/km^2, mainly due to long-distance commuting to Dublin's metropolitan area. Very low densities of less than 10 household/km^2, which occurs in rural EDs, are mainly restricted to mountainous or other inhospitable areas.

Regional differences in the distribution of households by dwelling age are shown in Fig. 5. This illustrates that in the GDR, most households are living in houses built before 1990 with the lowest percentage of houses built after 2000. The largest proportions of households living in dwellings built before 1990 are in Dublin City and Dún Laoghaire at 77.6% and 76.5%, compared to total county households, respectively. In 2006, only a few households were living in dwellings which were built after 2000. This indicates that there is a great opportunity to reduce domestic energy for space heating by improving the thermal insulation level of existing dwellings by introducing the new Building Code 2002.

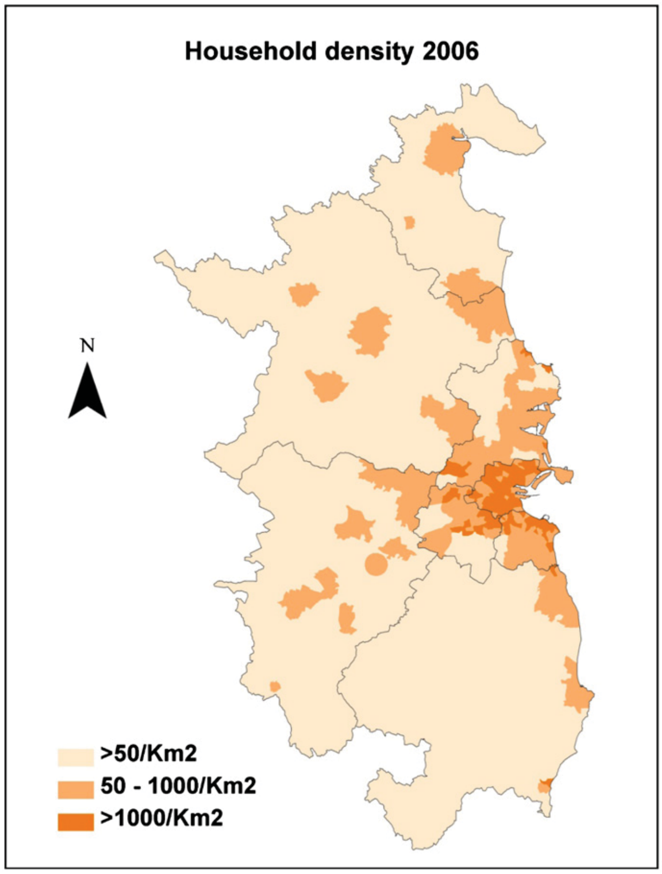

Fig. 4. Household density in the Greater Dublin Region, 2006.

The residential patterns illustrated by the previous figures have shown the principal characteristics of dwellings in the GDR. Significant urban–rural differentials are observed in terms of dwelling age and dwelling size. More households are living in small or medium dwellings in the major urban regions, such as Dublin City, South Dublin, and Dun Laoghaire, while the big house rates are high in the most rural areas and small towns due to the availability of more open space and presumable lower land purchasing cost. In the GDR, in excess of 60% of dwellings were built pre 1990, a period when thermal standards of construction were lower than they are today. Additionally, the highest share rate of about 80% is found in Dublin City and Dun Laoghaire. Significant variations are found in the proportion of households living in dwellings pre 1990. However, less regional contrast is evident in the distribution of households living in dwellings built in 1990 onwards. Dwellings completed after 2001 only share about 20% of total housing stock. However, the population has been projected to significantly increase in the next two decades. The changes in population and housing stock are likely to have a significant impact on the demand for residential dwellings, and consequently, on domestic energy demand.

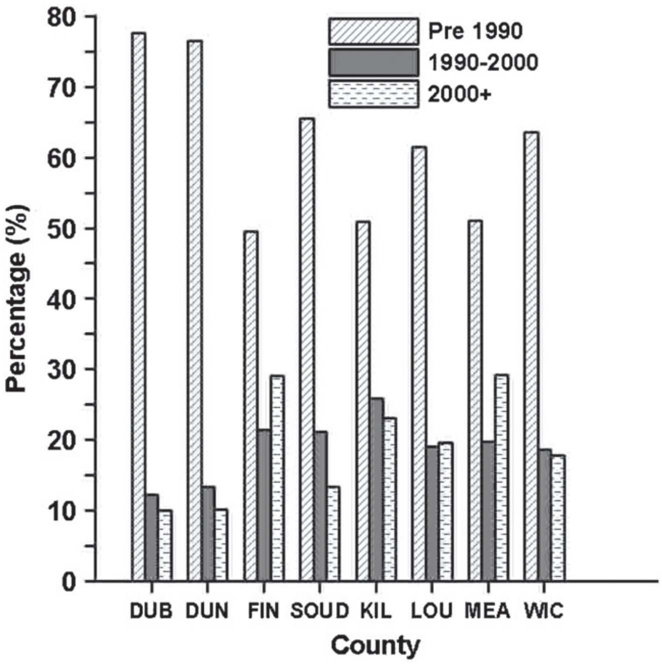

Fig. 5. Households by dwelling age as percentage of total households in 2006. (*DUB: Dublin City; DUN: Dun laoghaire; FIN: Fingal; SOUD: South Dublin; KIL: Kildare; LOU: Louth; MEA: Meath; WIC: Wicklow*).

4. Spatial analysis of household energy demand for space heating in the GDR

4.1. Simulated heating energy of dwellings in the GDR

This section analyses the spatial distribution of household energy demand in the Greater Dublin Region based on the GDR's housing profile which has discussed in Section 3. The heating energy demands for categorized households were calculated by dwelling age, size and floor areas based on the thermal balance model discussed in Section 2.

