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MEASURING INTEGRATED SUSTAINABILITY PERFORMANCE AND SELF-SUFFICIENCY OF THREE RESIDENTIAL PRECINCTS IN SYDNEY

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ABSTRACT

Sustainability performance of a local-scale urban form is significantly important to developing self-sufficient communities. In this paper, three contemporary low, medium and high density residential developments from Sydney were selected and measured considering three sustainability factors: energy; water and local food production as a part of the green infrastructure. Data was collected from Australian Bureau of Statistics (ABS) 2011 Census, georeferenced aerial imagery and planning and property databases. The selected case studies for this paper were analysed to determine the total energy and water demands and the potential of developments to integrate renewable energy and water to develop localised self-sufficient systems. The potential of on-site green infrastructure to provide positive ecosystem benefits through urban food production were calculated in this analysis. The assessment is conducted using Geographic Information Systems (GIS) methods and mathematical calculations. Research outcomes suggest that calculating impacts of different sustainability factors in different density precincts or local scale urban forms could provide clues for developing relevant sustainability strategies for various urban development projects. The methodology developed could be applied to designing new and retrofitting existing developments. Different density urban forms would require varying strategies to become sustainable.

Keywords: urban form; sustainability; energy, rainwater; local food production; residential

INTRODUCTION AND CONTEXT

The main aims of sustainable development are to contribute to the reduction in energy and resource consumption; to develop self-sufficiency and resilience and to build capacity in communities so that the people could live within the regenerative capacity of the earth. Out of a total of seventeen goals, creating sustainable cities and communities, responsible consumption and protection and improving food security are some of the important goals identified in the 2030 Agenda for Sustainable Development (Department of Economic and Social Affairs Unite Nations 2016). The present awareness of communities, governments, businesses, international agencies, non-governmental organisations and voluntary organisations clearly indicates the importance of implementing sustainable development within the built environments. Residential land 'one of the major determinants of urban structure' and typically comprises of approximately 40% of the total developed land in a city (Romanos 1976, p.4). The residential urban forms comprising of dwellings and their servicing infrastructure form integral parts of the current and future built environments. The morphologies of different density of residential developments could affect national energy demand and consumption over a long period of time. The sustainability of residential urban forms essentially needs to be objectively determined to assess progress towards these goals.

Domestic energy, water and food are considered in this paper as the three fundamental factors that influence the sustainability performance although other factors such as waste, vegetation etc. also have impacts on the performance. The 2050 carbon emissions from the residential sector compared to 1990 level would rise by 28.6% to 55.8 mega tonnes of CO_2 in Australia (Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) 2011). Approximately 94% of the primary energy consumption in Australia comes from fossil fuels. Australia's main energy generated from coal and oil sources and 32% of the total energy produced is consumed locally (Department of Industry and Science 2015). The electrical energy for domestic use (such as space heating and cooling, water heating, lighting, cooking, refrigeration) when generated in coal

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fired power stations can increase greenhouse gas emissions significantly. Therefore, using energy from renewable solar power, wind and others sources could significantly reduce and mitigate greenhouse gas emissions. Sydney Water supplies daily over 1.4 billion litres of water in greater Sydney region, but 70% of this water is consumed by the households and rest 30% by the businesses, industries and schools (Sydney Water 2016). The potable or drinking water requirement for a household is only a small percentage of the total water demand. But potable water is used for activities such as gardening, toilet flushing etc. which could use non-potable water. The uses of water sourced from of rain water and recycled water for non-potable uses could significantly reduce overall potable water demand and save water. By 2050, fifty percent more food would be required to be produced to feed nine billion people on earth and therefore, building an efficient food system in cities is an essential priority for future (World Bank 2016). Also a study concluded that for a small country like New Zealand, located one corner of globe, 96% reduction in food transport emissions is possible if all foods are grown within hundred kilometres farm to plate travel distance (Pritchard and Vale, 2003). The increasing needs for sustainable uses of energy and water and critical importance of food make these three factors integral for sustainability performance assessment of different urban forms.

A precinct is a very useful spatial representation of a local-scale urban form and is referred commonly as a neighbourhood, or district or community. At this level, buildings, land uses, green infrastructure such as trees and urban agriculture, and other factors work together to create a system. Measuring integrated sustainability performance at the precinct level unfolds the potential or adaptive capacity of the urban form to incorporate sustainable energy, water, and green infrastructure practices to develop self-sufficiency and resilience. It is significant as it represents an intermediate spatial scale between an individual building and an urban planning level. At this scale, the sustainability issues and their assessment methods could be distinctly different. Depending on the urban structure the blocks could contain various land covers such as tree cover, productive land, built up areas and other impervious areas as paved surfaces, driveways, and roads. The ownership patterns of these precincts vary from the strata title to body corporate to Torrens title types. Spatial dimensions and boundaries of precincts could be different, and their sizes could vary from large to small scales. In this paper, precincts are defined as a small community or blocks where some households could live in either in different dwelling types such as apartments or townhouses or single detached houses and the precinct boundaries match with the mesh block spatial boundaries as defined by the ABS.

Some best practice examples of sustainable precincts follow. ‘Beddington Zero Energy Development (BedZED)’ is a zero fossil energy, carbon neutral community and a high-density development on a brownfield site and is located in Sutton, south-east of London in the UK. The objectives of the project are 50% reduction in transport energy; 60% reduction in domestic energy; 90% reduction in heating demand; 30% reduction in water consumption; reduce waste and increase recycling and use locally sourced materials and to improve biodiversity and provide productive spaces for household food production (Energie Cties and Ademe 2008). This development has achieved 81% reduction in energy use for hot water and 45% less electricity use than the local average. Up to 20% of electricity demand generated by on-site solar PV panels and water consumption was reduced to 72 litres/day which 58% lower than London average. 18% of BedZED resident’s daily water consumption is from rainwater (Energie Cties and Ademe 2008; Chance 2008; Ellis and Moore Consulting Engineers et al. 2002). Lochiel Park is a nation-leading green village built on a former educational and training institution site and is located in Adelaide in South Australia. It covers a total area of 15 hectares of site out of which 4.25 hectares houses 100 dwellings and showcases exemplary sustainable technologies and also incorporates a community garden and home gardens for food production. The objectives of the project are to achieve: 78% reduction in potable water consumption, 74% reduction in greenhouse gas emissions and 66% reduction in energy use compared to the 2004 SA household average (Renewal SA, 2014). In 2012, this development achieved reduction of 64% energy consumption compared to a typical house in SA in 2004 and 60% saving of potable water compared to the 2004 average (Renewal SA, 2014).

