Domestic energy sustainability of different urban residential patterns: a New Zealand approach

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Abstract: A quantitative study was undertaken to calculate the potential sustainability of five residential blocks in Auckland, New Zealand (NZ) of differing physical densities. The main study considered five attributes of sustainability: domestic energy, transportation, carbon sequestration, food, and waste. This paper presents the results and mathematical methodology developed for one key aspect, domestic energy. Using aerial photographs, Geographic Information System (GIS) and ecological footprint assessment techniques, domestic energy demand, generation and deficit were calculated. Research outcomes suggest that the classic New Zealand suburb with a density of 18 households per hectare might have the greatest potential to be more sustainable.

Keywords: domestic energy use; ecological footprint; land area equivalent.

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1 Introduction

The multidimensional objectives of sustainability demand research, experimentation, continuous learning, promotion of community awareness, and debate from a global level to a local level. In New Zealand, the residential sector consumed about 13.3% (57 PJ) of total energy demand (EECA, 2000). This is mainly influenced by the residential sector's growth in floor area (60%), number of household dwellings (47%) and population (21%) between 1975 and 1998 (EECA, 2000). The average NZ house size is 112 sq. m^2 and the energy use data per household show a 5.6% decline from 39.8 GJ to 37.6 GJ per household per annum between 1991 and 1998 (EECA, 2000). The reason for this may be the construction of more energy efficient homes, but the rise in population still means a growth in the total energy consumption of the residential sector over the same period.

Dwellings and their servicing infrastructure form an integral part of the future built environment, and their pattern of development can affect national energy demand and resource consumption over a long period of time. Domestic energy use is also selected here because of its fundamental links to global warming through the use of non-renewable sources of energy (Boardman et al., 1995; National Centre of Climate Energy Solutions, 2005). Therefore, the residential sector has been the focus for this research. At present there is no way of determining objectively whether a given neighbourhood subdivision or proposed pattern of development has more or less potential to be sustainable than another. Broad environmental performance indicators formulated at national level do not gauge the energy flow-state of different urban patterns. A simple method is needed to allow different residential patterns to be compared and ranked so that impacts may be stated with a reasonable degree of confidence.

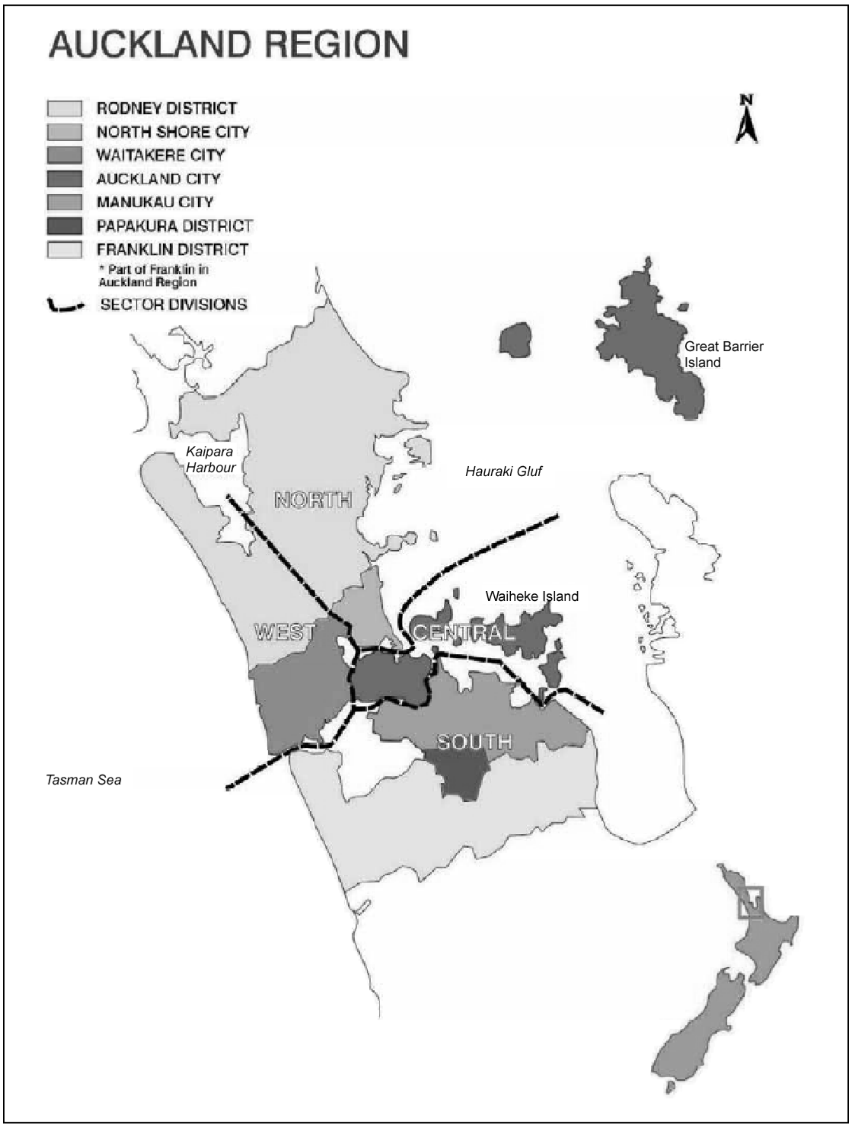
The original quantitative case study of five residential blocks in Auckland included five aspects related to the potential for increased residential sustainability: domestic energy use, transportation energy, carbon sequestration, food energy and waste. These were chosen as key global-scale aspects of environmental sustainability, as they are all linked to the twin issues of non-renewable energy and carbon dioxide emissions. In addition, the chosen aspects were ones which could be considered at the scale of the residential block, assuming changes in both construction technology and household behaviour, on the basis of the maxim of "Thinking globally and acting locally".

Aerial photographs, data from national databases and the GIS were used to develop mathematical methodologies for each of the five aspects based on ecological footprint assessment techniques. This paper presents the mathematical method and results from that study considering only domestic energy use.

2 Setting the scene

Auckland City is located in the fastest growing region of New Zealand and contains about one third of the population, 367,737 of the whole Auckland Region (Statistics New Zealand, 2001a). The Auckland Region, with a population of 1,158,891 (Statistics New Zealand, 2001b), mainly consists of four cities (Auckland, Manukau, North Shore and Waitakere) and three districts (Papakura, Rodney and Franklin). Auckland City lies in the Central Sector (see Figure 1) and has the prime Central Business District (CBD) of the region.

Figure 1 Auckland region map: local authorities and sector boundaries



Source: Auckland Regional Growth Strategy (1999, p.31)

The *Auckland Regional Growth Strategy 2050* was prepared by the Auckland Regional Growth Forum in 1999 in consultation with the regional community. It is currently under further review. This strategy supports compact urban development or intensification of residential urban areas as a major tool to contain 70% of future growth by 2050 within existing urban areas in order to promote environmental sustainability (Regional Growth Forum, 1999). This will necessitate a lifestyle change for the users, as the accepted goal for the average New Zealander is still the detached house and garden.