In this calculation of heating energy demand, different types of exposed elements of buildings should be accounted for, such as different wall types, floor types etc. Each element must have a corresponding *U*-value which is the measure of the rate of heat loss through a material. In this study, the *U*-values of each elements for different dwellings illustrated in Table 1 were assumed according to Building Regulations 1990, 1997, 2002 (DOEHLG, 1990; 1997; 2002b). Dwelling floor areas were estimated based on a housing study by the City of Dublin Energy Management Agency (Codema) (2002). Based on the housing census data for 2006, all dwellings were categorized into 10 dwelling-types associated with different dwelling age and size. Dwellings built pre 1990 were all assumed to have low thermal insulation according to the Building Regulation 1990 (DOEHLG, 1990). The thermal insulation level for dwellings built between 1990 and 2000 were estimated according to Building Regulation 1997 (DOEHLG, 1997). Similarly, dwellings built 2001 onwards were estimated with higher thermal insulation level based on Building Regulation 2002 (DOEHLG, 2002b).

The results, as shown in Fig. 6, suggest that energy consumption is most likely strongly related to floor area. Apparently, under conditions of similar insulation, energy for space heating is increasingly corresponding to growth in floor areas. In a similar floor area group, apartments seem to consume less space heating

Table 1
The profile of simulated dwellings.

Categories	Type	Average floor area (m^2)	U_{wall} ($W/m^2/K$) [a]	U_{roof} ($W/m^2/K$)	U_{window} ($W/m^2/K$)	U_{floor} ($W/m^2/K$)
House with 1–4 rooms	1	50	0.45	0.25	3.1	0.45
House with 5–6 rooms (Pre 90)	2	107	0.60	0.3	4	0.55
House with 5–6 rooms (91-00)	3	94	0.45	0.25	3.3	0.45
House with 5–6 rooms (01 & later)	4	99	0.27	0.16	2.2	0.25
House with seven or more rooms (Pre 90)	5	125	0.60	0.3	4	0.55
House with seven or more rooms (91-00)	6	145	0.45	0.25	3.3	0.45
House with seven or more rooms (01 & later)	7	164	0.27	0.16	2.2	0.25
Apartment (Pre 90)	8	62	0.60	0.3	4	0.55
Apartment (91-00)	9	56	0.45	0.25	3.3	0.45
Apartment (01 & later)	10	98	0.27	0.16	2.2	0.25

[a] $W/m^2/K$: Watts per Metre Squared per Degree Kelvin.

energy compared with houses, suggesting that apartments are more energy efficient due to compact building construction and less heat loss through building fabrics and ventilation. The results also show that houses built pre 2001 consume more energy for space heating than similarly sized houses constructed in 2001 onwards. These result from changes in Building Control Regulation introduced in 2000 for improving the energy efficiency of buildings in Ireland.

4.2. Simulated heating energy demand at ED level in 2006

In this section, the annual energy demand at ED level was disaggregated based on the simulated dwelling heating energy demand, having regard to regional housing profiles and household types. Data on electricity demand and natural gas consumption in 2006 were also used to adjust the bias of simulation. The simulated dwelling heating energy demand at ED level included both electricity use and natural gas consumption.

Table 2 illustrates annual heating energy demand of the sample major towns in the GDR. These values were calculated for each E.D. using the methodology in Section 2. It can be clearly seen that the Dublin metropolitan region and major towns consume more energy for space heating than EDs in remote rural areas due to the geographical distribution of households and the housing mix. In fringe counties, most EDs with high annual energy consumption are located in areas where residents can easily commute to Dublin City. If one looks into the details, it can be seen that in 2006, the highest annual heating energy demand was calculated at about 216 GW h/yr which is located in the ED of Blanchardstown Blakestown in Fingal, associated with a high household number of 10,581 (Table 2). The lowest annual heating energy consumption is less than 1 GW h/yr found in ED of Lugglass in Wicklow with small household number. Generally, the ED's average heating energy is about 21 GW h/yr (Table 2). Several EDs in east coastal areas are observed to have high heating energy demand compared with other EDs in inland fringe areas.

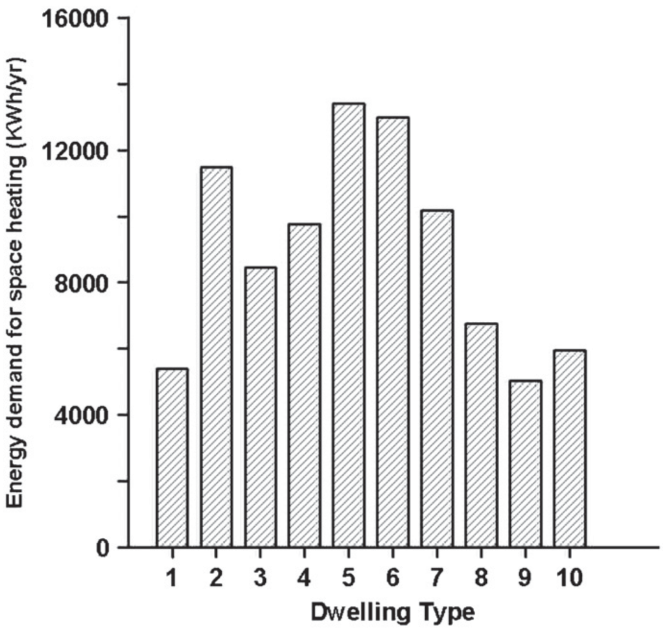

Fig. 6. Simulated dwelling energy demand by age and dwelling type.

The spatial pattern of annual heating energy demand per household is shown in Fig. 7. The large areas in Dublin City, Fingal and South Dublin stand out with lower annual heating energy demand per household of less than 21,000 kW h/yr, while most areas of Meath, Louth and Kildare have high annual heating energy consumption of over 23,000 kW h/yr. Average heating energy demand for the overall GDR is about 21,000 kW h/yr. When specified EDs are examined considerable variation exists. E.g., Kimmage has the lowest annual heating energy demand of 16,153 kW h/yr/household, mainly due to the high household density of 3321 persons/km^2 and high proportion (67%) of small dwellings with less than four rooms (Table 2). On the other hand, the highest annual heating energy demand per household occurs in the E.D. of Foxrock Beechpark with 26,383 kW h/yr associated with a household density of 1096 persons/km^2 and a high proportion (86%) in big dwellings with more than seven rooms (Table 2). The major towns, such as Dundalk, Navan and Drogheda, also have lower energy consumption for space heating due to relatively higher household density and a lower percentage of big house with seven or more rooms. The simulated results, shown in Table 2 and Fig. 7 clearly indicate that high household density is likely to reduce the annual heating energy demand per household. An increase in proportion of relatively small size dwellings can also decrease the annual heating energy demand per household.

