Linking residential densities, dwelling typologies and possible provisions for localised energy infrastructure in retrofitting urban forms
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Key words: local infrastructure; renewable energy; residential density; urban form; sustainability
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Abstract

In a resource constrained future, localised energy generation is likely to be a critical pathway to fulfill future energy demand. This paper presents how existing low, medium and high density residential developments with respective dwelling typologies could be retrofitted effectively with renewable energy infrastructure provisions. Localised energy infrastructure in this paper includes provision of photovoltaic modules (PV), solar hot water panels (SHW) and small wind turbines (SWT). This research initially reviews international and national pioneering residential projects applying renewable energy generation techniques. Key approaches and mechanisms are identified considering: residential densities; dwelling typologies; levels of distributed infrastructure provisions; energy outputs and funding, management and implementation methods. Using aerial photographs, GIS and census data, potential for localised energy infrastructure in three low, medium and high density case studies are determined. The factors considered are: dwelling orientation; available solar efficient building roof areas; dwelling typologies; occupancy pattern, demand and available land areas for localised infrastructure provisions. An energy infrastructure-residential urban form matrix developed is able to inform potential linkages of localised infrastructure provisions with dwelling typologies in different density residential urban forms. Research outcomes indicate that the dwellings’ typologies, site orientation, available roof and vertical surface areas and open spaces govern the possible provisions of on site energy infrastructure in different residential developments.
Linking residential densities, dwelling typologies and possible provisions for localised energy infrastructure in retrofitting urban forms

1 Introduction

Electricity generation from fossil fuel sources increases air pollution and harmful greenhouse gas emissions. Renewable energy systems can convert energy flows derived from solar radiation into electricity locally. They are a non-polluting, low maintenance and reliable source of power and are relatively easy to install. These systems could add a new dimension to achieving energy efficiency and reduction in greenhouse gas emissions, plus environmental benefits for communities and businesses as they could run conventional electrical appliances used for lighting, cooking and refrigeration. In this paper, localised energy infrastructure provisions in residential developments include solar water heaters (SWH), photovoltaic (PV) modules and small wind turbines (SWT). Onsite localised energy generation in residential areas requires conversion of solar or wind energy into electricity by using SWH or PV panels or small wind turbines.

Australia has a distinctive solar advantage as over 90 per cent of Australia’s land areas receive good solar radiation in excess of 1950 kilowatt hours (kWh/m²/annum) (Australian Trade Commission, 2009a). Solar water heaters (SHW) can be placed on the building roofs while PV systems can be set up on the ground, walls, pergolas and roofs of buildings, car ports and garages and can also be mounted on frames or integrated in building (BiPV) as a component. Operational efficiency of a SWH and a PV system is dependent on the amount of available solar radiation in a particular geographic location and the degree of shading on the solar panels. A 4 m² solar water heater can supply approximately 50–70% of domestic hot water demand in New Zealand (EECA, 2001). A 1 kWp photovoltaic system could supply around 3.74 kWh per day in Adelaide, Australia (Urban Ecology & Ecopolis Architects Private Limited).

Australia also has one of the best wind energy generation potentials in the world because of the availability of vast open spaces and varied climatic conditions. At the large scale, an average 2MW turbine can produce 6,000 MW hours annually in its 20 year life span which is sufficient to supply the energy demand of over 850 conventional houses (Australian Trade Commission, 2009b). A Canadian survey of small wind turbine (SWT) markets has categorised wind turbines into three types: mini wind turbines with a rated power output 300 W – 1kW; small wind turbines with output above 1 kW - 30 kW and medium wind turbines with output above 30 kW- 300 kW (Canadian Wind Energy Association, 2005). In this study, small wind turbines are classified as domestic small-scale turbines which have a rated capacity less than 10kW (Research Institute for Sustainable Energy (RISE), 2008). Components of a wind generator system for grid-linked electricity generation include wind generators, towers and inverters. An average height for SWT is about 20 m and therefore, it can be mounted on the building roofs or on the ground on towers. The performance of small wind turbines is determined by local average wind speed, elevation and, critically, local obstructions by terrain, trees, buildings and other features. Lack of correct measurements of wind generation potential has resulted in poor economic performance and long pay back period for small wind turbines in different parts of the world. Noise and vibration generated in operating small wind turbines within residential neighbourhoods are also important issues for the uptake of SWT technology for local energy generation (Encraft, 2009).
The Australian Federal Government’s Mandatory Renewable Energy Target (MRET) Scheme by 2020 and AU$500 million Renewable Energy Fund 2008 for renewable energy research aim to develop, commercialise and implement renewable energy in Australia (Australian Trade Commission, 2009b). Under the MRET scheme, solar water heaters accounted for 20.9% PV modules 0.6% and large scale wind energy generation 35.3% of all renewable energy generation capacity in 2006 (Australian Government Department of Resources, Energy and Tourism (ABARE), 2008, p.52). The Australian Government’s strong initiatives to promote uptake of localised solar generation are reflected through provisions for cash rebates under the Photovoltaic Rebate Programme (PVRP) (in areas connected or very close to a main-grid) and Renewable Remote Power Generation Programme (RRPGP) (in remote areas of Australia away from main-grid). The Residential and Medium-scale (RM) sub-programme under RRPGP offers up to 50 per cent rebates on the capital cost to support promotion of renewable energy systems in houses, schools and community buildings. Under the MRET and Renewable Energy Fund the Australian large scale wind industry will have a significant growth potential and could make a major contribution. Small scale domestic wind turbines are still not that common in Australia compared to SWH and PV panels. The importance of incorporating localized energy infrastructure in current and future settlement forms is significant. Existing residential areas can also be retrofitted with renewable energy systems to enhance their environmental sustainability performance. In addition, the planned new urban growth areas will provide an immense opportunity to incorporate efficient localised infrastructure provisions in future residential developments in Sydney (Metropolitan Strategy future planning) and elsewhere across Australia.