The fastest growing dwelling type is a flat or house joined to a business or shop. This category grew by 78% between 1991 and 2001. However, 78% of permanent private dwellings in 2001 are separate houses, a situation that has not changed since 1991 (Auckland Regional Council, 2003). By 2021, an additional 156,000 households will be living in the Auckland Region; an increase of 37%. Without a strong policy shift, the greatest numbers of new households will be formed in areas peripheral to the current urban area, with the exception of the Auckland CBD (Auckland Regional Council, 2003). The *Environment 2010 Strategy* identifies 11 priority issues necessary for New Zealand to manage the sustainability of natural and physical resources in parks, forests, lakes, mountain and marine ecosystems, thereby improving the overall quality of environment (MfE, 1995). Less work has been done on assessing quantitatively the potential sustainability of natural and physical resources embedded in urban residential environments in terms of productive land area, vegetation and biomass, solar energy generation capability and built-up urban forms. Further research is required to develop quantitative calculation methods to calculate sustainability performances and to monitor different patterns of urban forms for a range of factors that significantly affect sustainability. The assessment methodology formulated in the original research considering five important aspects of sustainability is an attempt to quantify the potential sustainability of the Auckland urban residential patterns at a local scale.

2.1 Site selection

Appropriate selection criteria for the sites allow important understanding of residential sustainability, provide effective results, open up aspects with significant associated values, add strengths to the quantitative methodology, and give a practical snapshot on the performance of different urban forms. The five case study sites were selected to provide a spread of residential urban forms at local level based on the following criteria:

- the distance from the city centre
- zoning pattern according to Operative Auckland City District Plan 1999
- site configuration and form
- proximity to the main transport corridors and shopping facilities
- total number of households (between 50–125)
- density pattern of area unit (obtained from 1996 census data).

However, it is possible that more selection criteria could be added based on the dynamic nature of the changing preferences of human habitats that would provide further research with more accuracy.

The distance from city centre is directly related to domestic energy use and takes into account different urban patterns with varying dwelling sizes and corresponding work travel distances, assuming Auckland CBD as the main employment node. The five residential blocks are located approximately between 10 km to 1 km from the Auckland CBD.

Zoning patterns according to District Plan, 1999, provide development outcomes as visualised by the local authority, while site configuration and form relate to typical subdivision layouts. The *Auckland District Plan Operative 1999, Isthmus Section, Part 7, Residential Activity* contains eight major residential zoning patterns ranging from residential historic heritage and low-density land form to low, medium and high intensity urban forms. These were assessed in selecting the residential blocks, as zoning regulations contribute considerably towards generating the nature of the subdivisions, and articulating three-dimensional urban forms with typical site configuration, ground coverage, total height of the buildings, and land-use patterns. The case study sites had both irregular and geometric forms bounded by peripheral roads. All the sites are located close to similar types of major transport arteries and reasonably vibrant shopping areas of Auckland City.

The proximity of main traffic arteries and shopping centres relate to the ability of the residents to use public transport and local shopping frequently, which would reduce the domestic energy use.

The total number of households living in the residential blocks links to the carrying capacity of the land, and the density patterns of the area units allow understanding of sustainability performances of the residential areas ranging from low, medium to high density in terms of their domestic energy uses. The total number of households ranged from 50 to 125 for the five selected residential blocks. Each block comprised a number of ‘mesh blocks’. The mesh block may be defined as “*the smallest geographic unit for which statistical data are collected and processed by Statistics New Zealand*” (Statistics New Zealand, 2001c). An intermediate scale of the ‘residential block’ is considered essential as the residential units at the level of a mesh block would be small, while a neighbourhood with a population of 5,000–10,000 would be of a greater size than the local level visualised.

> A residential block may be defined as an intermediate planning module placed just after a neighbourhood level in hierarchy in a descending order. It may consist of a mesh block or more than one mesh block, is mainly determined by the numbers of households contained, and the prescribed range is between 50 and 200 households per residential block. (Ghosh, 2004)

Residential blocks were selected based on density data for different area units from the 1996 *NZ Census*.

> Area units are aggregations of mesh blocks with unique names. They are non-administrative areas intermediate between mesh blocks and territorial authorities. Area units must either define or aggregate to define urban areas, rural centres, statistical areas, territorial authorities and regional councils. Each area unit must be a single geographic entity with a unique name. Area units of main or secondary urban areas generally coincide with communities of interest or parts thereof. Area units within urban areas normally contain 3,000–5,000 population. (Statistics New Zealand, 2001c)

Population density of an area unit is likely to differ from that of individual residential blocks within the area unit, as the latter are at a much more local level. Table 1 gives the density patterns of area units in persons per hectare in which the residential blocks are located.

Table 1 Population density of area unit and descriptor

Census area unit	*Population density of area unit* (*persons/ha*)	*Descriptor*
Freeman's Bay	36.7	Wellington Street
Ponsonby East	43.2	Richmond Road
Sandringham East	41.2	Sandringham Road
Roberton	27.4	Methuen Road
New Lynn North	17.3	New Lynn

2.2 Characteristics of selected sites

New Lynn, the farthest residential block from Auckland CBD, is located at the boundary of Auckland City but included within the jurisdiction of Waitakere City. According to the current *Waitakere City District Plan* this site is zoned as 'Living Environment 1' or 'Living 1' under the 'Human Environments' zoning category. There are eleven subcategories under 'Human Environments', and most of the urban and suburban residential areas of Waitakere City are covered by these. In the Living 1 category each residential unit should have a site area of not less than 400 sq. m (Waitakere City Council, 2003).

In the Auckland District Plan Operative 1999, while the category Residential 1 has a permitted density of one unit per 400 m^2 to protect the close-knit heritage character of the Victorian and Edwardian forms of residential development, Residential 5 has a permitted density of one or two units per site and one- to two-storeyed buildings to promote low-rise, low-density developments with generous open spaces around the dwellings. Residential 6, the largest zoning pattern of the isthmus, mainly guides a medium-intensity urban-development pattern and has two sub-categories: 6a (permitted density one unit per 375 m^2 and 8 m height) and 6b (permitted density one unit per 300 m^2 and 10 m height). Residential 7a, a sub-category of Residential 7, has high-intensity zoning, and permits the construction of relatively high-rise, multi-level, multi-family dwellings with a maximum height of 10 m within designated intensification areas (Auckland City Council, 1999). Table 2 explains the nature of the developments of selected residential blocks while Figures 2–6 graphically present the subdivision and zoning patterns of the selected residential blocks obtained from the Auckland Operative District Plan, 1999.