Fig. 8 shows the relationship between the heating energy use per household and household density in the case study regions. Heating energy use decreases with increasing household density. As for control population, the heating energy use per household is moderately related with household density.

Table 2
Household energy demand 2006 of sample urban areas in the Greater Dublin Region.

Sample urban areas	Household number	Household density (households/km^2)	Percentage of house with seven or more rooms (built pre 1990)	Percentage of houses with less than four rooms	Total energy demand (GW h/yr)	Average household energy demand (kW h/household/yr)
Kimmage	1428	3321	2.1%	67.6%	23	16,153
Airport	567	66	0.0%	4.9%	124	21,849
Blanchardstown - Blakestown	10581	1350	6.1%	25.2%	216	20,465
Dalkey	480	960	69.5%	2.4%	12	25,980
Foxrock - Beechpark	592	1,096	82.3%	4.0%	16	26,383
Naas	6506	359	15.2%	19.4%	144	22,135
Leixlip	4559	399	29.0%	12.0%	107	23,609
Maynooth	3693	109	13.7%	17.3%	81	21,918
Drogheda	9308	700	11.3%	24.7%	192	20,701
Dundalk	4542	186	12.4%	26.9%	93	20,558
Navan	1265	673	8.5%	31.6%	24	18,755
Lugglass	42	1	21.0%	25.4%	0.9	21,685

4.3. Sensitivity study of household energy demand to insulation level

The sensitivity of annual heating energy demand to dwelling thermal insulation level was studied based on the developed energy model and building characteristics of existing dwellings. The thermal insulation level of existing dwellings was assumed to be improved as the new construction insulation standards

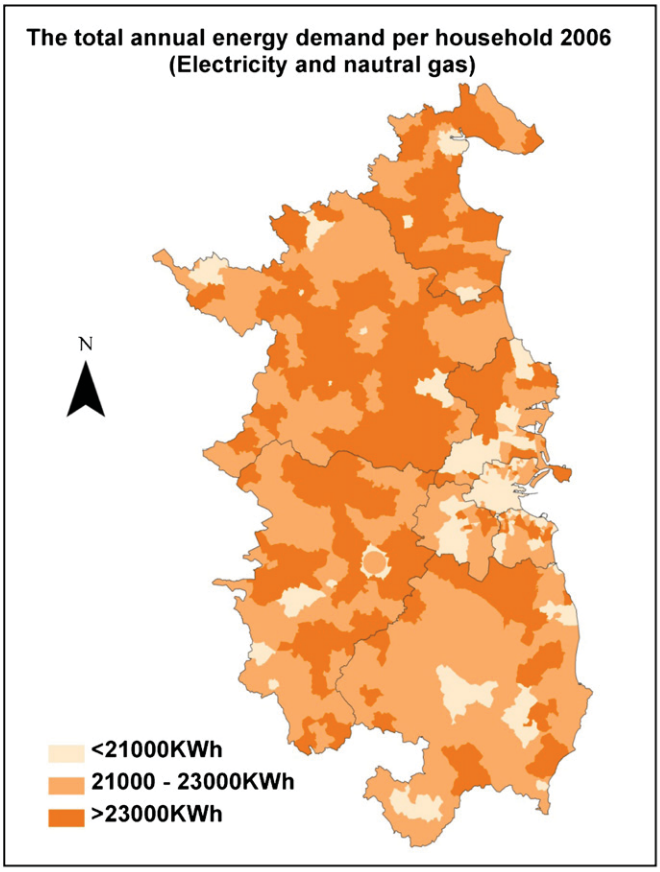

Fig. 7. Annual heating energy demand per household in 2006.

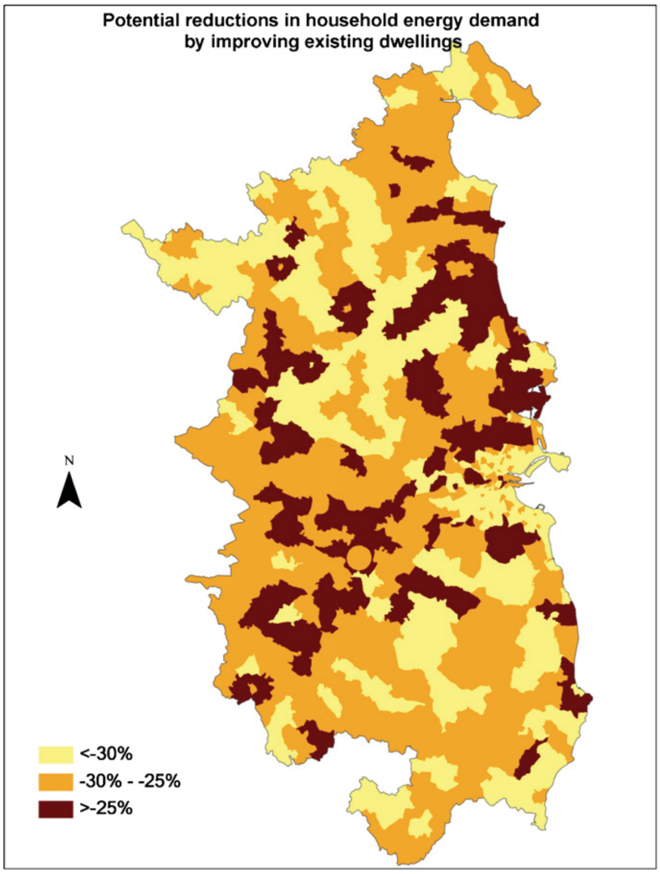

Fig. 9. Reductions in heating energy demand by improving insulation levels of existing dwellings.