This paper focuses on quantifying the potential onsite solar and wind energy generation from residential roofs using solar water heaters, photovoltaic modules and small wind turbines in existing high, medium and low density urban residential developments at local scales. The potential percentages of energy contributions to total domestic household energy demand were calculated for onsite solar and wind generation. An energy infrastructure-residential urban form matrix was developed. This matrix informs of the potential of localised infrastructure provisions in different residential urban forms of varying densities.

2 Best practice residential examples: approaches and mechanisms

2.1 Comparisons of national and international solar projects

At an international level and city scale, the ‘Million Solar Roofs Initiative’ in the USA (US Department of Energy, 2005), ‘100,000 Roofs Programme’ in Germany, the ‘New Sunshine Programme’ and ‘70,000 Roofs Programme’ (Japan) (Brown, 2001:109; Jiménez, 2004) demonstrate significance of localised solar energy generation from roofs. Freiburg in Germany has been working over more than the last 20 years to apply solar technologies in a variety of urban projects, such as PV (over 400 installations), thermal (for hot water), sunrooms or ‘winter gardens’, passive solar design, solar cooling and transparent solar insulation (solar heat on a wall converted into thermal energy) (Dauncey 2003). The Australian Federal Government’s ‘Solar Cities Program’ for urban centres across Australia, aims to enhance implementation and use of solar technologies such as photovoltaic systems, distributed solar generation, smart meter use and appropriate pricing methods for these technologies (ResourceSmart, 2009). Under this program in Adelaide, seven key solar installation projects have been undertaken and solar PV panels have already been installed in the Golden Grove Arts and Recreation Centre (albeit of only 4 kW output) (Solar City Adelaide, 2009).
Some best practice residential examples of national and international solar projects varying from low density developments to high density developments at local scales were compared (Appendix 1: Table 1) considering the following points:
- residential densities;
- urban scale;
- dwelling typologies;
- distributed energy infrastructure provisions;
- solar energy performance and funding, management, partnership and participation.

The comparison showed that at a development scale, for all residential densities studied, up to 50% of the total hot water demand can be supplied from appropriately installed water heaters (e.g. K2 Apartments) and combined heat and power (CHP) plants (e.g. BedZED, Hammarby Sjöstad). Grid connected PV modules can supply up to 10% (e.g. K2 Apartments) of the total electricity use and will depend on the system size and total area of PV panels installed. Funding sources for case studies include banks, energy agencies and government housing departments and projects were developed and managed by collaborative partnerships. Applications of SWH and PV technologies together can reduce electricity use in homes significantly.

2.2 Comparisons of national and international small wind turbine projects

The Warwick Wind Trials Project in the UK (2007-2008) has analysed data from 26 grid connected building mounted residential and other small wind turbine case studies (Encraft, 2009). This study identified on and off grid residential SWT preferences for 500W to 10kW capacities. Some best practice residential examples of national and international small wind turbine projects are compared (Appendix 1: Table 2), considering the following points:
- residential densities;
- urban scale;
- dwelling typologies;
- distributed energy infrastructure provisions;
- Annual (approximate) small wind turbine performance and funding

Comparisons of the small wind turbines case studies at different residential densities indicate that actual outputs of the SWT systems installed are significantly less than the predicted outputs, influenced by urban built up site conditions. There is also a considerable issue of noise while SWT systems are operating as presented in the Warwick trial with 21 building mounted turbines. However, new SWT technology in the Griffin Family home at Oregon, USA, can supply up to 55% of the electricity demand. The SWT case studies are currently funded either by private owners or being held under partnerships.

3 Three Australian case studies: selection criteria and characteristics

The factors for selecting three residential urban forms in Australia as case studies for this study were:
- urban form characteristics;
- location and proximity to future planned growth areas;
- proximity to transport and shopping;
- total numbers of households (30-60 households);
- dwelling typologies;
- site boundary contained within one ABS defined draft mesh block boundary 2006;
- household and population densities per hectare;
All the three case studies are located in the same area within the same local council in region of Western Sydney. In New South Wales, Sydney’s Metropolitan Strategy identifies that new land release areas will accommodate 30 to 40 per cent of urban growth over the next 30 years (NSW Government, 2005). The North West Growth Centre and South West Growth Centre, two key elements of the strategy, will provide for 160,000 new homes over the next 25 to 30 years (NSW Government, 2007). The case study areas are also located in proximity to one of the future Growth Centres, near existing important transport arteries and shopping malls.

The separate house has been a predominant dwelling typology until now in the suburb where the case studies are located. The residential areas in this suburb have been undergoing significant changes in their urban form characteristics. An increasing number of apartments and town houses are being built along the main roads that have public transport provisions. The case studies will be compared under an urban taxonomy or classification system which has been formulated across five urban spatial scales (Ghosh and Vale 2009). This taxonomy details different residential urban forms at community/neighbourhood, block and house(s) scales and focuses on residential densities and dwelling typologies. Residential neighbourhoods at local and neighbourhood scales and at various densities exhibit different patterns, such as low density low rise, medium density medium rise, high density high rise and with mixed residential typologies. In addition, using GIS, spatial land cover patterns of a total of seven local residential urban forms with varying physical densities (low, medium and high) in Auckland, New Zealand were compared from aerial photographs (Ghosh 2004; Ghosh and Vale, 2006). The spatial distributions of land covers vary considerably in different typologies of urban forms (Ghosh and Vale, 2009).