Table 2 Characteristics of selected residential blocks

Residential blocks	*Site form and zoning*	*Type of development*	*Location from Auckland CBD*	*Type of Subdivisions, minimum plots between adjacent roads*
New Lynn	Irregular Human Environments -Living Environment 1 (Living 1)	Low density, single- and very few double-storeyed, large, detached family houses, generous open spaces around dwelling, and long driveways	10 km Farthest Block	Rectangular and irregular 2 plots
Methuen Road	Parallelogram Residential 5 and 6a	Low density, mainly single-storeyed, very few double- and triple-storeyed, detached family houses of varying sizes, generous open spaces around dwellings, further subdivisions, large plots and long driveways	8 km Far to moderate distance	Rectangular, square and irregular 4 plots
Sandringham Road	Rectangular with splayed corner Residential 6a, 6b and 7a	Mix of a few double-storeyed attached, more single-storeyed detached- and semi-detached houses, wide pedestrian paths along road and wide front and rear garden spaces, some front spaces used for parking access and shorter driveways	6 km Moderate distance	Rectangular Min. and max. 2 plots
Richmond Road	Linear Residential 1	Residential heritage houses from Edwardian and Victorian era, mainly single-storeyed character detached houses, small garden at the front, rear open space, mainly off-street parking, very short pathways for access to houses	2 km Close distance	Rectangular Min. and max. 2 plots
Wellington Street	Trapezoidal Residential 7a	High density, attached double-storeyed row houses of different types, single-storeyed, semi-detached houses, common community open-space networks within block connected by pedestrian pathways, small front and rear courtyard, few driveways, parking provision for each house, though significant numbers of on-street parking	1 km Closest Block	Rectangular 1 plot

Figure 2 New Lynn

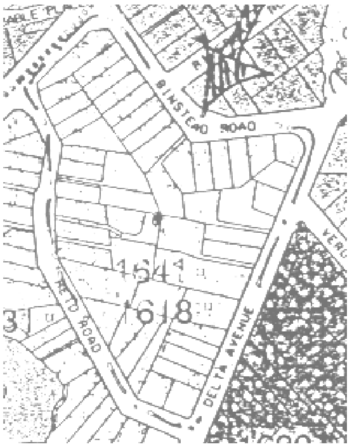


Figure 3 Methuen Road

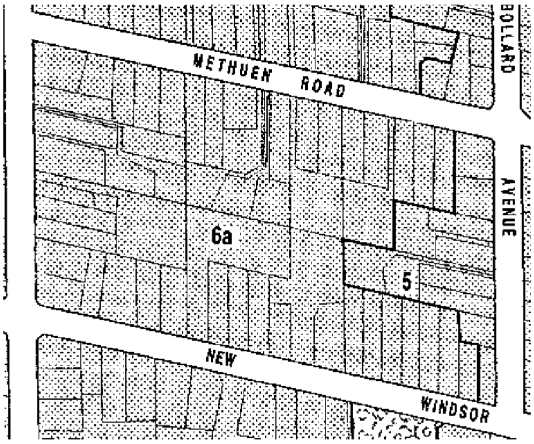


Figure 4 Sandringham Road

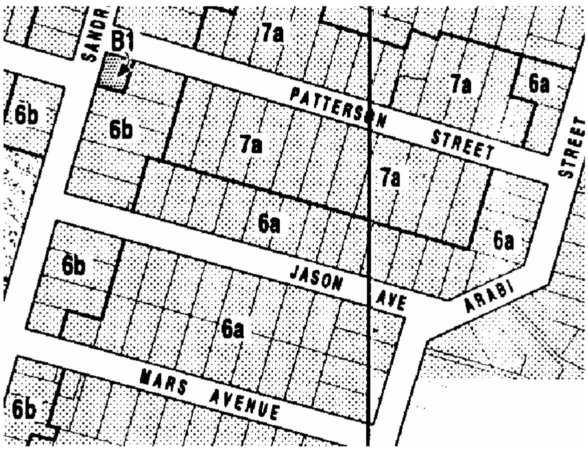


Figure 5 Richmond Road

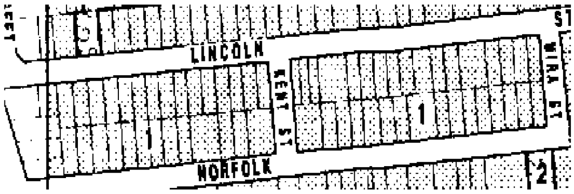
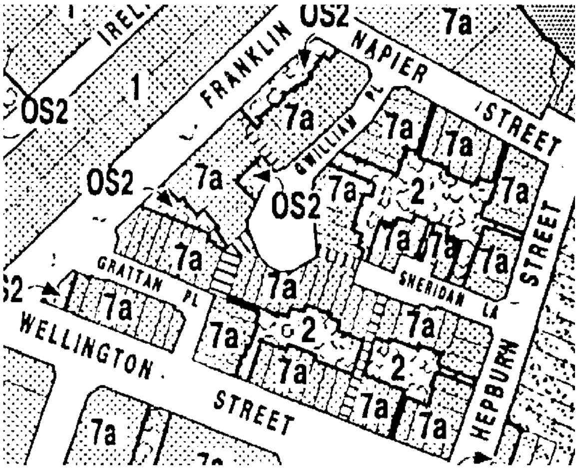


Figure 6 Wellington Street



3 Methodology and results

3.1 Data collection

Aerial photographs at a scale of 1 : 1000 were the main source of data for this research. Data collection was also carried out through rapid visual surveys to interpret the visual character of the area, topography of the block, nature and types of residential houses, approximate life expectancy of buildings, pedestrian connectivity to facilities and community open space, overall building heights, pathways, driveways, and parking provisions. Data relevant to the New Zealand situation were obtained from national databases such as the Census (Statistics New Zealand, 1991, 1996); the energy end-use database (EECA, 2000); energy efficiency guides for current and emerging technologies (CAE, 1996; CAE and EECA, 1996); databases and publications of regional and territorial authorities such as Auckland Regional Council and other Councils in the Auckland Region; and from research publications and books. National data were used to calculate the potential sustainability of the residential blocks where no regional or city data were available.

3.2 Land-use pattern

The year in which aerial photographs of the selected residential blocks were taken is important because population, number of households per hectare, and per capita energy use of the residential blocks were calculated based on the roof areas of buildings in that particular year. As aerial photographs of residential blocks taken in 1994 were the basis of the calculations for this study, all the data for calculations were aligned with the same base year to achieve appropriate results. The sustainability ranking of the blocks is therefore a 'snapshot' taken at a particular time, but could be updated using more recent data. The land-use patterns for the residential blocks were calculated and compared using both a manual method and 'CITYgreen' (American Forests, 2000) a method based on GIS, to check the accuracy of the results. Some minor variations were observed comparing the results, which seem to be within acceptable limits. GIS is also a useful and effective means of displaying data in multi-layered, multi-coloured maps, which are capable of being easily understood by the public. Sustainability principles introduced into urban development strategies at the level of land use (scale 1: 5,000–10,000) and master plans (1: 500–1,000) will help innovative planning and provide a clear framework at a more detailed level (Pauleit and Duhume, 2000). The small land-cover units can be distinguished by their various patterns of built and open spaces and are the product of the land use and development (Pauleit and Duhume, 2000).

> *… it must be borne in mind that, despite these developments, conventional aerial photographs are likely to remain the primary source of remotely sensed information for the foreseeable future at the land parcel level (i.e., 1:2,500–1: 500 scales) which is the basic building block of the databases used by those involved in urban planning and land administration.* (Masser, 2001)

The existing land-use patterns calculated contain mainly two categories:

- non-productive land: roof areas of buildings; road areas including half-site perimeter road width; paved/non-paved pathways and existing vegetation cover
- productive land (i.e., available for growing additional biomass): remaining open spaces (Ghosh et al., 2006).