A significant debate around sustainability performance of compact or high-density developments and sprawl or low-density patterns continues (William et al. 2000; Jenks and Demsey 2005; Newman and Kenworthy 1989; Gordon and Richardson 1997; Troy, 1996; Troy, Holloway and Randolph 2005). In the absence of a methodology to measure densities, significant difficulties and controversies exist in comprehending and measuring densities (Jenks and Dempsey 2005, p. 293). Research in the quest of a sustainable urban form indicates possibilities of having more than one alternative sustainable urban form (Williams et al. 2000; Jenks and Demsey 1996). This research brings together three sustainability factors to assess sustainability performance of different density urban forms. The analysis conducted in this research provides a snapshot on varying capacities of low, medium and high-density residential urban forms to become sustainable.

AIMS AND OBJECTIVES

The main aim of this paper is to conduct an integrated sustainability performance assessment in low, medium and high density urban forms or precincts located within one geographic location. The prime objectives of this research were to examine the following in three different patterns of urban developments.

1. To estimate the total energy demand and to measure to what extent current morphologies of the developments assist in solar/renewable energy generation on site;
2. To determine deficit or surplus or sufficient energy demand that could or could not be generated on site;
3. To measure rain water harvesting potential of building roofs for gardening use and to estimate rain tank requirements to utilise the water collected from the roofs in these selected developments;
4. To determine deficit or surplus or sufficient water demand that could or could not be collected on site from the building roof areas;
5. To calculate total dietary vegetable demand of the community in these developments and local food production potential of available productive land areas on site;
6. To determine deficit or surplus or sufficient vegetable demand that could or could not be produced on site;

This paper conducts a comparative analysis of three case studies considering three important sustainability factors: energy; water and local food production. The prime research question was to explore potential sustainability performance of urban forms considering three sustainability factors. This quantitative analysis was conducted on a scale larger than a single building scale to determine objectively how some of the other factors may have impacts on the performance.

RESEARCH METHODOLOGY

Selection of three case studies and data collection

Three low, medium and high density case studies were selected from the same Castle Hill suburb in The Hills Shire Council local government area (Fig 1) in New South Wales in Australia. This suburb is located at approximately thirty kilometres away from Sydney CBD towards the north western part of Sydney metropolitan area. Castle Hill is classified as a major strategic centre in Sydney's future planning documents and will function as a high-density centre with employment opportunities (Planning and Environment, NSW Government 2014). Castle Hill is also an older suburb with a predominant dwelling type of single detached houses with ample spaces around the buildings and a very good tree canopy cover throughout the suburb. North-West rail link has significant impacts on the urban form transformation in this area. The North-West rail link is currently under construction and the low density residential urban forms of Castle Hill are changing around the train station into medium and high density urban forms with built types such as townhouses and apartments respectively.

The three case studies are located within 10-15 minutes walking distance from the Castle Hill proposed train station and the large shopping centre known as Castle Tower Shopping Centre. The locations close to this shopping centre provide a variety of housing types as this area is currently going through the transformative stage and becoming a denser environment. The high density 'Case Study One' contains three storied two and one bedroom luxury apartments with private roof spaces for some apartments. The open spaces on the ground is limited and apartments are modern and have very good quality designs. The 'Case Study Two' has two storied contemporary townhouses with 3 bed rooms and common spaces at the front and private small backyard spaces at the rear. 'Case Study Three' is the typical low-density urban form with conventional detached residential houses. This houses are placed on large plots with ample open spaces as front and rear gardens. There are mature trees; the houses are one to two storied and could comprise of three or more bedrooms. One of the selection criteria was that the selected case studies should have residential as their predominant land use. This is because this paper is focused on calculating residential energy use at a precinct scale and residential land use patterns of all case studies allowed calculating the energy and water demand of households in the case studies effectively. All the three case studies are at a mesh block level, the smallest geographical area defined by the Australian Bureau of Statistics (ABS) classification (ABS 2011). The annual rainfall pattern, soil types and growing conditions are also same for these three case studies as they are located in the same local government area close to each other and provide a good comparison.

Data was collected from various sources and databases. The number of dwellings and population in the mesh blocks and spatial data on mesh block boundaries data were collected from the ABS 2011 Census data. The number of bedrooms in townhouses and apartments was collected from RP data. New urban information or data on the built up areas, site boundaries, and tree canopy cover were generated using Geographic Information System (GIS) methods. Data on household energy, water consumption were collected from different research reports, fact sheets and industry specifications. Figure 2 outlines the built form types in three case studies.

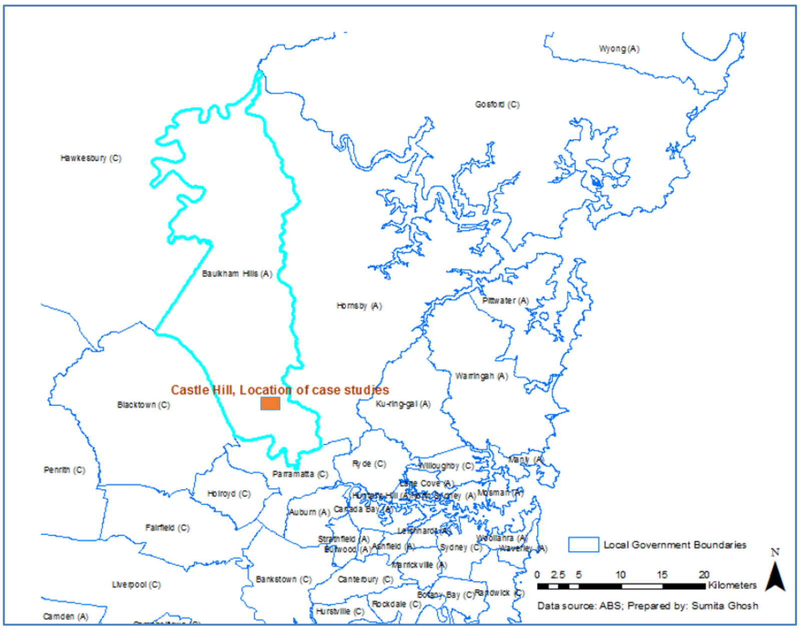

Fig 1: Location of Castle Hill in the Baulkham Hills LGA in Sydney (Data Source: ABS 2011 Census**)**