Case study One: high density - apartments consists of two - three storey and one - two storey apartment blocks (31 residential units) as one property and is contained in one mesh block. Each three storey apartment block has parking facilities in the basement. Case study Two: medium density – town houses/apartments has one to two storey town houses and some apartments (Total: 51 units) arranged in different rows within one property and is also contained in one mesh block. Case study Three: low density - separate houses has altogether 26 individual parcels each with a separate house (total: 24 residential homes) on the parcel. The low, medium and high density case studies are defined based on their population densities as their dwelling densities are similar in two cases (Table 3). In addition, these three case studies significantly differ in their urban form characteristics. The high density case study has fewer trees than the medium density development and the low density has a significant number of trees. Ample open spaces are available around the dwellings in the low density while the same is restricted in the other two developments.

Insert Fig 1: Photos – Three case studies

4 Methodology

4.1 Data collection

Primary data on relevant features/land uses in the built environments important for installing localized solar energy generation infrastructure and small wind turbines were calculated in the following categories in m² and then converted into hectares.

- Solar energy generation areas: building roof areas; solar efficient building roof areas;
- Small wind turbine areas: building roof areas; available open space areas (except tree canopy cover, paved/unpaved paths, surfaces and driveways);
4.2 Estimating solar efficient building roof areas and potential solar generation

The total available solar efficient roof areas were calculated considering the individual roof slope, roof form and building orientation and using a geometric method for all the three case studies. Any roof area oriented 45° on either side of north was considered solar efficient (Breuer 1994; Department of the Environment, Water, Heritage and the Arts, 2008). These areas were capable of onsite solar generation through direct installation of solar water heater and photovoltaic modules on the roof surfaces. However, SWH and PV modules can be mounted on frames in less solar efficient parts of the building roofs and can also be tilted to provide appropriate solar orientation for solar energy generation. The shading by on site tree canopy cover on the solar efficient part of the roofs was taken into account. The total available solar efficient roof areas and total building roof areas were digitised and estimated using ArcGIS.

Independent Pricing and Regulatory Tribunal of New South Wales (IPART) data indicates that average residential electricity consumption was about 7,700 kWh per household in 2006 for Sydney based on electricity network businesses information (IPART, 2007, p. 9). On average, percentages of total home energy uses in different categories are: standby (3%), cooking (4%), lighting (7%), water heating (25%), refrigeration (7%), other appliances (16%) and heating and cooling (38%) (Department of the Environment, Water, Heritage and the Arts, 2008, Your Home). The total average value of electricity use per household has been adopted for this study.

Solar water heaters or photovoltaic modules are generally available in the form of rectangular or square panels and therefore they do not adequately cover all the solar efficient roof areas with various configurations. A solar hot water system can provide 50% to 90% of domestic hot water demand (Alternative Energy Association, 2009). In this study, two solar water heating panels, 1m x 2m, equivalent to 4 m² per household capable of producing at least 2200 kWh (CAE, 1996, p.186) or 7.92 GJ/year, are fitted on the solar efficient residential roofs. Previous research on an existing low density low rise urban form in Auckland, New Zealand had demonstrated that solar efficient roof areas of only 158 out of 171 separate dwellings could accommodate two solar water heater panels on their solar efficient roofs; one could accommodate one solar panel and 12 buildings did not have appropriate solar orientations (Ghosh and Vale 2006). This research also showed that realistically only 58% of the total available solar efficient roof areas could be useful, and 42% of the solar efficient roof areas would be lost due to inappropriate roof designs, particularly the use of hip roofs. Minor retrofitting of the hip roofs to gable end roofs in conventional neighbourhoods could provide 26% more solar energy generation from the roofs due to the improved ability to accommodate rectangular solar panels (Ghosh and Vale 2006).
Different sizes of solar PV panels with different system sizes and efficiencies are available in the market from various manufacturers (BP Solar, Sharp and Mitsubishi) for home and commercial purposes. Typical size of a PV panel is about 600 mm wide, 1200 mm tall and 25 mm thick with an aluminum frame round the edge. Common panel types include: mono-crystalline silicon; poly-crystalline silicon and amorphous silicon or thin film panels. While crystalline silicon panels are the most efficient, amorphous silicon panels are only half as efficient for a given area. For grid-connected systems inverters are required to support the operation of PV panels. A typical domestic PV system is around 1kWp to 3kWp. A New Zealand study shows that a 1kWp (kilowatt peak) PV array could produce between 880kWh and 1750kWh per year (2.5kWh - 5kWh per day) and a 1kW array needs an area of around 8m² (EECA Energy Wise, 2009). In this research, it is assumed that average PV panels of size 0.6 m X 1.2 m could be fitted on the rest of the solar efficient roofs after placing solar hot water panels. 50 m² of photovoltaic modules can generate 100 MJ /day, assuming 10 per cent efficiency at the latitude of Melbourne (Redshaw and Dawber 1996). Each 1 m² of PV panel would generate 0.73 GJ annually (Ghosh 2004: 126). The corresponding energy generated from solar water heaters and PV modules was calculated in GJ/annum.

**4.3 Spaces and potential of small wind turbine generation**

Small wind turbines can be mounted on any residential building roofs or at gable ends or on stand alone towers at heights to catch the wind. Components of a grid-connected wind generator system include wind generators, towers and inverters. Using ArcGIS available open ground spaces for small wind turbine installation are determined for the three case studies. Availability of open spaces that were not in conflict with tree canopy cover, paved/unpaved paths, surfaces and driveways vary according to the urban form characteristics in the high, medium and low density case studies.