Additional measurements include total available solar efficient roof areas of buildings (oriented 45° on either side of North) (Breuer, 1994), and total site area. The land-use patterns for the residential blocks were calculated using 'CITYgreen' from aerial photographs and are presented in Table 3 and in Figures 7–10.

Comparison of percentages in different land-use categories for site areas of the residential blocks indicated that Wellington Street had the highest percentage of vegetation area (32.3%), lowest paved pathways (1.6%) as a percentage of total site area, and the highest solar efficient roof area (37.1%) as a percentage of total roof area of buildings. Sandringham Road remained at a median value for all land-use categories, while New Lynn had the highest value of productive land area (29.5%). Methuen Road accounted for the highest value of paved pathways (29.5%), and Richmond Road had the highest percentage share for area of half-perimeter road-width (30.0%). It is interesting to note that to a certain extent these quantitative results convey the nature of the residential form of development. Higher percentage share of productive land area indicates low-density detached development such as New Lynn. On the other hand, higher percentage share of area of half perimeter road width indicates that peripheral roads directly service subdivisions, for example, Richmond Road is a two-lot-deep linear residential development pattern where each subdivision abuts the peripheral roads. Figure 11 provides the comparison of land-use categories for all five residential blocks in percentages for a particular year.

Table 3 Existing land-use pattern, density per hectare and total solar efficient roof area

Parameter	*New Lynn*	*Methuen Road*	*Sandringham Road*	*Richmond Road*	*Wellington Street*
Total site area (ha) (100%)	5.27	8.25	6.72	3.13	3.56
Area of road with half-width, grass and pedestrian path (ha)	1.4 (26.6%)	1.16 (14.1%)	1.52 (22.6%)	0.94 (30.0%)	0.89 (25.3%)
Total trees and shrub area (ha)	1.1 (20.9%)	2.15 (26.0%)	1.21 (18.0%)	0.518 (16.7%)	1.15 (32.3%)
Total paved pathways excluding road area (ha)	0.50 (9.5%)	1.35 (16.4%)	0.67 (10.0%)	0.17 (5.4%)	0.056 (1.57%)
Buildings roof area (ha)	0.71 (13.5%)	1.6 (19.4%)	1.62 (24.1%)	0.87 (27.8%)	0.62 (17.41%)
Productive land area (ha)	1.56 (29.5%)	1.99 (24.1%)	1.69 (25.3%)	0.64 (20.1%)	0.83 (23.4%)
Total solar efficient roof area (ha) (as % total roof area)	0.21 (29.6%)	0.37 (23.1%)	0.48 (29.6%)	0.19 (21.8%)	0.29 (46.8%)
Total number of households	53	119	122	65	104
Total number of people	156	348	359	190	305
Density assuming number of persons/ha	30	42	53	61	86
Density assuming number of households/ha	10	14	18	21	29