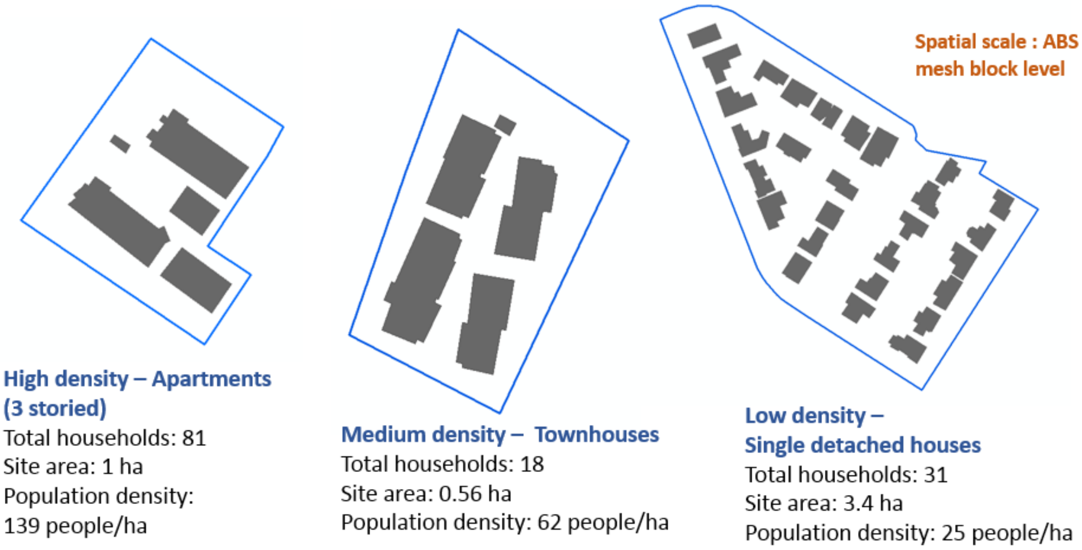

Fig 2: Layouts of built forms in three selected case studies (Drawn by: Sumita Ghosh)

Energy, water and green infrastructure measurement methods

Three different measurement methods or models were applied to measure energy, water, and local food production. This work builds on author's previous research that developed three separate GIS and mathematical models for energy, water and local food production using New Zealand case studies to measure sustainability performance for different density urban developments. However, this paper presents analysis using these models but further developed incorporating new methods to measure these three sustainability factors in Australian case studies.

Total household energy demand for space heating and electricity needs for cooking, lighting, refrigeration and many other different activities were calculated based on household sizes, locational aspects of the case studies with respect to NSW and using energy demand measurement tool developed by Australian Energy Regulator (2016). Total built up roof areas were calculated from georeferenced aerial photographs using GIS methods. Using these values of total built up roof areas, the potential of the case studies to generate renewable energy from the solar water heater and solar photovoltaic modules (PV) were calculated. The deficit energy demand was calculated from total energy demand and total available onsite energy from solar and local food production.

Total water demand for the households was calculated for the three case studies at the precinct scale. The roof rainwater collection possible from the total building roof areas and strategies for storing rainwater in a suitable size rainwater tank were examined using a measurement tool developed by Alternative Technology Association (ATA) (2016). Water savings for gardening use was calculated in this paper. Roof rainwater harvesting reduces the need for reticulated supply and associated energy and carbon emissions from mains water supply. It is also an important Water Sensitive Urban Design (WSUD) technology that could be applied at the precinct scale. This analysis provides an understanding on the availability rainwater from rain tank throughout the year in three case studies.

Local food production potential of low-density case study (Case Study Three), is high as at this scale this pattern of development could incorporate different food production typologies such as front and rear home gardens, community gardens and food gardening on the grass verges within the project boundary. In the medium-density case study (Case Study Two), the rear garden sizes were limited due to higher fragmentation of the open spaces within the site, therefore, these developments could incorporate only smaller food production spaces such as certain sizes of raised bed or planter boxes and some food production in the small rear gardens. In the high-density case study (Case Study One) with apartments, planter boxes in the balconies and a community garden in the common areas were considered. Only limited areas on the roofs could be converted into gardens and a handful of apartments have accesses to the building roofs. Recommendations were developed from these three residential case studies considering comparative and collective performance of energy, water, and local food production technologies to reduce its overall consumption. Surplus or deficit performance is also an indicator of self-sufficiency and resilience of communities living in these selected case studies.

This paper presents further refinements of the models through creation and additions of new and improved methods of calculations. The dwelling data collected in this paper is based on specific numbers of bedrooms and density and development patterns and differ from the methods applied in previous studies. In this paper the models have been applied using appropriate substitution of data and new methods of calculations for energy and water that have been formulated considering three Australian case studies. For example, Australian household energy use data used in this study is based on household size, seasonal variations, location of the area, facilities such as pool and energy sources such as gas used at home. Similarly, the water assessment in addition to total roof rain water collective potential, takes into account the feasibility of a rain tank installation and effectiveness of annual rain tank supply of water on site for gardening uses in the three different density urban forms. These three selected urban forms have varying capabilities guided by their morphological characteristics.

RESULTS AND DISCUSSIONS

Energy

The household sizes in the three case studies were calculated based on the ABS 2011 Census and RP data. It was assumed that one to two bedrooms apartments had a household size of two; three bedrooms townhouses had a household size of three and the separate houses with more than three bedrooms have the family size of four in this location. The total energy demand for each case study was calculated using Australian Energy Regulator (2016) tool considering varying household sizes for the local area of the Castle Hill. The total energy demand was calculated considering swimming pools and no gas connections in the high and low density developments in the Castle Hill. The medium-density development does not have any swimming pools and gas connection. Table 1 presents annual energy demand in the case studies. The building roof areas calculated by the GIS methods were utilised to determine total available solar efficient roof area for installation of solar roof water heater and solar PV modules in the precincts. The orientation of the building roofs are important as the roofs oriented towards north would efficiently generate more solar energy compared to roofs oriented in other directions such as south.

Table 1: Total residential energy demand in three case studies

	Case Study One	**Case Study Two**	**Case Study Three**
Total number of houses/townhouses/apartments	81 X 1 and 2 bedroom apartments	18 X 3 Bedroom townhouses	31 X 3 or more Bedrooms detached houses
Total number of households	81	18	31
Average 2 persons annual household energy demand (kWh/year)	9393		
Average 3 persons annual household energy demand (kWh/year)		10875	
Average 4 persons annual household energy demand (kWh/year)			11323
Total annual energy demand (GJ/year)	2739	705	1264

Calculated by author based on data sources: ABS, 2011; Australian Energy Regulator 2016; RP Data, 2016

Energy Matters (2016) estimated that for a small household of two people in a small home would require a 1.5 kW solar PV system while a medium size household with two to three people would need a 3 kW solar PV system to supply the energy demand. This energy demand includes energy used by the refrigerator, down lights, LCD TV and standby appliances, washing machine, dishwasher, computer and a small air conditioner at a household level (Energy Matters 2016). In Sydney based on available sunshine hours, it is calculated that on average daily energy generation from a 1.5 KW PV system would be 5.85 kWh and the same from a 3 kW PV system would be 11.7 kWh (Clean Energy Council 2011). A 1.5 kW solar system would require 10 square metres of roof space as altogether contains six panels and each panel is of size 1.6m x 1m (Infinite Energy 2016). Therefore, a 1.5 kW solar PV system covering 10 square metres of roof space would generate 2135 kWh annually at a daily rate of 5.85 kWh/day in Sydney (Clean Energy Council 2011; Infinite Energy 2016). It is calculated that solar PV module coverage on roof space would generate 213.5 kWh or 0.77 GJ per year.