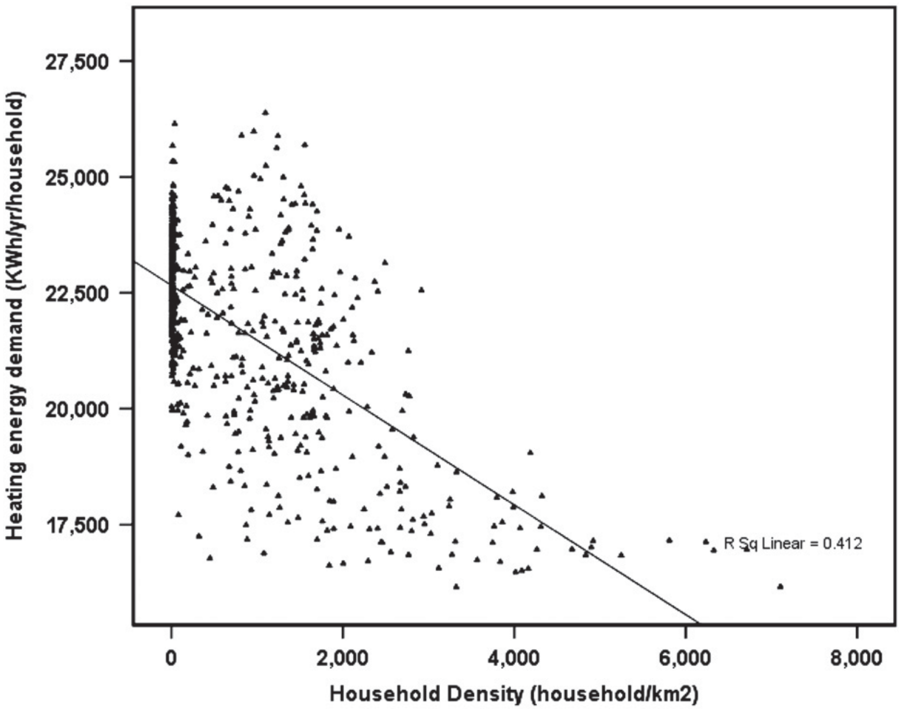

Fig. 8. Annual heating energy demand per household for heating and household density.

associated with the Building Regulations 2002 became operative. Dwellings, which were built before insulation and heating regulation were introduced in 2002, were assumed to be upgraded according to the new thermal insulation standards in this simulation.

The simulated annual heating energy demands are shown in Fig. 9 at ED level. Overall, in the GDR, annual heating demands are likely to decrease about 28% due to upgrading of existing dwellings, compared with current annual heating energy demand. Through improving thermal insulation of dwellings, large decreases in ED's annual energy demand are likely to occur in Dublin City, Louth and Wicklow due to high proportion of dwellings built pre 2001, while Kildare is expected to have smaller level of changes in annual energy demand. In the GDR, the overall average decrease in annual energy demand is about 28% within a range of 4–34%. The lowest decline of 4% in annual energy demand through insulation improvement is found in the ED of Dublin Airport due to about 83% of dwellings here being apartments which were built after 2001. The ED of Dalkey Avondale has the highest decrease of 34% in annual heating energy demand, accounted for by the high proportion (69%) of big dwellings built pre1990. The simulated results indicate that heating energy demand could significantly be reduced if existing dwellings could be improved through upgrading the thermal insulation. The insulation level is one of important factors which determine the household energy demand for space heating in the Greater Dublin Region.

5. Projected the future energy demand

It has been concluded that domestic heating energy demand is mainly influenced by the characteristics of urban form (household number, household density and dwelling profiles). Dwellings and their servicing infrastructure form an integral part of the future built environment and their pattern of development can affect the regional energy demand and energy-related greenhouse gas emissions over a long period of time. Building more energy-efficient homes and urban forms has therefore become the major objective for policy makers and urban planners coping with climate change. The main question is which kind of urban form is likely to reduce domestic energy demand for space heating. Based on the studies discussed above, the relationship between future heating energy demand and urban from was analysed. The future energy demands were also estimated according to the projected land use change for the GDR. First, the household density and heating energy demand was statistically analysed for four residential classes specified in the MOLAND model. Second, future energy demand was estimated based on the relationship between heating energy demand and residential settlements.

5.1. Relationship between heating energy demand and residential classes

The MOLAND (Monitoring Land Use/Cover Dynamics) urban and regional growth model used in this study is based on a spatial dynamics system called cellular automata (CA). The aim of this model is to assist spatial planners and policy makers to analyse a wide range of spatial policies and their associated spatial patterns (Barredo et al., 2003; Lavalle et al., 2004). By varying the inputs into the MOLAND urban model (e.g., zoning status, transport networks), the model can be used as a powerful planning tool to explore the future urban and regional development of the area of interest, under alternative spatial planning and policy scenarios. The outputs from the MOLAND urban model are maps showing