Figure 7 Land-use pattern map, Wellington Street

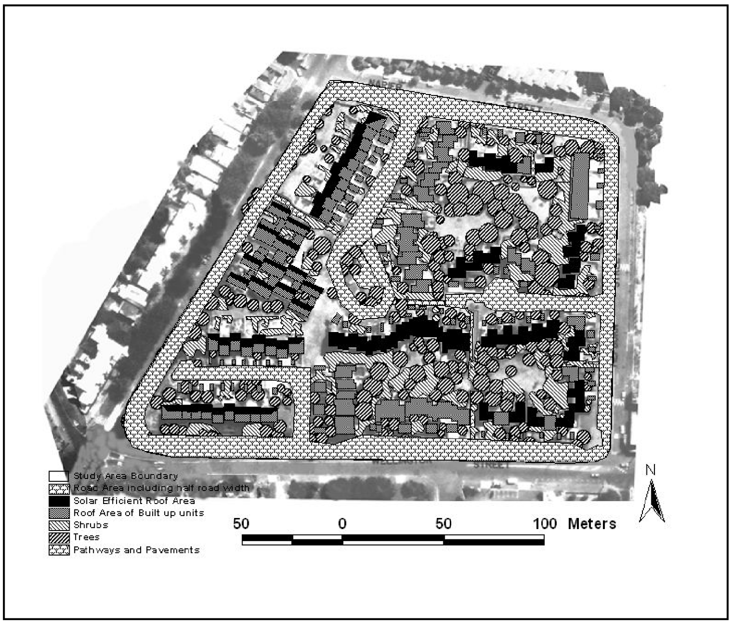


Figure 8 Land-use pattern map, Wellington Street, multiple layers

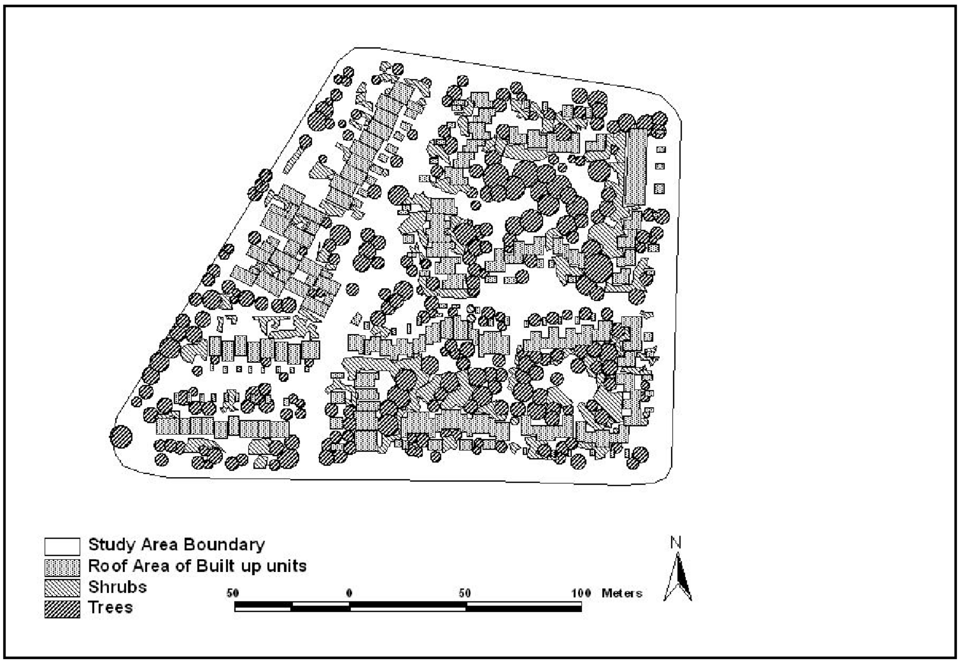
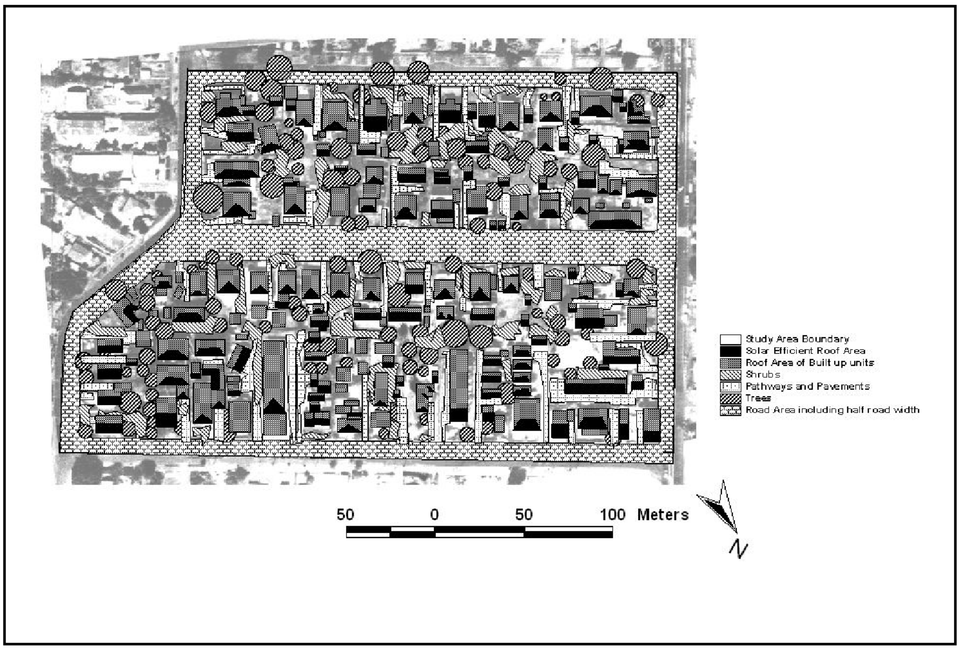
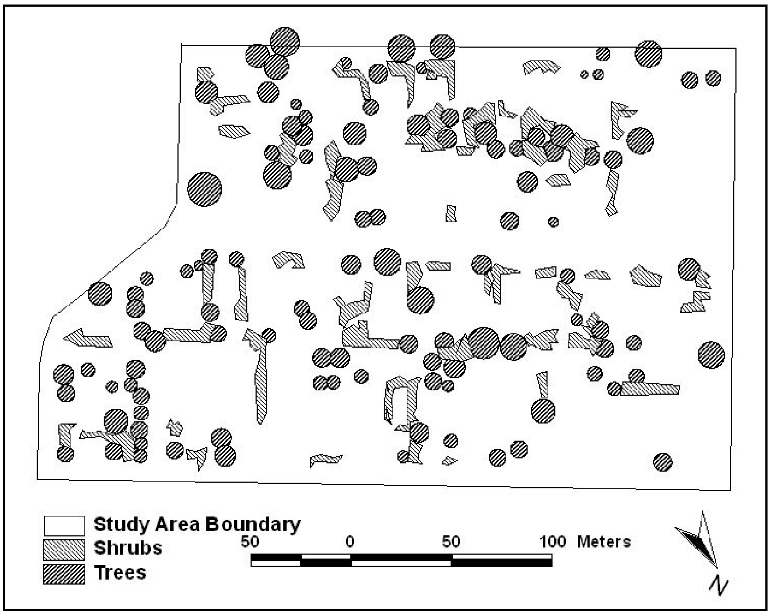


Figure 9 Land-use pattern map, Sandringham Road



Source: Ghosh et al. (2006)

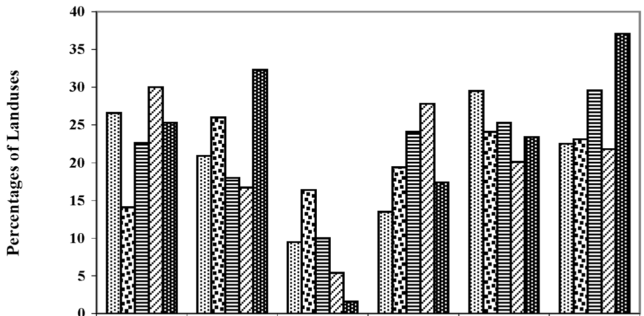
Figure 10 Land-use pattern, Sandringham Road, tree and shrub layers



Comparisons of land-use patterns per household take into account the number of people and households sharing the natural and physical resources of that residential area and indicate household share for the particular year in which the land-use pattern has been calculated.

It is also interesting to note that in spite of having the highest percentage share of solar-efficient roof area (37.1%) as a percentage of total roof area, Wellington Street has the lowest household share of solar-efficient roof area equal to 24.9 m^2, while Sandringham Road has the highest share equal to 39.1 m^2 per household in 1994.

Figure 11 Comparison of land-use percentages in 1994



	Road Width	Trees & Vege. Area	Paved pathways area	Buildings roof area	Productive land Area	Solar Eff.Roof area
New Lynn	26.6	20.9	9.5	13.5	29.5	22.5
Methuen Road	14.1	26	16.4	19.4	24.1	23.1
Sandringham Road	22.6	18	10	24.1	25.3	29.6
Richmond Road	30	16.7	5.4	27.8	20.1	21.8
Wellington Street	25.3	32.3	1.57	17.41	23.4	37.1

Being a low-density development, New Lynn had the highest household shares of site area, peripheral road areas including half-road width, tree and shrub area and productive land areas. Methuen Road, with the highest household share of paved pathways (113.5 m^2) and second lowest share of road areas (97.2 m^2), indicates that accessibility to the subdivisions from the peripheral roads is by long pathways and there are larger numbers of plots between adjacent roads. Figure 12 presents the comparison of land-use categories in square metres per households for all five residential blocks for a particular year.

Figure 12 Comparisons of land-use patterns per household in 1994

	Site area	Road Area	Area of Bldgs	Tree & Shrub Area	Productive Land Area	Pathways Area	Solar Eff. Roof area
New Lynn	994	256.3	134.1	188.9	294.3	95.2	29.9
Methuen Road	694.4	97.2	133.1	180.7	167.2	113.6	31.4
Sandringham Road	551	125	133.9	101.7	138.5	55.07	39.1
Richmond Road	481.1	144.5	133.4	79.37	98.5	25.9	29.0
Wellington Street	342.5	86.2	67.0	110.5	79.8	5.4	24.9

Site area per household is indicative of the occupancy and density status of the block, while tree and shrub area is a measure of the carbon sink available per household at residential block level. On the other hand, productive land area is the household's share of the land available for growing additional biomass onsite.

3.3 Total domestic energy requirements

Domestic energy use for each residential block was calculated by multiplying national average per capita domestic energy use for a particular energy end-use sector calculated from the Energy Efficiency Conservation Authority Energy (EECA) End-use Database (EECA, 2000) by the respective potential population of the residential block. This is presented in Table 4.