For an average family household, a Rheem 52C300 solar water with an area of 2475mm X 2425 mm or 6.0 m^2 would be able to reduce water heater use by 87% in Castle Hill, (Solahart 2016a). For a single or two persons household, a Rheem 52S160 solar water with an area of 1138 mm X 2490mm or 2.83 m^2 would be able to reduce water heater use by 78% in Castle Hill, Sydney (Solahart 2016b). From these two values, it is assumed that an average of 4.4 m^2 of solar water heater collector per household would be able to supply a significant share of household hot water demand and would generate 8.7 GJ per household per annum. The PV modules could be placed on the remaining available solar efficient roof area after installation of 4.4 m^2 of solar water heater collector per household basis. Total energy deficit or surplus or sufficient for the three residential blocks for the particular year '*y*' were calculated using the following formula.

Total deficit/surplus/sufficient energy (E_y) (GJ) = Total domestic energy demand (E_{dy}) (GJ) – Total available energy from solar water heater and/or PV modules (E_{ay}) (GJ)

$$E_y = (N_y \times E_{hy}) - [(N_y \times C_2) + \{\sum_{n=1}^{s} R_{sy} - (N_y \times C_1)\} \times C_3] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

(Ghosh, Vale and Vale 2006)

where, E_y = Total deficit/surplus/sufficient energy in in gigajoules (GJ); N_y = Total number of households in the residential block; E_{hy} = Total local area energy demand per household in GJ; R_{sy} = Sum of solar efficient roof areas in '*s*' numbers of built up units in m^2 and *C*1, *C*2, *C*3 are three constants, where C_1 = Total area of solar water heater required in m² per household and is equal to 4.4 m^2 per household; C_2 = Amount of energy generated per annum by a 4.4 m^2 solar water heater is equal to 8.7 GJ per household per annum; and C_3 = Total amount of energy generated per annum by 1 m² of PV module installation in GJ per household and is equal to 0.77 GJ per annum in Sydney.

Total site areas for all the case studies were calculated considering half road width of peripheral roads and full road width for roads within the case studies as service provision areas. In the 'Case Study One' considering 10% loss of roof areas for corners and to other problems, total available roof area is calculated to be equal to 2502 m^2. The installation of solar water heaters on the roof areas would require a total area of 356 m^2 per household considering each household would have a solar water heater. As some of the apartments have private roof areas, therefore, installation solar water heaters for all residents would depend on the collective decision of the residents for this case study. Out of a total of 2156 m^2 remaining roof area, 1620 m^2 would be utilised for solar PV installation of two 1.5 kW solar PV modules covering 20m^2 per household. The deficit energy is 788 GJ per year for the whole case study. Remaining 526 m^2 the roof area could be used for roof rainwater harvesting which is not sufficient. In this type of developments building integrated PV could be a good solution for solar energy generation as it uses under-utilised vertical surfaces of the buildings. However, this is not in the scope of this paper, therefore, not included. A decision needs to be made based on the actual energy and water bills and views of the residents which option would be suitable specifically for this development and trade-offs between different sustainable technologies.

In the 'Case Study Two', available roof area was calculated to be equal to 1521 m² and after allocating areas for solar water heater and solar PV modules, a reasonable roof area was remaining for roof rain water harvesting. The deficit energy is 271 GJ per year for the whole case study. The Figure 3 graph shows that in the high density and medium density case studies, energy deficit is 29% and 38% respectively as these two case studies have limited roof areas for solar installation. With the same allocation, energy deficit in low density case study 'Case Study Three' is 41%.The available roof area was calculated to be equal to 6685 m² which was significantly larger compared to other case studies. Based on the above model the energy demand, available energy, deficit energy and other details were calculated and presented in Table 2 and Fig. 3.

Table 2: Total annual energy deficit in three case studies

	Case Study One	**Case Study Two**	**Case Study Three**
Total site area (m²)	10296	5587	34096
Total annual energy demand (GJ/year)	2739	705	1264
Total available built up roof area (m²) (10% lost)	2502	1521	6685
Total area of solar water heater (m²)	356	79	136
Total solar energy generation on site from mounted solar water heater (GJ/year)	705	157	270
Total area of solar PV installation on roof (m²)	1620	360	620
Total solar PV energy generation on site (GJ/year)	1247	277	477
Total available solar energy on site (GJ/year)	1952	433	699
Total annual energy deficit (GJ/year)	**787**	**271**	**517**
Remaining roof area for roof rain water harvesting (m²)	526	1082	5929

Calculated by author

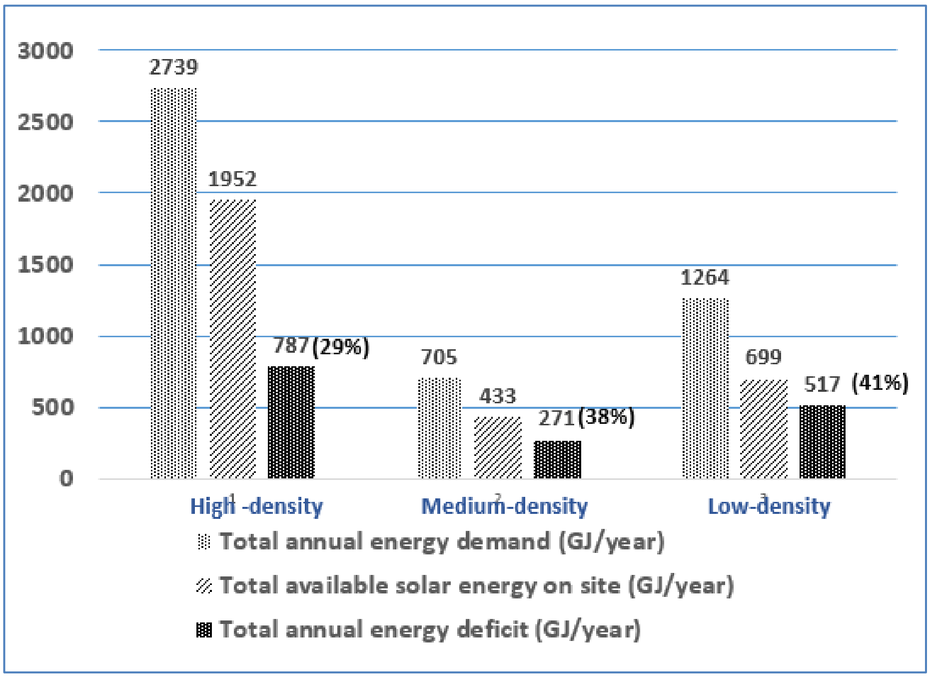

Fig 3: Total annual energy demand, availability and deficit in three case studies

Larger houses in the low density case study have ample of roof spaces left, therefore, they could accommodate up to four solar PV modules for solar generation for each household. Using the similar allocation of solar water heater and solar PV modules, a significant amount of roof area of 5929 m² was remaining for rainwater harvesting. A part of this area could be utilised to generate more solar energy with solar PV installation in the 'Case Study Three'. If each household in this case study installs two 1.5KW Solar PV in addition to two 1.5 kW solar PV modules, the total deficit energy could be reduced from 517 GJ/year (41%) to 39 GJ/year (3%). Additional 620m² of building roof area would be required for installing these PV modules leaving sufficient roof area of 5309 m² for rain water harvesting in the low density case study.

