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Estimating the Uptake of Distributed Energy in an Urban Setting

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Abstract: Distributed energy (DE) solutions encompass local power generation and technologies that reduce the net electrical demand of an end-user while maintaining lifestyle and comfort levels. The deployment of DE is increasingly being seen as an option to reduce greenhouse gas emissions through increased efficiency. Significant deployment of DE requires a paradigm shift from the centralised energy supply model that currently operates in the capital cities of Australia. Public acceptance of DE is necessary to bring this about as these options require 'ownership' at a local level (e.g. household, street or suburb).

In this paper we use geographic information system (GIS) methods to estimate the potential uptake of renewable electricity generation technologies in an urban setting. Estimates of the physical potential for deployment of small wind turbines and residential solar photovoltaic (PV) systems in the Greater Sydney region have been formulated from a combination of building type, technology performance and climate variables.

These estimates based on physical constraints are compared to penetration levels estimated by economic forecasts as constrained only by demand and supply at the state scale, as well as being compared to customer acceptance estimates determined from a survey of public attitudes to different technologies.

The work to date indicates that there exists significant physical potential for residential solar PV due to consistency of the solar resource and the dominance of one-storey detached dwellings in the residential building stock across the region. In contrast, the potential for wind is hampered by land use constraints. Solar PV is also more socially acceptable compared to wind. However, it appears to be economic feasibility that limits the deployment prospects for these technologies.

Keywords: *Distributed Energy (DE), Geographic Information System (GIS), renewable energy, spatial modelling*

1. INTRODUCTION

Distributed energy (DE) solutions encompass local power generation and technologies that reduce the net electrical demand of an end-user while maintaining lifestyle and comfort levels. The deployment of DE is increasingly being seen as an alternative option to reduce greenhouse gas emissions through increased efficiency. Significant deployment of DE requires a paradigm shift from the centralised energy supply model that currently operates in the capital cities of Australia. Necessary to bring this about is public acceptance of DE, as these options require ‘ownership’ at a local scale (e.g. household, street or suburb).

In this paper we use geographic information system (GIS) methods to estimate the potential uptake of renewable electricity generation technologies in an urban setting. Estimates of the physical potential for deployment of small wind turbines and solar photovoltaic (PV) systems in the Greater Sydney region are formulated from a combination of building type, technology performance and climate variables. These estimates based on physical constraints are compared to penetration levels estimated by economic forecasts as constrained only by demand and supply at the state scale, as well as being compared to customer acceptance estimates determined from a survey of public attitudes to different stationary energy technologies.

This paper is structured as follows. Section 2 contains a discussion on the various modelling platforms that were used to estimate the available wind and solar resources, and the deployment of associated energy technologies based on their cost effectiveness compared to other electricity generation options. Section 3 provides an overview of a survey of public attitudes to estimate the ‘social acceptability’ of various energy technologies and describes how these data were used in this paper. Section 4 contains a discussion on the methods used for estimating the physical, social and economic potential of the various technologies. Section 5 discusses the results and Section 6 concludes.

2. MODELLING PLATFORMS

2.1. The Air Pollution Model (TAPM)

The Air Pollution Model (TAPM) is a combined weather prediction and chemical transport modelling system (Hurley, 2008). TAPM solves the equations governing the transport of mass, momentum, energy, and moisture on a series of user defined, nested grids. Initial and boundary conditions for the meteorological fields are provided by a large scale analysis, generated by the (Australian) Bureau of Meteorology. The model is able to simulate the transport of tracers, primary particles, and a simple photochemical system including sulfates and nitrates, for a variety of source characteristics.

For this analysis, TAPM was run using a series of three nested grids. The outer grid spacing was 10 km, the middle grid 6 km and the inner grid 2 km. Each of the three grids were centered on Granville (33°49' S, 151°1' E) in Sydney. Each grid consisted of 70 cells in an east-west direction, 70 cells in a north-south direction and 25 cells (layers) in a vertical direction. The model is solved in a sequential order which passes larger scale information as boundary conditions to the next grid. This ensures that the model adequately treats processes outside the area of interest (the inner grid). The inner grid is 140 km x 140 km in size and captures the entire Sydney basin. The model was used to calculate meteorological parameters such as wind speed, temperature and pressure in each of the 122,500 cells of each of the three grids for each hour between 1 January 1997 and 31 December 2008.