Table 4 National per capita domestic energy use, New Zealand, 1995

Energy use	*Total energy use* (PJ)	*National per capita energy use* (GJ)
Water heating	20.1	5.45
Space heating	19.0	5.1
Refrigeration	3.7	1.0
Cooking	3.17	0.8
Lighting	2.64	0.7
Other	4.23	1.1

1 PJ = 1000000 GJ.

Assuming the aerial photo was taken in the year '*y*' and for that particular year '*y*',

$$Py = Gy/Fy \quad (1)$$

$$Ny = Py/Hy \quad (2)$$

where, Py = Population of the residential block; Fy = Per capita national floor space in m^2; Ry = Total roof area of built up units in m^2; Gy = Total ground coverage area in m^2 of built up units; Hy = Average national household size; and Ny = Total number of households in the residential block. Gy, calculated from total roof areas of buildings (Ry), assuming a 0.2–0.4 m overhang for a rectangular building, would be a corresponding 11% less than total roof area. This figure was then adjusted to allow for the percentage of two- and three-storey development revealed by the rapid visual survey.

Total energy requirements for the residential block for the year '*y*' were calculated as follows:

$$Ey = Py \times Epy \quad (3)$$

where, Epy = Per capita total national energy use in gigajoules (GJ), and Ey = Total domestic energy requirements in GJ.

3.4 Total domestic energy generation potential and deficit energy

The domestic energy generation potential of residential blocks was calculated using two methods: the Deficit Energy Method and the Land Area Method.

3.4.1 Deficit Energy Method

The Deficit Energy Method calculated the per capita deficit energy requirement for each residential block from the estimation of total energy use (Ghosh et al., 2006). The deficit energy use is the energy that could not be provided from on-site renewable sources. The energy use was grouped into two sections – water heating and the rest (space heating, cooking, refrigeration, lighting and others) – because the energy needed for water heating can be produced on-site using a solar water heater but energy for the rest of the activities will need to be electricity generated from photovoltaic (PV) modules.

For the particular year '*y*' when the aerial photograph was taken

$$Ewy = Ny \times C1 \quad (4)$$

$$Rwy = Ny \times C2 \quad (5)$$

$$Rpvy = Rsy - Rwy \quad (6)$$

$$Epvy = Rpvy \times C3 \quad (7)$$

$$Eay = Ewy + Epvy \quad (8)$$

$$Edy = Ey - Eay \quad (9)$$

where *Eay* = Total available energy in GJ; *Edy* = Total deficit energy in GJ; *Ewy* = Total available energy from solar water heater in GJ; *Epvy* = Total available energy from PV modules in GJ; *Rsy* = Total solar efficient roof area of built up units in m^2; *Rwy* = Total area of solar water heater required for the residential block; and *Rpvy* = Total area of solar efficient roof available for PV module installation. *C*1, *C*2, *C*3 are three constants, where *C*1 = Amount of energy generated per annum by a 4 m^2 solar water heater in GJ per household and is equal to 7.92 GJ per household per annum; C2 = Area of solar water heater required in m^2 per household and is equal to 4 m^2 per household; and *C*3 = Amount of energy generated per annum by 1 m^2 of PV module installation in GJ per household and is equal to 0.73 GJ per annum.

It was assumed that 4 m^2 per household of solar water heater area would be sufficient on average for all sizes of household (CAE, 1996; CAE and EECA, 1996) and would need to be placed on part of the solar efficient roof area. Fifty square metre of photovoltaic (PV) modules can generate 100 MJ/day, assuming 10% efficiency for Auckland (Redshaw and Dawber, 1996). It is calculated that 1 m^2 will generate 0.73 GJ per year. PV modules could be placed on the remaining available solar efficient roof area after installation of 4 m^2 of solar water heater collectors.

Results obtained from the study for total domestic energy use and energy generation potentials of the residential blocks are presented in Table 5. It calculates the total energy requirements of the residential blocks, total available energy that could be generated by placing solar water heater and photovoltaic modules on solar efficient roof areas of the dwellings, and also the deficit energy that could not be generated on site, all calculated in GJ per year.

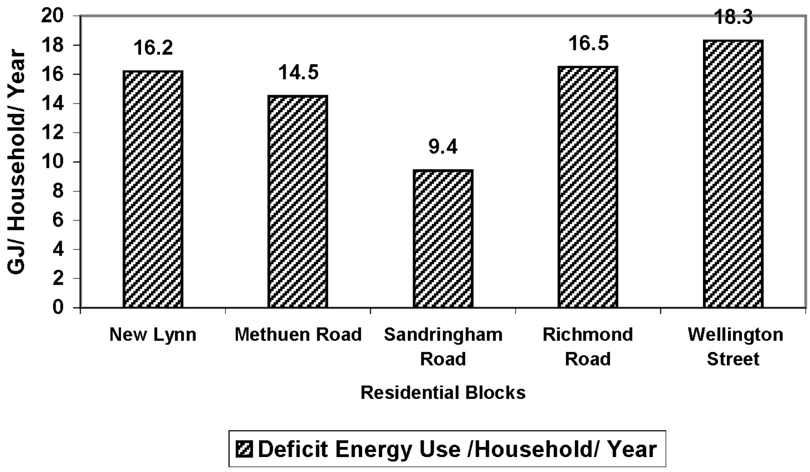
Table 5 Comparison of annual energy use, available and deficit energy requirements, 1994

Parameters	*New Lynn*	*Methuen Road*	*Sandringham Road*	*Richmond Road*	*Wellington Street*
Total number of households	53	119	122	65	104
Total energy use in residential block (GJ/year)	2277	5080	5241	2774	4321
Total available Energy from Solar water heater on site (GJ/year)	420	943	966	515	824
Total available energy from PV modules on site (GJ/year)	999	2405	3127	1188	1596
Total potential energy from solar water heater and PV modules on site (GJ/year)	1419	3348	4093	1703	2420
Total deficit energy requirement (GJ/year)	858	1732	1148	1071	1901
Total deficit energy requirement per household (GJ/year/household)	16.2	14.5	9.4	16.5	18.3

Energy refers to only domestic energy.

The deficit energy per household per year is least for Sandringham Road and is equal to 9.4 GJ per household per year, while that for Wellington Street is highest and equal to a value of 18.3 GJ per household per year. Figure 13 presents the deficit domestic energy in GJ per household for one year.

Figure 13 Deficit energy use per household in 1994



3.4.2 Land Area Method

The Land Area Method is based on Ecological Footprint techniques and converts the deficit energy consumption to land areas (Ghosh et al., 2006) to calculate the maximum offsite land area needed to meet the overall energy demand of the residential block to grow the energy they need. The total energy requirements of each residential block were added and converted into the corresponding land area in hectares. Generally, the land-to-energy ratio for New Zealand is assumed to be 120–150 GJ per hectare per annum (Wackerangel and Rees, 1996). Assuming the average land-for-energy ratio is 135 GJ per hectare per year, the total amount of available productive land on and off site was calculated for each housing area as well as per household. This method is a further development of the Deficit Energy Method. The use of land area provides a common basis to allow the summing of data for a range of sustainability variables.

Land area equivalents of domestic energy demand, generation and deficit were calculated for the five residential blocks to allow comparison in between different residential blocks in terms of their overall degree of sustainability incorporating five aspects of sustainability.

Land area equivalent of '*required*' domestic energy per household per annum for a residential block may be defined as the household share of land area required to produce the domestic energy demand for a particular year.

Land area equivalent of '*available*' domestic energy per household per annum for a residential block may be defined as the household share of the on-site land area required to contribute to generating to meet the domestic energy demand for that particular year.