Water

Based on the solar energy analysis the area required for solar generation was deducted from total roof areas available and the remaining roof areas were calculated for roof rainwater harvesting for the three case studies. Assuming 20% of these available roof areas in three case studies would not qualify for rainwater collection as these areas would be lost due to various reasons such as corner areas, inaccessible, unsuitable shape and size, difficulty to connect some of the roof areas to rainwater tanks on the ground and others. Assuming only 80% of the roof areas would be usable for rainwater harvesting, the available roof areas in three case studies were estimated.

Using the following formula (Ghosh and Head 2009), approximate annual roof rainwater collection potential was calculated.

$$\sum_{n=1}^{i} R_v = \sum_{n=1}^{i} R_b \text{ X } C_1 \text{X } (A_r/1000) - \sum_{n=1}^{i} R_b \text{ X } (F_f /1000) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

where, R_v is total roof rain water collection volume in cubic metres; R_b is total building roof areas in square metres; i is the total number of building roof areas in the development; A_r is the mean annual rainfall data in millimetres for the time period 2009-2014 for Sydney and is equal to 1155mm per year (Bureau of Meteorology (BOM) 2015); F_f is the amount of water required for first flush diverters and is equal to 0.2 litres/m² (Ghosh et. al 2009) and C_1 is the constant equal to 0.9 and assumes that 10% collected rain water loss due to evapotranspiration (Ghosh et. al 2009).

The total annual water demands for the case studies were estimated assuming the water demand of 294 litres of water per day per capita in Sydney (Sydney Water 2016). 35% of the total water household consumption is required for gardening use (Rainwater Harvesting Association of Australia, 2011). For the 'Case Study Three' considering addition solar energy scenario, it is adopted for the rainwater collection that 5308 m² roof area would be available for rainwater harvesting for gardening. The values are calculated presented in Table 3.

Table 3 demonstrates that if all rainwater collected from the roof areas in three case studies would have been utilised, then the 'Case Study One' could supply only 8% of its gardening water demand and the 'Case Study Two' could supply up to 68%. The 'Case Study Three' could supply 100% of its gardening demand and in addition, would generate 36% of its gardening water demand as a surplus which could be used for other non-potable purposes such as toilet flushing and washing clothes.

Table 3: Roof rainwater harvesting potential in three case studies

	Case Study One	**Case Study Two**	**Case Study Three**
Total annual water demand for gardening (35% of total household water use) **(cubic meters)**	5221	1315	3230
Total available roof area for rain water harvesting (m²)	421	866	4246
Total annual rainwater collection potential from the available roof areas (cubic meters)	437	900	4414
Rainwater supply potential of available roof of the total gardening demand (%)	8%	68%	136%

Calculated by author

Storing harvested rainwater in rainwater tanks for regular use is important. Effective rainwater use depends on the volume and efficiency of rainwater tanks to store and supply water in a timely manner throughout the year. The capacity of a 50,000 litres rainwater tank in high and medium density case studies and individual building level rainwater tanks with 5000L capacity in low-density case study were examined. For the low density case study, an average roof area of 216 m² for each house was considered while in the medium and high density case studies spatial distributions of main building blocks were considered. It is assumed that the on-site rain tanks would supply 100% of the water needs for gardening. Rainwater tank water uses for three case studies were calculated using Alternative Technology Association (ATA) (2016), Australia online tool 'Tankulator', and presented in Table 4.

Table 4 indicates that based on the assumption of rain tank sizes only 60-62% of harvested rainwater from the roof could be used by the rain tanks as rest volume of the water could be lost due to overflowing of the tank. Selecting the correct tank sizes are important as storing the overflow amount water could be possible. Availability of spaces on site for installing appropriate size rain tanks needs to be considered at the design stage for new developments and existing spaces on site could be used to retrofit existing developments.

Table 4: Roof rainwater harvesting potential considering rain tanks

Rain tank Measures	**Case Study 1**	**Case Study 2**	**Case Study 3**
Total annual roof rainwater harvesting potential (Litres (L))	437000	900000	4414000
Total daily water use from rain tanks for gardens (L/day)	14303	3602	8849
Number of days/year water available & % of days available	18 (5%)	154 (42%)	304 (83%)
Number of days/year tank water overflows (days)	0	1	20
Volume of rain water overflow per year (L/year)		15730	1319298
Rainwater tank water used per year (L/year)	260396	553602	2696938
% of total rainwater harvested water used by the rain tanks (%)	60%	62%	62%
Water required from mains supply per year or annual water deficit for gardening (L/year)	4960199	761129	539338

Local food production as part of a green infrastructure

An ABS household survey conducted in 1992 on backyard production of vegetables in New South Wales (NSW). Households in NSW grew 28% of their total home production of vegetables which included tomatoes, potatoes, cabbages, capsicum, cauliflower, carrots and beetroots, lettuce and peas (ABS 1992). According to this survey, an Australian backyard grew, 70.4 kg vegetables on average, and tomatoes were the most popular vegetable (ABS 1992).

According to Australian Government's 'Healthy Eating' recommendations on daily vegetable servings and intake distribution in the three groups of vegetables, 425 kcal to 255 kcal energy from vegetables is required daily for an average person. It is calculated that the average energy required daily from the vegetables approximately ranges from 12% to 20% of the recommended daily average food energy intake per person of 2150 kcal (Haug et al. 2007). The total vegetable demand is calculated to be equal to an average value of 330 kcal of the total daily diet for an average person in Australia (Ghosh 2011). Ghosh (2014) developed a local food energy model that assessed local food production potential of low to medium density residential urban forms at a community scale in Australia and New Zealand. In absence of specific Australian data on the productive capacity for these case studies, productive capacity of vegetables is adopted to be equal to an average value of 0.007 GJ 0r 1673 Kcal per m² of the productive land area (Ghosh, 2014).