Estimates of shortwave radiation at the surface were extracted from the inner grid. The values calculated by the model include attenuation from the effects of cloud cover and absorption by atmospheric gases. In this analysis, the effects of cloud cover are only partially dealt with, because with a horizontal spacing of 2 km the resolution of the model does not adequately treat the effects of shallow convection on cloud generation. As such, some degree of over prediction of the flux of shortwave radiation may be expected. Hourly average wind speed estimates were extracted from the inner grid at a height of 25 m above the ground while temperature was determined from the lowest layer (10 m). The effects of turbulence and terrain are explicitly calculated in the model through roughness coefficients. We used TAPM v.4.01 for our calculations.

2.2. Energy Sector Model (ESM)

The Energy Sector Model (ESM) is an Australian energy sector model used by the CSIRO as a scenario analysis tool. The sectoral scope of ESM is the electricity and transport sectors. We employed the electricity module only for this paper.

The model optimises, finding the portfolio of centralised (i.e. large power stations) and distributed generation (DG) technologies that would minimise the total estimated cost of the electricity system over the period 2006 to 2050. It utilises linear programming techniques to mirror real world plant investment decisions by simultaneously taking into account:

- The requirement to earn a reasonable return on investment over the life of electrical generation plant;
- That the actions of one plant affects the profitability of all other plants simultaneously and dynamically;
- That the consumption of energy resources by one plant affects the price and availability of that resource for other plants and the overall cost of electricity generated; and
- Electricity market policies and regulations.

The model projects uptake on the basis of cost effectiveness, but at the same time takes into account the key physical and policy constraints on the operation of electricity markets such as requirements for peaking plant, current renewable energy and gas legislation, existing plant in each state and lead times in construction of new plant. Graham et al. (2008) provides more detail on the assumptions of the ESM.

3. SOCIAL SURVEY OVERVIEW

In 2007, the CSIRO conducted a postal survey of around 2,000 households on attitudes and opinions about household energy issues (Gardner and Ashworth, 2007). Models based on analysis of the responses allow three outcome measures: intention to reduce household electricity consumption; acceptance of demand management technology, and; acceptance of DG technology to be predicted from a range of demographic and psychological variables.

The demographic variables were state of residence, age group, electricity consumption, gender, education, employment type, household income, household size and household type. The psychological variables were knowledge of energy/environment, pro-environmental beliefs, pro-environmental behaviours, pro-economic values, attitude to reduced consumption, and subjective norms about reduced consumption.

To understand preferences related to the type of energy source used for DG, a survey question asked people to identify what energy sources they would be willing to use for an example household generator.

Section 4 discusses the methods used to estimate the physical, social and economic potential for renewable DG in the Greater Sydney region by combining outputs from the modelling platforms, responses from the household energy survey and various simplifying assumptions.

4. METHOD

The hourly data from TAPM were used to estimate the output from a 1 kilowatt (kW) solar PV panel and a 10 kW wind turbine. The PV panel was assumed to produce 1 kW for a shortwave radiative solar flux of 1000 W/m^2 at an ambient temperature of 25°C. A temperature correction factor (Equation 1) was applied assuming the panel was operating at 30°C above ambient (Mills, 2001) and had a loss of 0.4% per degree increase in ambient temperature:

$$\mathrm{kW} = \mathrm{R}^{\mathrm{in}} \times \mathrm{LF} \tag{1}$$

Where,

$\mathrm{LF} = 1 - (0.4\Delta \mathrm{T}/100)$,
$\Delta \mathrm{T} = \Delta \mathrm{PT} + (\mathrm{AT} - 25)$,
R^{in} = Power of short wave radiation flux over one square metre,
LF = loss factor,
ΔPT = panel operating temperature above ambient and,
AT = ambient temperature.