Land area equivalent of '*deficit*' domestic energy per household per annum for a residential block may be defined as the household share of the off-site land area required to generate the remaining domestic energy demand for that particular year.

Assuming for the particular year '*y*',

$$Ly = Ey/C4 \quad (10)$$

$$Lay = Eay/C4 \quad (11)$$

$$Ldy = Edy/C4 \quad (12)$$

where *Ly* = Land area equivalent of total required energy in hectares; *Lay* = Land area equivalent of total on-site energy available in hectares; *Ldy* = Land area equivalent total of off-site deficit energy in hectares; and *C*4 = Annual productivity of New Zealand soil per hectare for producing energy crops in GJ per hectare (equal to 135 GJ per hectare). Table 6 provides a comparison of land-area equivalents calculated in hectares for the residential blocks.

Table 6 Comparison of land area equivalents and descriptors

	New Lynn	*Methuen Road*	*Sandringham Road*	*Richmond Road*	*Wellington Street*
Total land area equivalent of required energy (ha)	16.9	37.6	38.8	20.5	32.0
Total land area equivalent of required energy per household per year (ha)	0.32	0.32	0.32	0.32	0.31
Total land area equivalent of on site available energy (ha)	10.5	24.8	33.5	12.6	17.9
Land area equivalent of total on site available energy per household per year (ha)	0.198	0.208	0.281	0.194	0.172
Total land area equivalent of off site deficit energy	6.35	12.83	8.5	7.9	14.08
Total land area equivalent of off site deficit energy per household per year (ha)	0.119	0.107	0.07	0.122	0.135
Ratio of deficit off site to available on site per household per year (D1)	0.6	0.5	0.25	0.63	0.79
Ratio of deficit off site to total required per household per year (D2)	0.37	0.33	0.22	0.38	0.44

'Energy' refers only to domestic energy of selected residential blocks.

*D*1 and *D*2 are the important descriptors of domestic energy use of urban forms or residential patterns identified in the process of developing this quantitative methodology of measuring urban form.

*D*1 = Land area equivalent of deficit energy per household per annum/Land area equivalent of available energy per household per annum

$$= Lhdy/Lhay \quad (13)$$

where *Lhay* = Land area equivalent of on site available energy per household per year in hectares; *Lhdy* = Land area equivalent of off-site deficit energy per household per year in hectares.

The value of ratio *D*1 varies from 0 to ∝. When the ratio is equal to zero, the energy sustainability is at a maximum, and when the value is equal to ∝, there is a minimum degree of sustainability. At a value equal to 1, the degree of sustainability is 50% and decreases with the increasing value of the ratio.

*D*2 = Land area equivalent of deficit energy per household per annum/Land area equivalent of required energy per household per annum

$$= Lhdy/Lhy \tag{14}$$

where, *Lhy* = Land area equivalent of required energy per household per year in hectares. The value of ratio *D*2 varies from 1 to 0. When this ratio is equal to 1, the degree of sustainability is minimal; when the value is 0, there is a maximum degree of sustainability. Moreover, this ratio is indicative of the percentage of non-sustainability. For example, when the ratio is equal to 0.2, the block is 20% unsustainable in terms of energy supply.

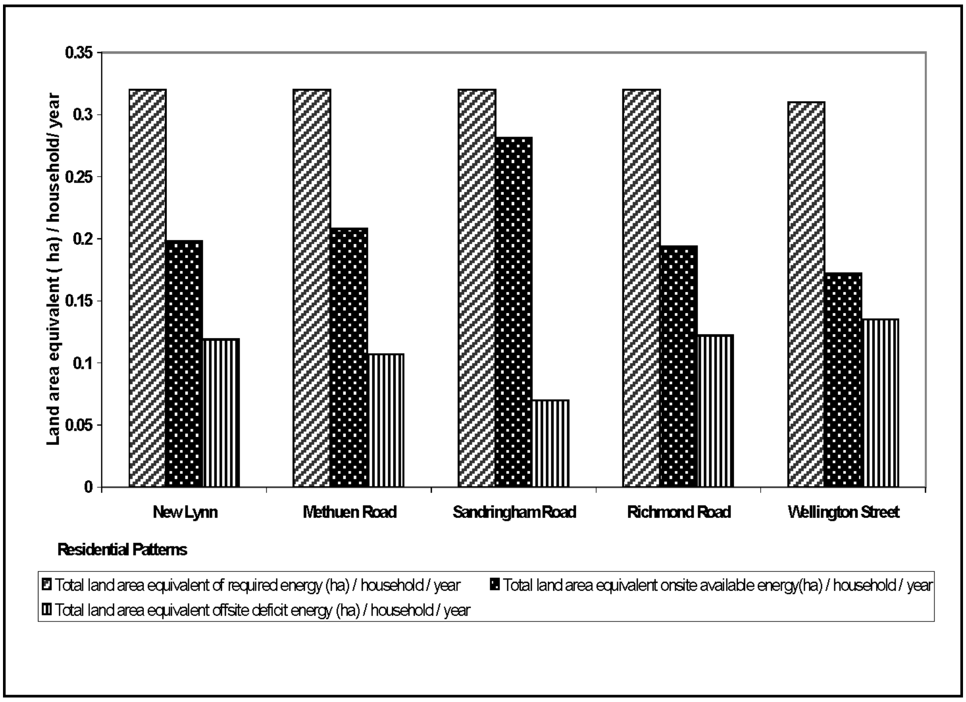
3.5 The most sustainable residential block

The sustainability performance of five residential blocks in Auckland was measured in terms of domestic energy use. When the five residential blocks were compared in terms of their total energy requirements per household per year expressed in land area equivalents per household per year in hectares, almost no variations were observed, as would be expected using national average data. Considering available on-site energy generation potential per household per year, the corresponding land area equivalents per household per year in hectares show significant variations.

Sandringham Road had the highest value of land area equivalent of on-site available energy per household per year, which is equal to 0.281 ha per household per year, while Wellington Street, the high intensity residential pattern with household density of 29 households/ha, had the lowest value of on-site available energy per household per year, which is equal to 0.172 ha per household per year. It is also important to observe that Richmond Road, a traditional heritage pattern of development with household density of 21 households/ha (land area equivalent of 0.194 ha/household/year), had a more or less similar ability to generate onsite energy as the New Lynn household density with 10 household/ha (land area equivalent of 0.192 ha/household/year). Correspondingly, land area equivalent of off-site deficit energy required per household per year in hectares is lowest for Sandringham Road (0.07 ha/household/year) and highest for Wellington Street (0.135 ha/household/year). Land area equivalent of off-site deficit energy required per household per year is equal to 0.122 ha for Richmond Road. Similarly, that for New Lynn is equal to 0.119 ha, while for Methuen Road it is equal to 0.107 ha.

Figure 14 presents comparative values of domestic energy requirements, and generation and deficit in terms of land-area equivalents in hectares per household per year for five residential blocks. Figure 14 indicates that considering only domestic energy consumption and generation, Sandringham Road, with a household density of 18 households per hectare and at a moderate distance from the CBD, has the highest potential sustainability, and Wellington Street, with a household density of 29 households per hectare, has the least potential sustainability.