The productive potential of case studies to grow vegetables were calculated using the following formula.

$$L_y = L_d - L_p \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, $L_y =$ Total deficit/surplus/sufficient dietary energy to supply vegetable demand in GJ; L_d = Total dietary energy demand for vegetables in GJ and L_p =Total available energy from production of vegetables from available on site productive land in GJ (Ghosh 2014).

'Case study One' and 'Case study Two' have limited on site areas for food production on-site. In the 'Case Study One', mainly a community garden could be located in the common areas. Using GIS methods, it is calculated that 118m² of land was available in the common areas of the apartments. Also each apartment has a balcony, which could contain a smaller planter box of .6 m² or 1.0mX0.6m for vegetable production. The total available productive land area is calculated to be equal to 167 m² considering the planter box in each apartment and space available in the common areas. In the 'Case Study Two' each townhouse has its defined boundary and a small backyard. There is an excellent canopy cover on site which in some townhouses shades the backyards. Availability of productive spaces in common areas and relevant rear gardens of the townhouses were considered and was calculated using GIS. The common areas could include a small productive garden, and the available productive area is 222 m². In addition to this, it was considered that 2 m² or two 1mX1m planter boxes on wheels could be easily located in the backyards which could be moved as required to get solar access to growing vegetables. Considering these two typologies, the total available productive land area is calculated to be equal to 240 m².

A detailed land cover analysis was conducted on ‘Case Study Three’ as it could include various typologies food producing spaces. Land uses or land covers linked to food production or land uses that could be converted into food production spaces such as open spaces, lawns, front and rear gardens were measured using GIS methods in the low-density case study. Average sizes of front and rear gardens in ‘Case study Three’ are 248 m^2 and 321m^2 respectively. Land areas under the tree canopy covers were considered unsuitable for vegetable production due to root conflicts and shade. The front and rear gardens in ‘Case Study Three’ had similar tree canopy cover 43.2% and 42.8% respectively. Table 5 presents the results of analysis.

Table 5: ‘Case study Three’ garden area analysis for local food production space calculation

Garden Characteristics	Case study Three (Area (m^2))
Total front garden area	7205
Total rear garden area	9315
Total tree canopy area in front garden (as % of total front garden area)	3110 (43.2%)
Total tree canopy area in rear garden (as % of total rear garden area)	3990 (42.8%)
Total lawn cover in front garden	2326
Total lawn cover in rear garden	2762

Calculated by author

Based on the planning requirements in the ‘Case Study Three’, an area of 24 m^2 in each parcel would be allocated as mandatory principal open space. It is assumed that the rest of the productive land available onsite excluding building footprints, paved covers, tree canopy cover and roads could be used for vegetable production. Table 6 presents local food production potential of vegetables in three case studies.

Table 6: Local food production potential of vegetables in three case studies

	Case Study One	Case Study Two	Case Study Three
Total site area (m^2)	10296	5587	34096
Total number of households	81	18	31
Available onsite productive land area (m^2)	167	240	4301
Total annual vegetable demand as a part of total dietary energy (GJ/year)	70	18	43
Total annual vegetable production potential on site (GJ)	1	2	30
Annual deficit energy in supplying total vegetable demand (GJ/year)	69	16	13
% of the annual demand supplied from onsite production (%)	2	10	69

Calculated by author

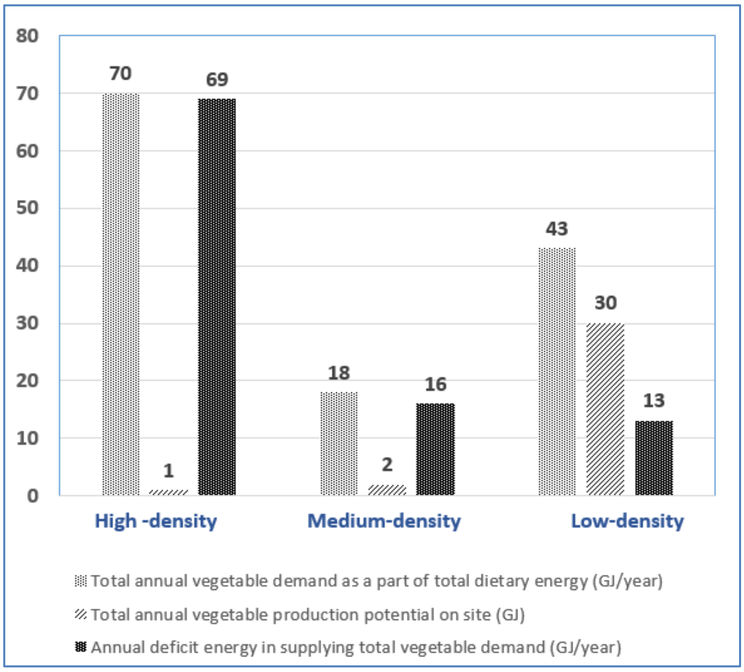

Fig 4: Local food production potential of vegetables in three case studies

From the Table 6 and Figure 4, it is clear that the low-density 'Case Study Three' could supply 69% of the vegetable demand on-site due to the availability of land areas at parcel levels. Productive land area available on-site in the 'Case Study Three' was estimated to be equal to 4301m². 'Case Study One' could produce only 2% of the total annual vegetable demand onsite due to limited availability of land and allocation of most of its roof areas for renewable energy generation and rainwater collection. Rooftop gardens or green roofs for local food production could enhance the productive capacity of high-density development. However, this case study could still have a community garden in the common areas which could foster better social connections and help the residents in local food growing activities.

Sustainability performance of case studies

Sustainability performance of three case studies on household basis is compared. This shows that the low density case study performed very well considering all the three sustainability factors. It very interesting to note that single detached houses 9 dwellings/ha or 25 people per hectare has the highest potential to be sustainable if all the sustainable technologies and practices applied collectively. The collective performance of energy and food on household basis in energy unit of GJ is similar high and medium densities but the same in the low density case study is approximately 61% higher than other two case studies. Considering energy, water and local food production potential and deficiencies in the three case studies, per household potential was calculated, compared and presented in Table 7 and in a graph in Fig 5.