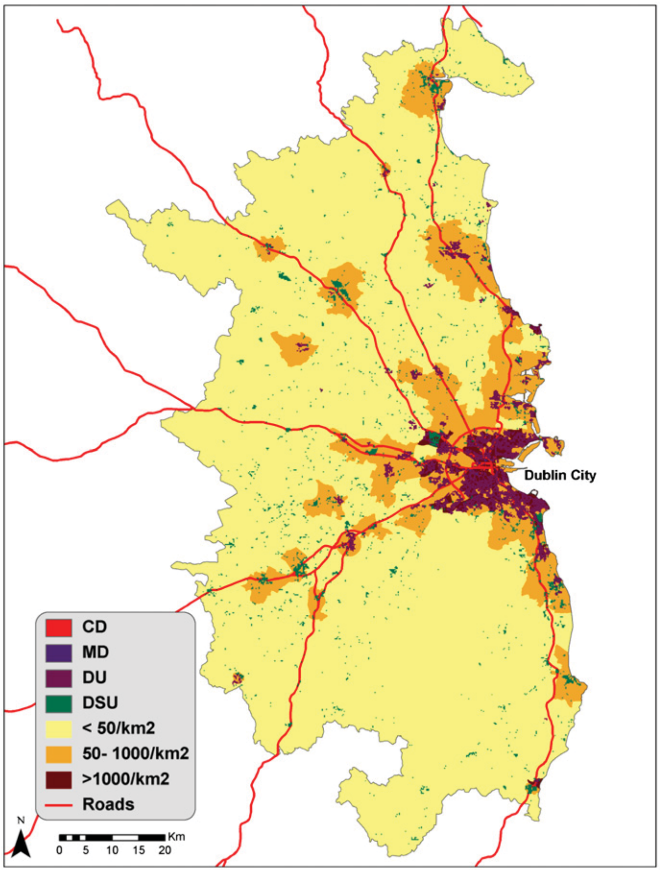

Fig. 10. Overlay map for household density and classes of residential settlements. Red curve line presents major roads; Red colour shows Continuous Dense Urban Form (CD); Blue means Continuous Medium Dense Urban Form (MD); Discontinuous Urban form (DU) and Discontinuous Sparse Urban Form (DSU) are shown in brown and green, respectively. Yellow colour indicates household density. (For interpretation of the references to colour in this figure legend, the reader is reffered to the web version of this article.)

the predicted evolution of land use in the area of interest. The MOLAND model uses 24 cell states representing the land use or land cover classes. The four residential land use classes, residential continuous dense urban fabric (CD), residential continuous medium-dense urban fabric (MD), residential discontinuous urban fabric (DU) and residential discontinuous sparse urban fabric (DSU), are very important for this study.

The relationship between the residential settlement pattern and household density in 2006 is displayed in Fig. 10 overlain by four classes of urban residential settlements and major roads in the GDR. It can be clearly seen that the residential continuous dense urban forms are corresponding to areas with high household density, while discontinuous sparse urban forms are reflecting the areas with low household density.

The major residential settlement centres occur along the main roads due to easily accessible transport facilities for commuters. Most residential dense settlements are centralised in the Dublin's Metropolitan Areas or major town regions. Only a few residential dense and medium dense urban forms are observed in Dublin City centre areas with household density in excess of 7000 households/km^2. Conversely, household densities of less than 20 households/km^2 can be found in rural regions (residential discontinuous sparse urban fabric). Major towns and large urban regions tend to have the densest residential settlements of the GDR. The geographical distribution of settlement patterns is very strongly influenced by the transport network system. The urban residential settlement areas are usually tightly constrained

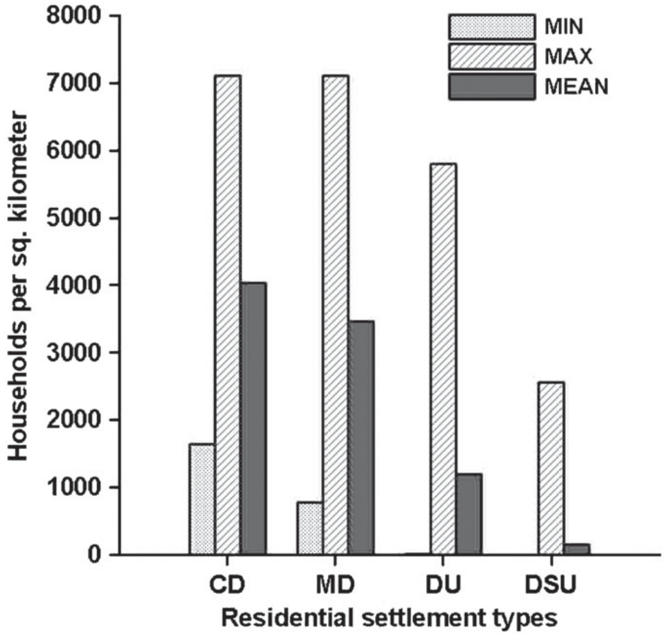

Fig. 11. Household density for four residential patterns of MOLAND (Continuous Dense Urban Fabric (CD); Residential Continuous Medium-Dense Urban Fabric (MD); Residential Discontinuous Urban Fabric (DU); and Residential Discontinuous Sparse Urban Fabric (DSU)).

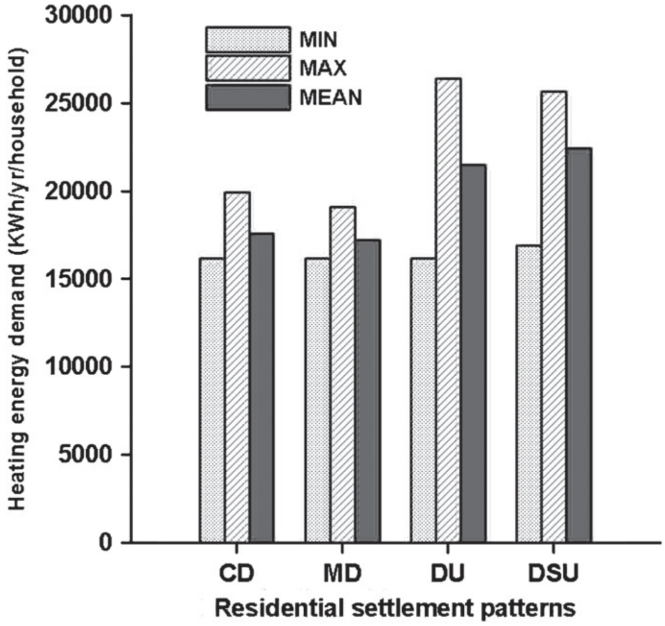

Fig. 12. Heating energy demand per household for four residential patterns of MOLAND.

around main towns or commuter towns where residents can conveniently access to public transport system. In addition, big urban areas are also found in or near east coastal areas with high household density. Conversely, most remote rural EDs are reflected as discontinuous sparse urban areas with very low average household density of 153 households/km^2.

The relationship between the population density and four residential forms is illustrated in Fig. 11. The statistical results indicate that the residential dense urban areas have an average household density of 4036 households/km^2, whilst the average household density of residential discontinuous sparse area is only 153 households/km^2. The minimum household density for discontinuous sparse urban forms is only 1 household/km^2 which is much lower compared with the continuous or medium dense urban forms. A few very dense areas of 7104 households/km^2 are found for residential continuous dense and medium dense urban forms within Dublin City Centre.