From the available NSW Wind Atlas data, it is assumed that the case studies would have approximately around 4.9m/s wind speed (Department of Energy, Utilities and Sustainability, 2009) although local wind speed can only be identified accurately using on site anemometers. As the case studies are located very close to each other the same local wind speed has been adopted for all the case studies. In the market, from different suppliers and manufacturers (Todae in Sydney, Proven Energy etc.) different types of small wind turbines are available. Urban areas have comparatively lower wind speed compared to rural areas. In this study we consider the values for Todae’s Whisper 1kW wind turbine grid connected system. At a wind speed of 12 mph or 5.4 m/s it can generate 6.8 kWh per day or 2400kWh per annum (Todae, 2009). The Warwick Wind Trials Project demonstrated that in their case studies the actual wind speeds (around 2.0m/s) were much less than the anticipated wind speeds (around 5.0m/s) and actual performance was far less than predicted outputs, with a capacity factor of only 0.85% (Encraft, 2009). At 100% capacity factor a 1kW wind turbine would produce 8,760kWh per year, and at 0.85% it would produce only 74.5kWh per year. Therefore, it is assumed in this study that actual performance would be much less than predicted and would be equal to 100kWh per year from a 1kWp SWT.

The apartments were considered to have one or more roof mounted small wind turbines on each block while town houses could have one or more in each row as well as on the ground if space is available. It is assumed that one small wind turbine could be installed in each of the separate houses either on the roof or on the ground. Total wind energy generation from small
wind turbines was calculated for each of the case studies. In this study, total available open
spaces on the ground (except trees, roads, driveways and other impervious surfaces) that
could be potentially used for small wind turbine generation in three case studies were
compared based on area calculations. However, installation of wind turbines is affected by
height of trees and buildings and other features that affect wind speed. Setting up an
anemometer prior to small wind turbine installation to correctly measure wind generation in a
particular location in any urban areas is recommended (Webb (Alternative Technology
Association), 2007). The heights of different features affecting the performance of SWTs
require specific analysis of each installation in different case studies. This is not in the scope
of this paper and will be addressed in future research.

**Insert Fig 3: Available open spaces (except trees, roads, driveways and impervious
surfaces) – Three case studies**

5 Results

5.1 Densities and relevant land uses

Percentages of building roof areas in high and medium densities are similar at approximately
covering 30-32% of the total site areas while the same value in the low density case study is
20.5%. It is interesting to note that available open space areas excluding tree canopy cover,
paved/unpaved paths, surfaces and driveways in high density is 8.1% and in the low density
case study is 10.6%. These two case studies in spite of having significant differences in
population densities, have closer values in percentage availability of open space areas. Open
space areas are lower in medium density due to more numbers of trees and placement of
buildings with respect to site. On the other hand, percentage of solar efficient roof areas is
highest in the medium density case study influenced by appropriate roof forms and better
solar orientation of buildings. A comparison of total site areas, relevant land uses and
densities in three case studies is given in Table 3.

**Insert Table 3: Total site areas, relevant land uses and densities in three case studies**

5.2 Onsite solar energy generation

Assuming each household would have a SWH and could then utilize the remaining available
solar efficient roof areas for PV, the combined (SWH and PV) onsite localized energy
generation potential are compared on the basis of per capita, per household and the percentage
share of total domestic energy demand of the residents that can be provided by SWH and PV
in each of the case studies (Table 4). Two scenarios: Scenario 1 (50% utilization of remaining
solar efficient roof areas after installation of SWH) (Fig. 4) and Scenario 2 (100% utilization
of remaining solar efficient roof areas after installation of SWH) (Fig. 5) were considered.

The low density case study has the maximum potential and can provide an additional 36.7%
of total domestic energy demand (100%) in Scenario 1 and up to additional 143.7% in
Scenario 2 for the same. Practically the building roof of each of the houses in the low density
case study is able to accommodate a solar water heater with a total area of 4m² which is
sufficient for a household. In a low density conventional residential development, a good
number of houses have hip roofs which can reduce the potential availability of areas for PV
panel installation. But remaining roof area after installing SWH can be used for installation of
PV panels. The high density case study is not able to accommodate SWH on the building roof but can install PV panels on the roofs.

In Scenario 1, solar hot water and solar PV in the medium density development can contribute 66.7% of total domestic energy demand. In Scenario 2, solar hot water and solar PV in the medium density development can contribute more than the total domestic energy demand (104.8%). The medium density can accommodate PV panels and SWH efficiently on the available higher solar efficient roof areas with appropriate roof forms.

The roof forms in the high density development restrict installation of a greater number of PV panels, unlike the K2 apartments in Melbourne where spaces for installation of PV panels were considered at the design stage. In Scenario 1, the roof areas in the high density case study are not sufficient to cater to all the resident households and can contribute 45.9% of total domestic energy demand (100%). In Scenario 2 with the full utilization of available solar efficient roof areas, high density development could contribute 63.4% of the total domestic energy demand. Frame mounted PV panels could be installed in these existing developments to provide domestic electrical energy demand though this study does not cover that potential. It has also been demonstrated through the best practice examples at Vauban, Hammarby Sjöstad, Christie Walk and others that with appropriate design high density developments could effectively incorporate solar panels for hot water and PV panels for electricity generation (Table 1). “Solar” hot water can be provided by onsite biomass CHP plant as demonstrated in BedZED, although there have been problems with the system in this example (BioRegional, 2009).

Insert Table 4: Onsite SHW and PV energy generation –Scenario 1 and Scenario 2

At a per capita level, the medium density case study has the best performance in both the scenarios (Scenario 1: 18.1 GJ/annum and Scenario 2: 28.5 GJ/annum) while high density generates only 6.1 GJ/annum in the Scenario 1 and slightly more (8.4 GJ/annum) in the Scenario 2. The low density development can generate 13.3 GJ/annum in Scenario 1 while in Scenario 2 it is enhanced up to 23.8 GJ/annum. At a household level, the low density case study has the best performance in terms of GJ/household/annum in both the scenarios (Scenario 1: 37.7 GJ/annum and Scenario 2: 67.6 GJ/annum). The high density generates 12.7 GJ/annum in Scenario 1 and 17.5 GJ/annum in Scenario 2. The medium density development can generate 18.5 GJ/annum in Scenario 1 while in Scenario 2 it is increases up to 29.1 GJ/annum. It is interesting to note that at both per household and per capita levels, onsite generation outputs of the medium density development are around the similar values of 18 GJ/annum while high and low density developments vary significantly. The values of the high density development are likely to decrease further if adequate numbers of solar water heaters can not be accommodated on site or alternative technologies for hot water are not applied. The performance of this particular high-density case study in terms of accommodating SWH systems has been impacted by its roof shapes and building orientations. This results from this case study do not necessarily indicate that all residential developments built at this density would have the same results as we have witnessed SWH can be accommodated efficiently at higher densities (e.g. K2 Apartments, Christie Walk).