Table 7: Collective performance of three case studies on household basis

	Case Study One	Case Study Two	Case Study Three
Total number of households	81	18	29
Total annual domestic energy deficit (GJ/household/year)	9.7	15.1	16.7
Total annual solar energy available (GJ/household/year)	24.1	24.1	38
Annual deficit energy in supplying total vegetable demand (GJ/household/year)	0.9	0.9	0.4
Annual available energy in supplying total vegetable demand (GJ/household/year)	0.01	0.11	0.97
Annual combined energy and food potential (GJ/household/year)	**24.11**	**24.21**	**38.97**
Annual water deficit for gardening per household (cubic meters/household/year)	61.2	42.3	17.4
Rainwater tank water used per household per year (cubic meters/household/year)	3.2	30.8	87.0

Calculated by author; Note: Solar energy available in Case Study Three considers 3% deficit when two additional solar PV are installed

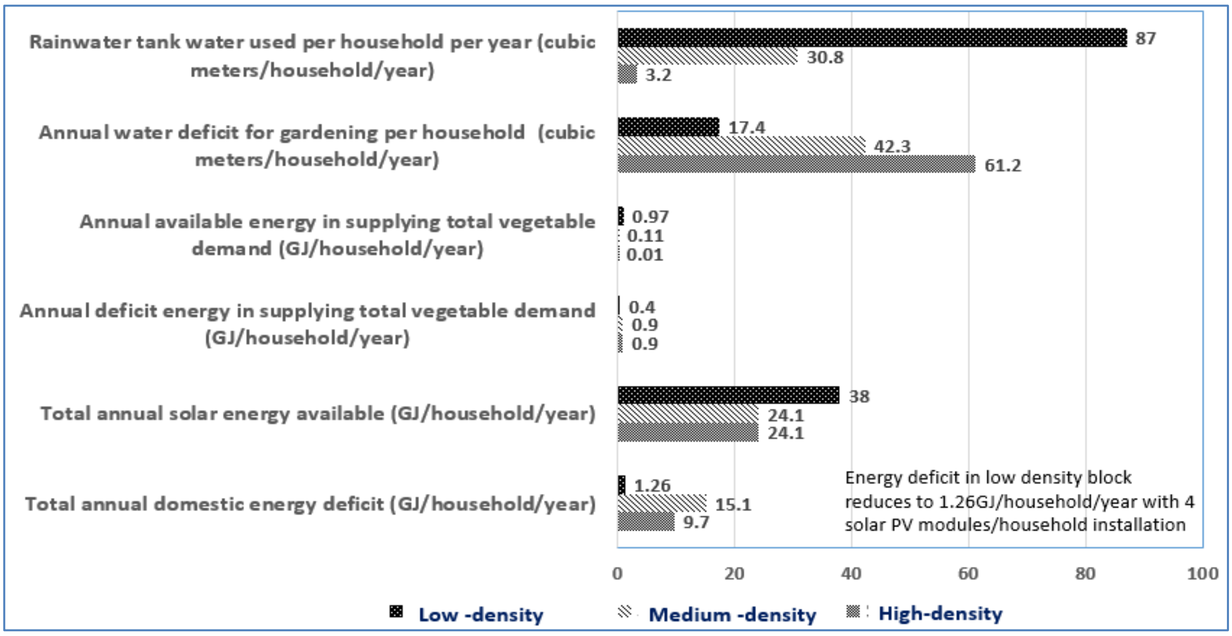

Fig 5: Sustainability performance of three case studies on household basis

It is also possible to integrate efficient practices in higher densities. ‘Beddington Zero Energy Development (BedZED)’ in the UK is an example of high-density best practice development that has achieved 81% reduction in energy use for hot water. Up to 20% of electricity demand generated by on-site solar PV panels and water consumption was reduced to 72 litres/day which 58% lower than London average. 18% of BedZED resident’s daily water consumption is from rainwater. The collective sustainability performances of different density developments depend on an optimum balance of energy and opportunities on-site, land cover types such as built up area, tree canopy cover, productive land etc., number households living on the block and their lifestyle patterns and many other factors.

RECOMMEDATIONS AND CONCLUSIONS

From the analysis, it is clear that the sustainability performances of different density developments depend on an optimum balance of energy and opportunities on-site, land cover types such as built up area, tree canopy cover, productive land etc., number households living on the block and their lifestyle patterns and many other factors. It is also important to understand how that block is integrated within the wider precinct and city-scale urban forms. For example, high density and medium density developments could generate all their vegetable needs in a small urban farm or a community garden close to the block to become sustainable but may not be growing food on site. On the other hand, a low-density development could also have the similar option to adopt in addition to growing their all vegetable needs on-site. It is essential to comprehend the trade-offs between different sustainable technologies and practices to maximise the sustainability performance. Recommendations follow.

- To incorporate sustainable technologies and practices for energy, water and food at the design stage for new developments and for retrofitting existing residential developments;
- To formulate appropriate sustainable design and planning policies that support integration of these practices in the residential built environments;
- To develop appropriate incentive schemes for making sustainable technologies financially feasible;
- To conduct training programmes to make residents aware of the critical importance of integrating sustainable technologies and practices within buildings and in the surrounding environments;
- To develop collaborative partnerships between government authorities, private organisations, renewable energy industries, local governments and community groups for the successful uptake of the technologies and practices;

Sustainable built environments aim to create a socially sustainable, environmentally responsive and economically feasible development. The high costs of solar PV modules is a major barrier in Australia. The uptake of solar technologies would require more cost effective solutions and better awareness of the communities. Moreover, focus only on environmental sustainability aspects could make people invisible in the sustainability assessment process. Behaviour change plays a significant role in the implementation of these sustainable practices and renewable technologies. Behaviour changes at the local scale could make a significant impact on overall settlement sustainability at a larger city scale. For example, if unused productive land as private gardens and spaces on the public realm could put to productive uses, these could make meaningful contributions to sustainability. Moreover, some of the motivations for the uptake of sustainable practices depend on the individual or households. Growing local food is directly dependent on personal and household motivations to grow food locally. But solar energy generation is mainly technological and includes indirect components of behavioural change shaped by sustainability knowledge and awareness.

Developing community awareness is a very useful way to make behaviour change for adapting to sustainable lifestyle and self-sufficiency. Collaborative partnerships of different companies, local governments and communities would be essential. More research needs to be conducted on the cost-effective approaches to implement sustainable technologies so that they become affordable to invest. There are significant challenges to address existing technical knowledge gaps although these have developed well in the last decade. Relevant planning processes and legislative framework for implementing practices would be essential. These sustainable technologies could be developed as a system for applications at a block scale. For example, tri-generation and co-generation could provide localised infrastructure for energy generation. WSUD practices incorporating rain gardens, rain tanks, bio-retention systems, wetlands and pollutant removal traps could improve stormwater quality and management and promote water savings. Trees could provide rainfall interceptions to reduce stormwater runoff while growing food on-site could foster socially connected better societies and improved public health. Creating new urban information base and databases with actual usage patterns could provide more accurate analysis. A higher numbers of block scale urban forms need to be analysed to standardise the models. However, the models in this paper could be applied in other cities with appropriate substitution of data. The inclusion of more sustainability factors is possible to develop the model further.

This paper provides a holistic approach to assessing sustainability at a community scale. The 'Precinct' or 'Block' is an important module in which multiple aspects work together to provide a meaningful performance. Future communities would require informed urban policy bases; economic benefits and integrated implementation of sustainable technologies in sustainable precincts. Sustainable behaviour changes of communities, households and businesses would play a major role. Integrated systems could create meaningful, resource efficient, and liveable and healthy communities and resilient future cities.