The power output from the wind turbine was estimated for each hour of the twelve-year period using the average hourly wind speed estimate and the performance characteristics of a WestWind 10 kW turbine (http://westwindturbines.co.uk/products/10kwwindturbine.asp, Accessed 23 March 2009). The turbine was assumed to be installed at a height of 25 m.

Outputs from the wind turbine and solar panels where used to estimate the capacity factors for these technologies at a 2 km spacing over the Greater Sydney region. These data were imported into *ArcInfo* v.9.3, a GIS software application, to form an estimate for each collection district (CD) in the Australian Bureau of

Statistics (ABS) data set (ABS, 2007a,b). Upper bounds of potential electrical output from these two devices where determined for each CD (~200 households).

Solar resource estimates were obtained by calculating the total roof area for semi-detached and detached dwellings assuming that one quarter of the useable area was available for optimal installation. Useable roof space was estimated by assuming an area of 154 m^2 for a one storey detached, 77 m^2 for a two storey detached, 110 m^2 for one storey semi-detached and 55 m^2 for two storey and above semi-detached dwelling (Mills, 2001).

The potential wind resource was calculated for each CD by assuming simply that 5% of land was available for the installation of wind turbines in agricultural areas, 1% was available for residential areas and 2.5% was available for all other areas including commercial and industrial. In each CD, ABS data for land use type was used to determine the number of turbines that could fit within each sub region. Each turbine was assumed to be a 10 kW unit installed at a height of 25 m. The turbines were assumed to be spaced 100 m apart (around 10 times the blade diameter) resulting in a potential density of 100 turbines per km^2. Hourly outputs derived from TAPM data were used to calculate the annual electrical output from the turbines.

In order to consider economic feasibility, ESM was used to derive a least-cost portfolio of electricity generation technologies required to meet electricity demand at the state scale over the period 2006 to 2050 assuming carbon pricing consistent with assumptions in the CPRS-15 scenario (Commonwealth Department of Treasury, 2008). The plant capacity factors used in the economic model were the spatial average capacity factors derived from the physical analysis. To approximate the level of deployment in the Greater Sydney region, estimates of economic decentralised plant deployment for NSW were re-scaled assuming that uptake is proportional to dwelling stock for solar PV and proportional to population for small scale wind. Note that, excluding the capacity factor calculations, the economic analysis is essentially independent of the analysis of physical potential, so that total physical capacity limitations did not constrain the economic uptake estimates.

A social acceptance rating for each technology in each CD was determined from the social survey. The rating was calculated by correlating the survey data with 2006 Census data on age, education, employment and occupation. The rating was used to scale the physical outputs to derive a scaled value representing a simple estimate of the potential capacity that is both physically feasible and socially acceptable.

5. RESULTS

5.1. Distribution of renewable resources and physical potential

Outputs from TAPM for the capacity factors are displayed in Figures 1 and 2. Capacity factors represent the ratio of actual electricity output of a plant over a year to its technical maximum net electricity output based on its rated capacity. Figure 1 clearly shows that wind turbine output is greater along the coastal fringe and in the far west where the turbulence created by the built environment is less marked. Figure 2 shows that the solar resource capacity factor is significantly higher than that for wind. The capacity factor is lowest in the western suburbs of Sydney due to the performance de-rating from higher ambient temperatures. Conversely, the capacity factors are higher in the Blue Mountains (west of Penrith) and on the coast where ambient temperatures are lower.

Based on the physical resource availability and land use constraints outlined in Section 4, Figures 3 and 4 show the maximum electricity production of solar PV and small wind turbines by CD in the Greater Sydney region. Figure 3 shows the influence of land use and resource availability on wind turbine output with outer areas featuring greater installed capacity than CDs dominated by residential housing. In contrast, Figure 4 shows that CDs with a greater proportion of detached dwellings (i.e. more roof space) are able to potentially have more installed PV.