Based on the knowledge of the characteristics of urban form in the Greater Dublin Region, the energy demand per household for different settlement patterns was also analysed. The overall statistical analysis results on the relationship between domestic heating energy demand and residential settlement patterns are shown in Fig. 12. This figure illustrates that the average energy demand per household for residential dense urban area is 17,567 kW h/yr which is 4,846 kW h/yr less than that of the residential discontinuous sparse areas (22,414 kW h/yr). The highest average heating energy demand per household is 22,414 kW h/yr for the discontinuous sparse urban forms, whilst the lowest average energy demand per household of 17,214 kW h/yr is for continuous medium dense urban forms.

The heating energy demands for discontinuous urban forms have a wide range of 16,153–26,383 kW h/yr. The maximum heating energy demand for the continuous urban forms is decreased by in excess of 25% compared with 25,672 kW h/yr for the discontinuous sparse urban forms. The minimum energy demand per household is not very different for four residential urban forms.

The results indicate that the dense residential areas have much higher energy efficiency and nearly 22% lower energy consumption for space heating compared with sparse residential settlement areas, probably because of better urban planning and dwelling insulation standards. As for discontinuous settlements, the residents in discontinuous sparse areas need more energy for space heating than residents in discontinuous urban areas. In contrast, the continuous dense urban fabric, which primarily consists of high compact mixed commercial and residential buildings, seems to have slightly higher average energy demand for space heating compared to medium dense urban settlements. A contribution to this observation may be related to the energy demand arising from commercial activities in the Dublin city centre area.

5.2. *The compact city scenario and dispersed city scenario*

The compact city scenario restricts all future (post-2006) residential development within the Metropolitan area. This scenario is an extreme version of the Regional Planning Guideline settlement strategy which residential development is highly restricted within the Metropolitan Area and on a more restricted basis within the Hinterland Area (Walsh and Twumasi, 2008).The dispersed city scenario contains no policy restriction on residential development. The two scenarios reflect the extreme range of alternative settlement geographies for a particular population projection for 2026 (Walsh and Twumasi, 2008).

The population of the GDR is projected as 2305,560 in 2026, increasing by 30% compared with the population in 2006. The rapid growth in population at an average rate of 1.5% per year will continue to drive up housing requirements for this period of 2006–2026 in the GDR. More residential settlements therefore require to be developed to meet the considerable increasing housing demands. Fig. 13 illustrates the simulated required areas of four residential settlement patterns under the two different urban land use scenarios, coping with same population growth rate. It shows no outstanding difference for the two categories of dense residential urban settlement patterns, whilst considerable contrast occurs in discontinuous residential urban settlements. A few residential settlements in Dublin City centre are specified as continuous dense urban forms (CD), which are 1.9 km^2 under the

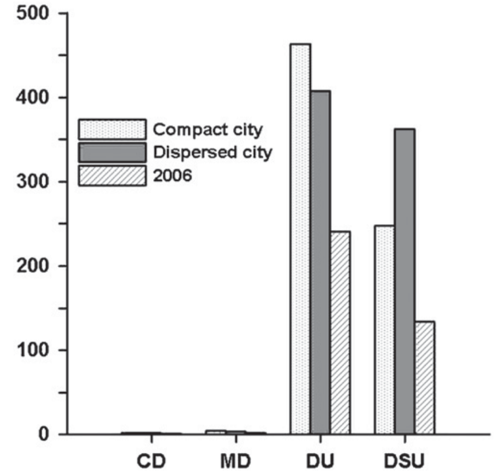

Fig. 13. Urban residential settlement areas (km^2) for different urban development scenarios, 2026.

compact scenario, 1.8 km^2 for the scenario of dispersed city and 1.1 km^2 for 2006. Similarly, the continuous medium dense urban forms (MD) are only found in the Dublin City centre area for both land use scenarios of 2026. The proportion of areas of dense urban forms (CD and MD) are still very low despite the likely dramatic increase in dense urban forms by 79% for the compact city scenario and 50% for the dispersed city scenario compared with the 2006 level, respectively. The total areas of discontinuous urban forms (DU) are about 463.0 km^2 for the compact scenario, while 407.3 km^2 for the dispersed city scenario, which both increased by in excess of 70% compared with the residential settlement level in 2006. Under the dispersed city scenario, in 2026 the total area of discontinuous sparse urban forms (DSU) doubles compared with 2006 — a much higher figure compared with that of the compact city scenario. Likewise, the discontinuous urban forms grow in area by 85% for the scenarios of dispersed city scenario compared with that in 2006.

5.3. Projection of future heating energy demand under two urban land-use scenarios

Fig. 14 shows the estimated heating energy demand and energy-related CO_2 emissions for the two scenarios. Simulation results show that the average heating energy demand per household (23,406 kW h/yr) for the dispersed city scenario is likely to increase by 9.4% compared with the energy consumption level of 2006 (21,392 kW h/yr). Conversely, under the compact scenario, the heating energy demand per household is estimated to decrease by 8.3% compared with that for 2006. Residents in the compact city scenario are likely to use 16.2% less heating energy than residents for the dispersed city scenario. The compact development is likely to reduce domestic heating energy consumption compared with the dispersed development.

The energy-related CO_2 emissions were estimated based on the emission factors of 0.264 kg/kW h for natural gas and 0.636 kg/kW h for electricity. From Fig. 14, it can be seen that CO_2 emissions per household per year for the dispersed scenario are much higher than that of the compact scenario. The compact city scenario could also significantly decrease heating-energy-related CO_2 emissions compared with the scenario of dispersed city.

The results show that there are substantial differences in the heating energy demand per household and related CO_2 emissions per household between the two extreme cases of scenarios. Generally, residents living in compact settlements are more energy-efficient in case of energy consumption for space heating, than residents living in dispersed residential settlements.