Insert Fig 4: Comparisons of onsite energy from SWH and PV (Scenario1 – 50% utilisation)

Insert Fig 5: Comparisons of onsite energy from SWH and PV (Scenario 2 – 100% utilisation)
5.3 Onsite small wind turbine generation

Locating small wind turbines on the apartment block roofs in the high density case study is possible as demonstrated in Southorn Court (Table 2). Energy outputs from SWT mounted at the gable end were considered as available open spaces areas are close to the blocks and therefore may not effectively be used for SWT generation. In the medium density case study, building roof mounted small wind turbines are possible but due to lack of open spaces and obstruction by trees stand alone SWT are not advisable. A number of properties in the low densities with larger parcel sizes can accommodate stand alone SWT though performance is likely to be affected by the micro characteristics of the areas. More or less each house has the potential to install SWT for generating onsite energy. Analysing the possibilities of installing small wind turbines in different residential dwelling typologies in practical residential case studies all over the world, the following numbers of installation of SWT in three case studies are possible in this study. A comparative analysis on available localised energy generation from SWT is provided in Table 5.

- High density – apartments: 4 SWT per apartment block and total 12 numbers;
- Medium density - townhouses: 2 SWT per block and total 10 numbers;
- Low density – separate houses: 1 SWT on the roof of each house and total 24 numbers;

Insert Table 5: Small Wind Turbine (SWT) Generation

A comparison of these three systems, SWH, PV and SWT indicates that the annual localized energy generation potential from the SWH and PV are significantly higher. It is essential to note that applications of SWT at smaller domestic levels have been relatively new and recent compared to SW and PV technologies. Though the SWT has significant potential as renewable onsite energy system, again its performance is determined by the variable local wind speed, obstructions and operational noise within urban built up settings. Therefore, SWT requires significant and appropriate technology development and feasibility studies for its applications at subdivision or lot scales. Further research should focus on these issues and initiatives and incentives should be directed for the uptake of this technology.

5.4 An energy infrastructure-residential urban form matrix

An energy infrastructure-residential urban form matrix was formulated considering density-wise potential application possibilities and implementation confidence for the three different urban forms at varying physical densities (Table 6). Low and medium density development shows a higher feasibility for installation of solar water heaters, solar photovoltaic modules and small wind turbines. For existing high density developments the potential installation of SWH is unlikely and SWT is marginal (depending on the available unobstructed open spaces). High density development can perform very well using PV panels on solar oriented roofs and walls.

Insert Table 6: An energy infrastructure-residential urban form matrix

6 Discussions and conclusions

Successful applications of solar energy systems (SWH and integrated solar PV), small wind turbines (SWT) and passive solar design, (the effects of this have not been discussed in this
paper, but clearly a development sited to provide good solar efficient roof area will also provide good passive solar potential) would require appropriate building designs, orientations for solar access, roof forms, wind generation capacity consideration and suitable product choices based on price, quality, performance and environmental impacts. Retrofitting existing residential urban forms with localised infrastructure provisions will depend on their specific spatial characteristics. In addition, governance, continued management and ongoing operation of these renewable systems at household and community levels require personal and group initiatives and behaviour change. A study of a low density conventional residential neighbourhood in New Zealand showed that at least 1.4 t/person/year CO2 emissions reduction is possible (this would be greater in Australia because of the greater use of coal-fired electricity generation) and energy generated from solar efficient appropriate roof form can contribute 80% of the household electricity demand (Ghosh and Vale, 2006, p. 223). The Combined Heat and Power (CHP) and small wind turbine technologies have had very limited application in Australia. In high and medium density residential neighbourhoods CHP plants can be useful as demonstrated in the BedZED development.

Small wind turbines in the Hockerton Housing Project and also in many others trialled under the Warwick Wind Trials Project did not perform well due to site conditions, technical, noise and other factors (Hockerton Housing Project, 2009; Encraft, 2009). There are research and technical gaps in small wind turbine technologies as it is a new technology for residential areas and also there is a need to develop standardised implementation methods, funding and rebate schemes and delivery mechanisms. On the other hand, solar technologies are comparatively better developed than small wind turbines and have received considerable government attention and funding. They have been successfully implemented over many years in Freiburg, Skottparken, BedZED, Hammarby Sjöstad, Christie Walk and many others (Table 1). There are implementation barriers rather than research gaps which can be resolved by more targeted policies matching goals with actions.

Current urban sustainability research is focussed on exploring more than one sustainable urban form (Williams et al 2000). Localised energy infrastructure provisions using solar water heaters, photovoltaic modules and small wind turbine renewable technologies in different residential patterns with varying physical densities, characteristics and dwelling typologies can generate multiple sustainability benefits (such as electrical energy savings and reduced greenhouse gas emissions). This potential needs to be utilised considering their form specific potential and local climatic conditions and also within changing government policy perspectives. For example, attached terraced/town houses and apartments could be consciously orientated towards the north in high and medium density developments as demonstrated in the K2 apartments, a public housing development in Melbourne, Australia. The separate houses in low density conventional neighbourhoods would require placing of each house to have adequate solar access for onsite generation. These technologies need to be incorporated at conceptual design stages for all single to neighbourhood scale developments. Developing collaborative partnerships between communities, energy/power service providers, manufacturers, developers, architects/designers, funding agencies, regional and local governments and research institutions is essential and highly beneficial for the uptake of these new renewable technologies.