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REFERENCES

Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). (2011) 'Energy in Australia', *Department of Resource Energy and Tourism*, Canberra, Australia.

Australian Bureau of Statistics (ABS), (1992) *Home Production of Selected Foodstuffs*, Australia, Australian Bureau of Statistics, Canberra.

Australian Bureau of Statistics (ABS) (2011) *Mesh Blocks*, Statistical Geography Fact Sheet, ABS, Australia.

Australian Energy Regulator (2016) *Energy made easy: the power to compare*, Australian Government. Available at: https://www.energymadeeasy.gov.au/benchmark

Alternative Technology Association (ATA) (2016) *Tankulator*, Available at: http://tankulator.ata.org.au/

Bureau of Meteorology (BOM) (2015) *Climate Data Online*, Available at: http://www.bom.gov.au/climate/data/index.shtml

Chance, T. (2009). Towards sustainable residential communities: the Beddington Zero Energy Development (BedZED) and beyond. Environment and Urbanization 21(2). 527–544.

Clean Energy Council (2011) *Consumer guide to buying household solar panels (photovoltaic panels),* Available at: http://www.solarchoice.net.au/blog/wp-content/uploads/Solar-Choice-Clean-Energy-Council-Solar-PV-Consumer-guide.pdf

Department of Economic and Social Affairs, Unite Nations (2016) *Sustainable Development Goals*, Available at: https://sustainabledevelopment.un.org/sdgs

Department of Industry and Science. (2015). 'Energy matters – Solar power consumer guide', Department of Industry and Science, Canberra, Australia.

Ellis and Moore Consulting Engineers, Gardiner and Theobald, Peabody Trust, Bill Dunstar Architects, ARUP, Bioregional, ZED Factory. (2002). *BedZED – Beddington Zero Energy Development, Sutton*. General Information Report 89. Housing Energy Efficiency, The Government's Energy Efficiency Best Practice Programme. Watford, UK: Building Research Establishment (BRE), UK Government.

Energie Cties and Ademe. (2008). Guidebook of Sustainable Neighbourhoods in Europe. Available at: http://www.energy-cities.eu/

Energy Matters (2016) *How many solar panels needed to power a home?* Available at: http://www.energymatters.com.au/residential-solar/home-solar-sizing/

Ghosh, S., Vale, R. and Vale, B. (2006) 'Domestic energy sustainability of different urban residential patterns: a New Zealand approach', *International Journal of Sustainable Development*, Vol. 9 (1), pp. 16-37.

Ghosh, S. and L. Head, L (2009) 'Retrofitting suburban garden: morphologies and some elements of sustainability potential of two Australian residential suburbs compared', *Australian Geographer*, Vol.40 (3), pp. 319 - 346.

Ghosh, S. (2011) *Growing healthy local food: sustainability potential and household participation in home gardens*, Fifth State of Australian Cities National Conference (SOAC), Melbourne, Australia, pp. 1-11.

Ghosh, S. (2014) 'Measuring sustainability performance of local food production in home gardens', *Local Environment: The International Journal of Justice and Sustainability*, Vol. 19 (1), pp. 33-55.

Haug, A., Brand-Miller, J.C., Christoperson, O.A., McArthur, J., Fayet, F. and Truswell, S., (2007) A food ‘‘lifeboat’’: food nutrition considerations in the event of a pandemic or other catastrophe, *Medical Journal of Australia*, Vol. 187(11/12): 674- 676.

Infinite Energy (2016) *1.5 kW Solar System*, Available at: https://www.infiniteenergy.com.au/solar-system-sizes/1.5kw-solar-system

Jenks, M, Williams, K. and Burton, E. (1996) ‘A Question of Sustainable Urban Form’, Conclusion in: M. Jenks, E. Burton & K. Williams (Eds) The Compact City– A Sustainable Urban Form?, London, E. & F. N. Spon.

Jenks, M. and Dempsey, N. (2005) ‘The language and meaning of density’, in: M. Jenks & Dempsey (Eds) Future Forms and Design for Sustainable Cities, pp. 287–309, Architectural Press, Oxford.

Planning and Environment, NSW Government (2014) A Plan for Growing Sydney, Available at: http://www.planning.nsw.gov.au/~/media/Files/DPE/Plans-and-policies/a-plan-for-growing-sydney-2014-12.ashx

Newman P.W.G. and Kenworthy J. R. (1989) ‘Gasoline consumption and cities: comparison of US cities with a global survey’, *Journal of American Planning Association*, vol. 55, pp. 24–37.

Pritchard, M. and Vale, R., (2003) How to save yourself (possibly the world) on 20 minutes a day, Proceedings of the 6th Conference of the Sustainable Energy Forum, Threshold 2000, Can Our Cities Become Sustainable? Auckland, New Zealand.

Rainwater Harvesting Association of Australia, (2011) *Water use*, Available at: http://www.rainwaterharvesting.org.au/home/water-use

Renewal, SA. (2014). *Lochiel Park: our achievements*. Adelaide, Australia: Government of South Australia. Available at: https://renewalsa.sa.gov.au/

Romanos, M. C. (1976) Residential Spatial Structure Lexington, MA, D. C. Health.

RP Data (2016) RP Data Professional - Residential Property System, Available at: http://www.corelogic.com.au/products/rp-professional

Solahart (2016a) *Rheem 52C300 Roof Top Solar Hot Water System*, Available at: http://www.solahart.com.au/products/solar-water-heating/rheem-52c-series/52c300/

Solahart (2016b) Rheem *52S160 Roof Top Solar Hot Water System*, Available at: http://www.solahart.com.au/products/solar-water-heating/rheem-52s-series/52s160/

Sydney Water (2016) *Water use and conservation*, Available at: https://www.sydneywater.com.au/SW/education/drinking-water/Water-use-conservation/index.htm

The World Bank. (2016) *Overview on food security*, Available at: http://www.worldbank.org/en/topic/foodsecurity/overview

Troy, P.N. (1996) The perils of urban consolidation: a discussion of Australian housing and urban development policies, Federation Press, Sydney, Australia.

Troy, P, Holloway D and Randolph, B. (2005) Water Use and the Built Environment: Patterns of Water Consumption in Sydney, Research Paper No. 1, City Futures Research Centre, University of New South Wales, Sydney, Australia.

Vertical Veg (2016) *What size container do I need?* Available at: http://www.verticalveg.org.uk/what-size-container-do-i-need/

Williams, K., Burton, E. and Jenks, M. (2000) ‘Defining sustainable urban form’, in: K. Williams, E. Burton & M. Jenks (Eds.) Achieving Sustainable Urban Form, London, E. & F. N. Spon.