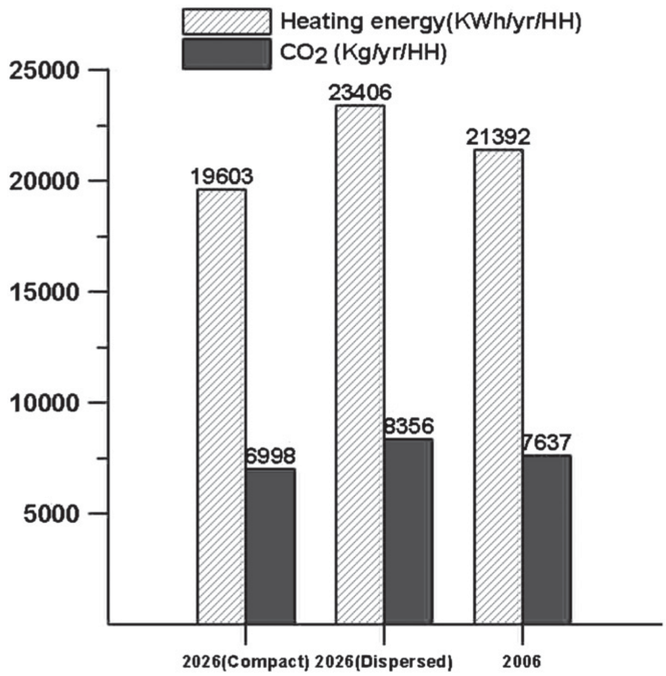

Fig. 14. Heating energy demand per household and related CO_2 emissions for 2026 scenarios and 2006.

The results also illustrated that, in densely developed areas, residents use less heating energy than residents in lower density household areas. This is mainly the result of more efficient energy supply system and less heat loss through ventilation and construction.

Increasing air temperature is likely to reduce the household energy demand within the case study region. Household energy demand for space heating is therefore estimated by integrating the potential climate change in temperature. With a 1.0 °C increase in temperature in 2026, the potential reduction of household heating energy demand has been estimated for each ED based on the 2006 Housing Census data. An average decrease of 8% in household energy demand for space heating is likely to occur cross the GDR, under a scenario of about 1.0 °C increase in temperature in 2026. The projected household heating energy demands for two land use scenarios were weighted based on the potential reduction derived for each ED to estimate the future household energy demand under climate scenario. The geographical distributions of estimated annual household energy demand for space heating are shown in Fig. 15 and Fig. 16 for the compact scenario and the dispersed scenario, respectively, with 1.0 °C increase in temperature. Results clearly show that compact scenario is dominated by lower annual heating energy demand for space heating, compared with that of the dispersed scenario. Spatial statistical results show that average annual heating energy demand per household for the GDR is 18,897 kW h/yr for the dispersed city scenario and 18,122 kW h/yr for the compact city scenario, both under an assumed increase of about 1.0 °C in temperature in 2030s. When controlled for dwelling type, heating energy demand is more sensitive to climate change than household density. As a result of all of this, based on the 2006 level, increasing temperature is likely to reduce heating energy demand per household by 11–15% in the 2030s under both land use scenarios. In addition, more energy consumption for space heating could be saved by a compact, rather than dispersed city pattern.

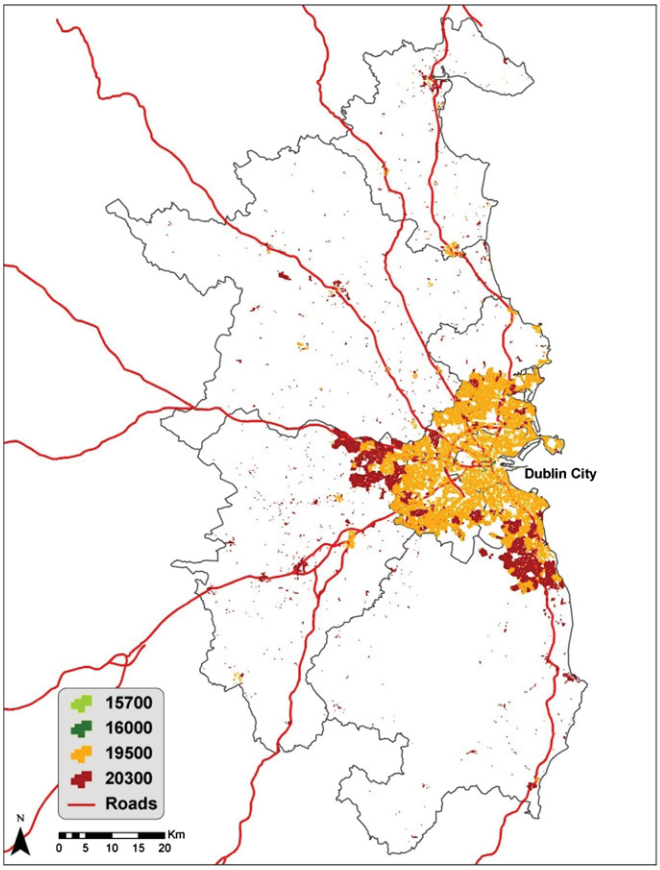

Fig. 15. Annual energy demand per household (kW h/yr/household) for space heating for compact city scenario with 1 °C increase in temperature in 2026.