Practical applications of form-specific sustainability initiatives could evolve new sustainable forms and could efficiently retrofit existing residential developments. The low density developments have a better potential for localised energy generation which can trade off their possible higher energy use for transport. The high and medium density developments already
have this transport advantage provided resident communities can access it, and choose to access it appropriately. These two types of developments can further enhance their sustainability performance through an optimal balance of specific features of built forms which allow increased onsite generation. Our built environments in urban, suburban and rural areas will not change dramatically within the climate change time frame. Sustainability efforts on localised energy infrastructure provisions in varied patterns of built environments can contribute meaningfully in developing sustainable cities in Australia.

Acknowledgements

The authors would like to acknowledge support of all who have provided help for this research. The authors would also like to thank anonymous referees for their valuable comments.

References


Environment Design Guide (BDP), Australia.


Figures

Fig 1: Photos – Three case studies (Photos by: Sumita Ghosh)

Fig 2: Total available solar efficient roof areas – Three case studies
Fig 3: Available open spaces (except trees, roads, driveways and impervious surfaces) – Three case studies

Fig 4: Comparisons of onsite energy from SWH and PV (Scenario 1 – 50% utilisation)
Fig 5: Comparisons of onsite energy from SWH and PV (Scenario 2 – 100% utilisation)

Table 3: Total site areas, relevant land uses and densities in three case studies

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<tr>
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<th>High density - Apartments</th>
<th>Medium density - Townhouses</th>
<th>Low density – separate houses</th>
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<tr>
<td>Total site area (ha*)</td>
<td>0.70 (100%)</td>
<td>1.17 (100%)</td>
<td>2.58 (100%)</td>
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<tr>
<td>Total building roof areas (ha)</td>
<td>0.21 (30.0%)</td>
<td>0.37 (31.6%)</td>
<td>0.53 (20.5%)</td>
</tr>
<tr>
<td>Available open space (ha)</td>
<td>0.057 (8.1%)</td>
<td>0.025 (2.1%)</td>
<td>0.273 (10.6%)</td>
</tr>
<tr>
<td>Trees, roads, driveways &amp; impervious surface areas</td>
<td>0.43 (61.9%)</td>
<td>0.78 (66.3%)</td>
<td>1.78 (68.9%)</td>
</tr>
<tr>
<td>Solar efficient roof areas (ha)</td>
<td>0.043 (19.4%)</td>
<td>0.15 (39.9%)</td>
<td>0.20 (37.7%)</td>
</tr>
<tr>
<td>Total number of dwellings or units</td>
<td>31</td>
<td>51</td>
<td>24</td>
</tr>
<tr>
<td>Total population (no. of people)</td>
<td>65</td>
<td>52</td>
<td>68</td>
</tr>
<tr>
<td>Total number of households</td>
<td>31</td>
<td>51</td>
<td>24</td>
</tr>
<tr>
<td>Dwelling or unit density/ha</td>
<td>44 dwellings or units /ha</td>
<td>44 dwellings or units /ha</td>
<td>9 dwellings/ha</td>
</tr>
<tr>
<td>Population density/ha</td>
<td>93 people/ha</td>
<td>44 people/ha</td>
<td>26 people/ha</td>
</tr>
</tbody>
</table>

* ha = hectares, Source of population and dwelling data: ABS 2006 Mesh Block Census Data
Table 4: Onsite SWH and PV energy generation – Scenario 1 and Scenario 2

<table>
<thead>
<tr>
<th></th>
<th>High density</th>
<th>Medium density</th>
<th>Low density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total household energy demand (GJ/annum)</td>
<td>859.3</td>
<td>1413.7</td>
<td>665.2</td>
</tr>
</tbody>
</table>

**SCENARIO 1 - 50% utilisation**

<table>
<thead>
<tr>
<th></th>
<th>High density</th>
<th>Medium density</th>
<th>Low density</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWH (GJ/annum)</td>
<td>245.5</td>
<td>403.9</td>
<td>190.1</td>
</tr>
<tr>
<td>Available solar efficient roof areas after allocating SWH (m²)</td>
<td>407.4</td>
<td>1477.2</td>
<td>1960.5</td>
</tr>
<tr>
<td>Assuming 50% solar efficient areas used for PV considering existing roof forms</td>
<td>203.7</td>
<td>738.6</td>
<td>980.3</td>
</tr>
<tr>
<td>Total PV generation (GJ/annum)</td>
<td>148.7</td>
<td>539.2</td>
<td>715.6</td>
</tr>
<tr>
<td>Total energy obtained from SWH &amp; solar PV modules (GJ/annum)</td>
<td>394.2</td>
<td>943.1</td>
<td>905.7</td>
</tr>
</tbody>
</table>

**SCENARIO 2 - 100% utilisation**

<table>
<thead>
<tr>
<th></th>
<th>High density</th>
<th>Medium density</th>
<th>Low density</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWH (GJ/annum)</td>
<td>245.5</td>
<td>403.9</td>
<td>190.1</td>
</tr>
<tr>
<td>Available solar efficient roof areas after allocating SWH (m²)</td>
<td>407.4</td>
<td>1477.2</td>
<td>1960.5</td>
</tr>
<tr>
<td>Assuming 100% solar efficient areas used for PV considering existing roof forms</td>
<td>407.4</td>
<td>1477.2</td>
<td>1960.5</td>
</tr>
<tr>
<td>Total PV generation (GJ/annum)</td>
<td>297.4</td>
<td>1078.3</td>
<td>1431.2</td>
</tr>
<tr>
<td>Total energy obtained from SWH &amp; solar PV modules (GJ/annum)</td>
<td>542.9</td>
<td>1482.3</td>
<td>1621.3</td>
</tr>
</tbody>
</table>