Figure 14 Land area equivalents per household per year for domestic energy demand, generation and deficit



It is evident from these five case studies that density, mix of housing types, and land-use patterns will influence the potential sustainability of different residential patterns. These land-use parameters contribute greatly to urban sustainability at the local level. The orientations of buildings' roofs are most important to generate useful solar electricity from PV modules and hot water from a solar water heater. Site configuration, subdivision pattern of lots, number of lots between two adjacent roads, site perimeter, residential building density per hectare, floor area, and household density per hectare are also considered important for local sustainability of residential patterns.

4 Conclusions

The debate on sustainability tends to adopt only compact developments as '*today's visionary solution*' (Guy and Marvin, 1999) for achieving sustainable future urban form.

In New Zealand, urban growth policies also tend to recommend an increase in the footprint density of housing in urban areas. William et al. rightly commented that

> "The search for the ultimate sustainable urban form perhaps now needs to be reoriented to the search of a number of sustainable urban forms which respond to a variety of existing settlement pattern and contexts." (William et al., 2000)

The performance of five residential blocks in Auckland was measured in terms of domestic energy use. The study indicates that compact urban form may limit the potential for improved energy sustainability of residential blocks. The sustainability factors illustrated in this paper are limited to one in order to demonstrate this approach. Further research could be carried out to demonstrate the impact of behavioural change, energy conservation in the home, the appropriate orientation of buildings, or the adoption of more energy efficient technologies. Lower density housing may also allow for benefits, such as more biomass potential and solar heating opportunities, which are often overlooked in the density argument. As the approach is flexible, inclusion of a wider range of factors than those used in the original study is possible, and the inclusion of other factors might well change the rankings of the residential blocks. In future, the mathematical methodology developed in this research can be applied to the formulation of urban density standards in relation to energy consumption and development patterns of urban areas using a larger sample size. This new model opens up the possibility of developing a model that could help estimate the comparative degree of increased environmental sustainability of various urban forms at local, regional and national levels.

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References

American Forests (2000) *CITYgreen: Calculating the Value of Nature, 4.0 User Manual*, American Forests, Washington, USA.

Auckland City Council (1999) 'Part 7: residential activity, city of Auckland', *District Plan, Isthmus Section, Operative*, Auckland City Council, New Zealand, pp.A11–A17.

Auckland Regional Council (2003) *The Demand and Supply of Housing in the Auckland Region 1991–2001*, Auckland Regional Council, Auckland, New Zealand, p.3.

Boardman, B., Favis-Mortlock, D., Hinnells, M., Lane, K., Milne, G., Palmer, J., Small, E., Strang, V. and Wade, J. (1995) *Decade: Domestic Equipment and Carbon Dioxide Emissions, Second Report*, Energy and Environment Programme, Environmental Change Unit, University of Oxford, UK.

Breuer, D.R. (1994) *Design for the Sun: Vol. 1 Working Manual*, Energy Efficiency Conservation Authority (EECA), Auckland, New Zealand.

Center for Advanced Engineering (CAE) and Energy Efficiency and Conservation Authority (EECA) (1996) *New and Emerging Renewable Energy Opportunities in New Zealand*, University of Canterbury, Christchurch, New Zealand.

Centre for Advanced Engineering (CAE) (1996) *Energy Efficiency: A Guide to Current and Emerging Technologies*, The University of Canterbury, Christchurch, New Zealand, Figure 2.4(a).

Energy Efficiency and Conservation Authority (EECA) (2000) *The Dynamics of Energy Efficiency Trends in New Zealand: A Compendium of Energy End-Use Analysis and Statistics*, Energy Efficiency and Conservation Authority (EECA), Monitoring and Analysis Unit, Technical and Research Group, Wellington, New Zealand, Table C7, p.112, Figure 2.2(a); pp.29, 34, Figure 2.4(a).

Ghosh, S. (2004) *Simple Sustainability Indicators for Residential Areas of Auckland*, PhD Thesis, School of Architecture, The University of Auckland, New Zealand, p.226.

Ghosh, S., Vale, R.J.D. and Vale, B.A. (2006) 'Indications from sustainability indicators', *Journal of Urban Design*, Oxfordshire, UK, Vol. 11, No. 2, pp.263–275.

Guy, S. and Marvin, S. (1999) 'Understanding sustainable cities: competing urban futures', *European Urban and Regional Studies*, Vol. 6, No. 3, pp.268–275.

Masser, I. (2001) 'Managing our urban future: the role of remote sensing and geographic information systems', *Habitat International*, Vol. 25, No. 4, pp.503–512.

Ministry for the Environment (MfE) (1995) *Environment 2010 Strategy*, Ministry for the Environment, Wellington.

National Centre of Climate Energy Solutions (2005) *Greenhouse Gases from Residential Energy Use,* National Institute of Water and Atmospheric Research (NIWA) Science, Available at: http://www.niwascience.co.nz/ncces/cem/2002-03/residential, Accessed on: 4 November.

Pauleit, S. and Duhume, F. (2000) 'Assessing the environmental performance of land cover types for urban planning', *Landscape and Urban Planning*, Vol. 52, No. 1, pp.1–20.

Redshaw, D.J. and Dawber, K.R. (1996) *Sustainable Energy Options for New Zealand*, The University of Otago Press, Dunedin, New Zealand.

Regional Growth Forum (1999) *Auckland Regional Growth Strategy: 2050 – A Vision for Managing Growth in the Auckland Region*, Regional Growth Forum, Auckland Regional Council, Auckland, New Zealand, p.38.

Statistics New Zealand (1991) *New Zealand Census of Population and Dwelling (Super Map)*, Department of Statistics, Wellington, New Zealand.

Statistics New Zealand (1996) *New Zealand Census of Population and Dwelling (Super Map)*, Department of Statistics, Wellington, New Zealand.

Statistics New Zealand (2001a) *Auckland City Census 2001: New Zealand Census of Population and Dwelling*, http://www2.stats.govt.nz/domino/external/pasfull/pasfull.nsf/web/, Accessed on: 12 September 2005.

Statistics New Zealand (2001b) *Auckland Region Community Profile*: *New Zealand Census of Population and Dwelling*, Available at: http://www2.stats.govt.nz/domino/external/web /CommProfiles.nsf/, Accessed on: 12 September 2005.

Statistics New Zealand (2001c) Available at: http://www.stats.govt.nz/ census/2001-definitions-questionnaires/chapter-6.htm, Accessed on: 12 September 2005.

Wackerangel, M. and Rees, W. (1996) *Our Ecological Footprint: Reducing Human Impact on Earth*, New Society Publishers, Gabriola Island, BC, Canada.

Waitakere City Council (2003) 'District plan guidelines: human environments', *Waitakere City Council Operative District Plan 2003*, Available at: http://www.waitakere.govt.nz/AbtCnl/ pp/districtplan/infosheets.asp#1, Accessed on: 12/09/05.

Williams, K., Burton, E. and Jenks, M. (2000) 'Defining sustainable urban form' in Williams, K., Burton, E. and Jenks, M. (Eds.): *Achieving Sustainable Urban Form*, E and FN Spon, London.