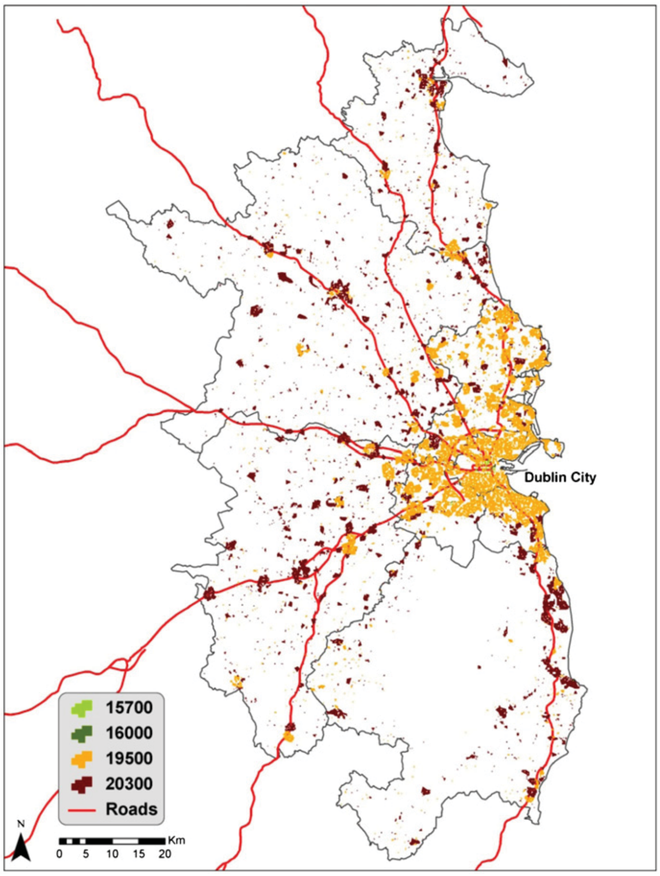

Fig. 16. Annual energy demand per household (kW h/yr/household) for space heating under the dispersed city scenario with 1 °C increase in temperature in 2026.

6. Summary and discussion

In this study, the relationship between domestic energy demand and urban settlement structures was investigated based on an energy simulation model and a land-use model. The results indicate that the residential urban form has a significant impact on energy demand for space heating.

The domestic heating energy is sensitive to four land use characteristics related to urban form: type, age and size of housing and household density. The simulated results indicate that the larger the house, the more energy is used per household. Similarly, residents of older houses use more energy than residents in newer ones due to the different dwelling thermal insulation level. Less energy consumptions are found for residents living in apartments compared with residents in houses mainly due to less heat loss through the construction and ventilation.

In dense urban settlements, such as the Dublin City with high household density, residents are likely to have lower energy consumption for space heating compared to that of suburban regions with low household density. The mean energy demand per household for residential dense urban areas (17,567 kW h/yr) is lower than that of the residential discontinuous sparse areas (22,414 kW h/yr). This indicates that dense residential areas have higher energy efficiency than discontinuous or sparse settlements. The residential areas with low energy consumption usually are dominated by high density households and smaller housing units. Areas with high energy consumption usually are located in rural fringe areas which are dominated by a low household density and large houses with more rooms. The results evident that the dense residential settlements have higher energy efficiency and consume nearly 22% less of energy for space heating compared with sparse residential settlements, illustrating the impacts of better urban planning and improved dwelling insulation standards on energy efficiency.

Domestic heating energy demand per household was estimated for two extreme urban development scenarios: the compact city scenario and the dispersed scenario. The results illustrate that the compact city scenario is likely to decrease the domestic heating energy consumption per household by 16.2% compared with the dispersed city scenario. Correspondingly, the energy-related CO_2 emissions could be significantly decreased compared with the dispersed city scenario. The results from the above analysis of domestic energy use for space heating strongly support the compact urban development. Even taking global warming into account, compact city pattern could save more energy (15%) than dispersed one (11%), assuming an increase of 1.0 °C in temperature in 2030s. The above analysis of domestic energy use for space heating strongly support the adoption of compact urban form in future GDR development.

Spatially, investigations of household energy demand for space heating is a big challenge due to the limitations of available energy data. Additionally, the current available historic data only covers short time periods to test the model for conditions comparable to the modifications induced by human activities. The method, which is used to calculate individual household space heating energy demand, are ultimately estimates only based on assumptions of existing and near future housing stock characteristics such as floor area, insulation levels and other building elements. Since individual dwelling energy demand data are not available, it proved not possible to examine case study dwellings at this scale. In this study, the rebound effect, which has been recognised by researchers as an important factor to derive efficient energy policies (Hass and Biermayr, 2000; Vine et al., 1994), is neglected to simulate the future household energy use and CO_2 emissions. It might result in an overestimation of energy saving potential due to the ignorance of the impact of consumer behaviours on residential energy demand for space heating. Consequently, it is strongly recommended that further studies are maintained to better understand the functions of the energy simulation model and detail the factors that influence modelling uncertainty and how it could be reduced.

The MOLAND model is a useful tool for policy makers to monitor and evaluate current and future land use changes. The outputs of the MOLAND model also can be employed to investigate the environmental and economic problems. However, there are some limitations of the model in terms of the present study on energy demand. For example, Gross National Product, which has been used to investigate the effect of climate change on energy consumption, is not considered in the MOLAND model. The MOLAND model cannot simulate the future housing stock changes which is crucially important to residential energy demand for space heating. Perhaps most worringly, MOLAND appears deficient in identifying both Continuous Dense and Medium Dense Urban land use categories for the study area. In fact, currently no model exists that shows exactly what would happen in the future. At best, we can hope that the estimated uncertainty produced by the model contain the true range of variation. All the results of the present research confirm the hypothesis that climate change and land use will profoundly affect energy consumption and greenhouse gas emissions in the Greater Dublin Region.

Generally, this study develops a possible way to promote sustainable development through the integration of energy and climate change mitigation in urban development in the GDR. The key findings provide local government and organisations with some useful information regarding housing development and climate change mitigation. Urban planners can also use this method to forecast and estimate the potential impacts of development on energy demand system and environment, including air quality and greenhouse gas emissions, to reduce the potential environmental and climate risks. This method could be commonly used in study on sustainability of major cities and metropolitan areas in terms of land use planning, energy efficient urban form development and climate change mitigation.

However, the present research only covers a few aspects of the challenges which lie ahead for the global issues of energy-related climate change and urban sustainable development. Further research is required to investigate the complex interactions between energy demand, climate change and land use change. An interdisciplinary approach is required to explore the environmental and social problems associated with climate change and other environmental disasters. There is an urgent need to quantify climate risk and figure out the best way to mitigate the impacts of climate change. The application and improvement of energy efficient measures should be undertaken as soon as possible. Priority requires to be given by policy makers to these aspects of the energy system, climate policy and sustainable development policy as a matter of urgency, and the approach taken and findings in this study may assist in some ways.

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