Table 5: Small Wind Turbine (SWT) Generation

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy obtained from SWT (GJ/annum)</td>
<td>4.32</td>
<td>7.2</td>
<td>8.64</td>
</tr>
<tr>
<td>% energy obtained from SWT (Total domestic demand)</td>
<td>0.50</td>
<td>0.51</td>
<td>1.30</td>
</tr>
<tr>
<td>Per household energy generation (GJ/annum)</td>
<td>0.139</td>
<td>0.141</td>
<td>0.360</td>
</tr>
<tr>
<td>Per capita energy generation (GJ/annum)</td>
<td>0.066</td>
<td>0.138</td>
<td>0.127</td>
</tr>
</tbody>
</table>
Table 6: An energy infrastructure-residential urban form matrix

<table>
<thead>
<tr>
<th>Conventional Residential Urban Form</th>
<th>Localised energy infrastructure potential</th>
<th>Implementation confidence (contribution to domestic energy demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar Water Heater (SWH)*</td>
<td>Solar Photovoltaic modules (PV)*</td>
</tr>
<tr>
<td>High density - Apartments</td>
<td>Unlikely</td>
<td>Feasible</td>
</tr>
<tr>
<td></td>
<td>Lack of sufficient building roof areas and difficult to cater for higher numbers of households</td>
<td>Available building roof areas of apartments or alternative spaces used for installation of PV panels</td>
</tr>
<tr>
<td>Medium density - Townhouses</td>
<td>Feasible</td>
<td>Feasible</td>
</tr>
<tr>
<td></td>
<td>Nearly sufficient building roof areas matching with numbers of households</td>
<td>Significant part of building roof areas or alternative spaces can be used for installation of PV panels</td>
</tr>
<tr>
<td>Low density – separate houses</td>
<td>Feasible</td>
<td>Feasible</td>
</tr>
<tr>
<td></td>
<td>Sufficient building roof areas balanced with numbers of households</td>
<td>In excess availability of building roof areas or alternative spaces used for installation of PV panels</td>
</tr>
</tbody>
</table>

*Note: Installation and localized energy generation potential of SHW, PV and SWT are affected by local conditions such as shading and obstacles by trees, amount of available solar radiation and wind generation.
### Appendix 1 - Table 1: Comparisons of national and international solar projects

<table>
<thead>
<tr>
<th>Projects</th>
<th>Residential dwelling densities, urban scale and typologies</th>
<th>Distributed energy infrastructure provisions</th>
<th>Solar energy performance</th>
<th>Funding, management, partnership and participation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hockerton Housing Project (HHP), Nottinghamshire, UK</td>
<td>- 2 dwellings/ hectare</td>
<td>7.65 kW array of PV. Two 5.5 kW and 6 kW wind turbines, all grid-connected and passive solar gain from south-facing conservatories;</td>
<td>The renewable energy system provides all the energy for the houses; Annual output from PV 5110 kWh</td>
<td>Developed in partnership with Co-operative Bank &amp; Ecology Building Society; Self-build HHP managed by a temporary legal entity Hockerton Housing Partnership;</td>
</tr>
<tr>
<td>BedZED</td>
<td>- High density</td>
<td>- Small-scale CHP plant using tree surgery waste - PV panels</td>
<td>Hot water heating 45% and electricity for lighting and cooking 55%, less than conventional UK housing</td>
<td>Peabody Trust with Bill Dunster Architects and Bio Regional Development Group; Mixed-use, mixed-tenure development</td>
</tr>
<tr>
<td>Skotterparken, Ballerup, Denmark</td>
<td>- High density</td>
<td>Six solar heating systems 100 m² each; 6 m² solar panel/apartment; district heating network;</td>
<td>382 kWh/m² including saved network losses; decrease in heat demand by 50% compared to conventional housing; 600 m² solar collector area annual solar heating yield 274 kWh/m²</td>
<td>Funded partly by the European Union, the Danish Energy Agency, and the Danish Ministry of Housing; undertakes feasibility studies on specific energy savings in schools, and a new, locally based energy agency;</td>
</tr>
<tr>
<td>Hammarby Sjöstad, Stockholm, Sweden</td>
<td>- High density</td>
<td>Solar panels on some of the roofs; a heat pump uses moist heat &amp; the waste heat generated by main power system, 212 PV modules in facades, balconies &amp; windows in 2 multi family blocks</td>
<td>Solar panels meet 50% hot water needs PV cells produce 32 MWh and supply 70% energy needs of efficient refrigerator/freezer</td>
<td>Developed in partnership with City of Stockholm, Stockholm Water Company, Fortum and the Stockholm Waste Management Administration</td>
</tr>
<tr>
<td>Solar Apartment, Vauban, Freiburg, Germany</td>
<td>- High density</td>
<td>- A 23 m² thermal solar collector array for space heating &amp; domestic hot water - A 5-kWp PV system - Wood-chip-biomass CHP plant</td>
<td>Heating energy consumption 10% less than conventional housing in Germany</td>
<td>Started as a NGO initiative but later funded by Redevelopment Fund of the Federal State of Baden-Württemberg and the City of Freiburg; participation of co building groups (architects, managers), community &amp; students</td>
</tr>
<tr>
<td>Earthsong Eco-neighbourhood, Waitakere City, New Zealand</td>
<td>- 20 dwellings or units / hectare</td>
<td>Solar hot water panels on the roofs of most of the houses; No PV panels</td>
<td>Energy use is 42% less than usual</td>
<td>Initiated by Cohousing New Zealand Limited, Shared ownership by the owners in the cohousing community; a non-profit, resident-driven eco housing development, supported by EECA, local councils, universities and research centres</td>
</tr>
<tr>
<td>Christie Walk, Adelaide, Australia</td>
<td>- 135 dwellings or units /ha</td>
<td>A 5kW grid connected photovoltaic (PV) system is installed on the north facing roof. Produced approximately 22kWh/day and approximately 3450 kWh in first 5 months</td>
<td>Decrease in electricity use 58% in 1 person and 48% in 2 person homes compared to South Australian average;</td>
<td>Non-profit development structure - Urban Ecology Australia Inc. (UEA) &amp; Wirranendi Incorporated, private and ethical investment from Community Aid Abroad, Ethical Investment Trust and Bendigo Community Bank, significant voluntary and community participation</td>
</tr>
<tr>
<td>K2 Apartments</td>
<td>- 200 dwellings or units /ha</td>
<td>22kW BP Solar grid-interactive PV system; 130 m² flat-plate solar collector array on north facing roof; 4400 litre Edwards Solar Hot Water system</td>
<td>- PV panels supply 10% of total electricity - Solar collector supply 50% of the domestic hot water demand</td>
<td>Office of Housing, Property Services and Asset Management in partnership with the State Government of Victoria, Australia &amp; Department of Human Services, Victoria; Managed by non-government, not-for-profit housing agencies</td>
</tr>
</tbody>
</table>

Appendix 1 - Table 2: Comparisons of national and international small wind turbine projects

<table>
<thead>
<tr>
<th>Projects</th>
<th>Average Wind Speed (m/s)</th>
<th>Residential dwelling densities, urban scale and typologies</th>
<th>Distributed energy infrastructure provisions</th>
<th>Annual (approximate) small wind turbine performance and funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hockerton Housing Project, Nottinghamshire, UK</td>
<td>2.9m/s</td>
<td>- 2 dwellings/ hectare - Local scale - 5 earth sheltered houses</td>
<td>On-Grid, stand alone two 5.5 kW and 6 kW wind turbines at hub height of 26 m; 7.65 kW array of PV</td>
<td>Annual outputs from 2 wind (Proven &amp; Iskra) turbines 4400kWh &amp; 5256 kWh; Developed in partnership with Co-operative Bank &amp; Ecology Building Society; Self-build HHP managed by a temporary legal entity Hockerton Housing Partnership;</td>
</tr>
<tr>
<td>Southern Court, UK</td>
<td>4.59m/s &amp; 5.02m/s respectively</td>
<td>- High density - House(s) scale - 7 storey block of flats</td>
<td>On grid, building roof mounted 2 SWT 600W (Ampair 600 230); pole mounted on flat roof by ballast;</td>
<td>Annual outputs from 2 wind turbines Actual total output = (74.63 + 50.27) kWh Predicted total output = (1012.26 + 1084.48) kWh</td>
</tr>
<tr>
<td>Residential Development, Leicester, UK</td>
<td>2.18 m/s</td>
<td>- High/medium density - Local scale - Group of houses</td>
<td>On grid, building roof mounted 1.0 kW (Zephyr Air Dolphin); free standing pole close to the house;</td>
<td>Actual output = 63.75kWh Predicted output = 217.43kWh</td>
</tr>
<tr>
<td>Lillington Road, UK</td>
<td>2.2m/s</td>
<td>- Low/medium density - House(s) scale - Semi detached house</td>
<td>On grid connected to 230V main power supply, building roof mounted 600W (Ampair 600 230); pole mounted to gable end; solar thermal and solar PV panels</td>
<td>Actual output = 54.88kWh Predicted output= 216.45 kWh</td>
</tr>
<tr>
<td>Birds Hill, UK</td>
<td>2.27m/s</td>
<td>- Low density - House(s) scale - Separate house with large open space southwest</td>
<td>On grid, building roof mounted 400W (Eclectic StealthGen 400); pole mounted to gable end;</td>
<td>Actual output = 47.85 kWh Predicted output = 156.83kWh</td>
</tr>
<tr>
<td>Home near Silver Islet, Ontario, Canada</td>
<td>Not known</td>
<td>- Low density - House(s) scale - Separate house</td>
<td>Off-Grid, stand alone 1.3 kW (Whisper), 2-blade wind generator on a 15m tubular steel tower and 4 - 75 watt Siemens PC4 solar panels</td>
<td>Provides power for most conventional household needs; Electrical appliances include lighting, stereo, TV/VCR, small kitchen appliances, microwave, vacuum cleaner, power tools, hair dryer, water pump (120 V AC), washing machine, and an ultra-efficient fridge/freezer;</td>
</tr>
<tr>
<td>Home in Ward, Colorado, USA</td>
<td>Elevation - 2743 m</td>
<td>- Low density - House(s) scale - Separate house</td>
<td>A hybrid electric system powered by wind, solar, and a generator; Off-Grid, 1.5 kW (Bergey) wind turbine, 21-m stand alone tower Solarex PV panels, 480 watts</td>
<td>Provides power for most conventional household needs; Electrical appliances include television, stereo, two computers, toaster, blender, vacuum cleaner, and hair dryer;</td>
</tr>
<tr>
<td>Griffin’s Family Home, Salem, Oregon, USA</td>
<td>Low wind speed area</td>
<td>- Low density - House(s) scale - Separate house</td>
<td>On grid stand alone 1.5 kW (African Wind Power) small wind turbine on a 32m tower; Pole mounted 1800 W PV array; Solar water heater;</td>
<td>Combined estimated annual electricity generation of 7,939 kWh and annual savings 2600 KWh; small wind turbine provide 55% of electricity; Private ownership; Owners’ received Energy Trust incentives and Oregon Residential Energy Tax Credits</td>
</tr>
</tbody>
</table>

Source: Encraft, 2009; Hockerton Housing Project Trading Ltd., 2009; CanWEA, 2009; Energy Trust of Oregon Incorporated, 2009;