In aggregate, our analysis indicates a maximum physical potential, per annum, of around 29 gigawatt hours (GWh) of wind generation and 6,900 GWh of solar PV generation in the Greater Sydney region. This corresponds to around 120 megawatts (MW) of installed wind turbines and around 4,500 MW of installed solar PV and capacity factors of ~3% and ~17.5% respectively.

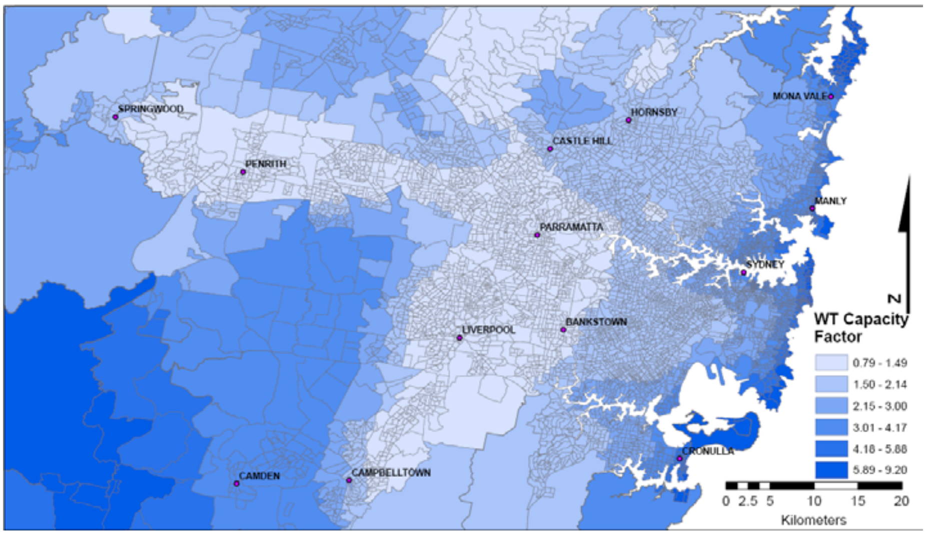

Figure 1. Estimated capacity factor for wind turbines by collection district, Greater Sydney region

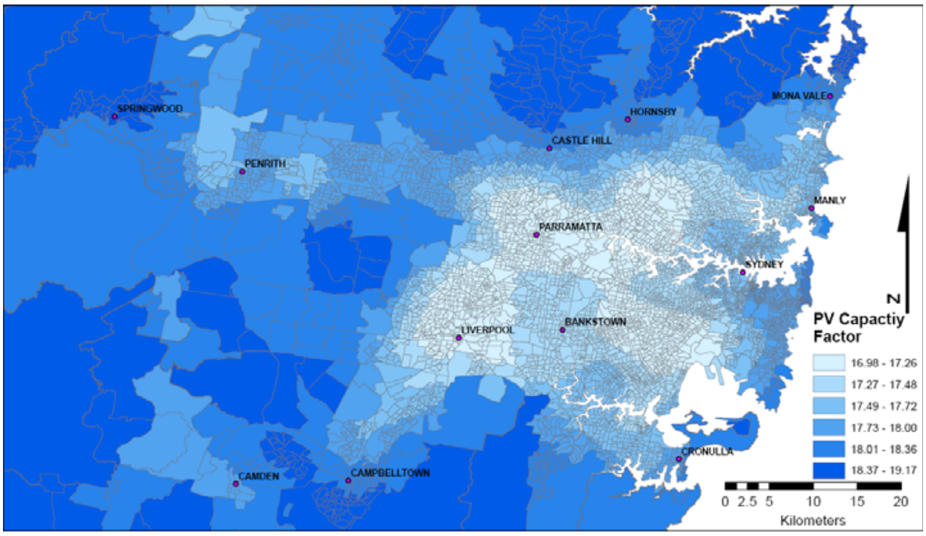

Figure 2. Estimated capacity factor for solar photovoltaic by collection district, Greater Sydney region

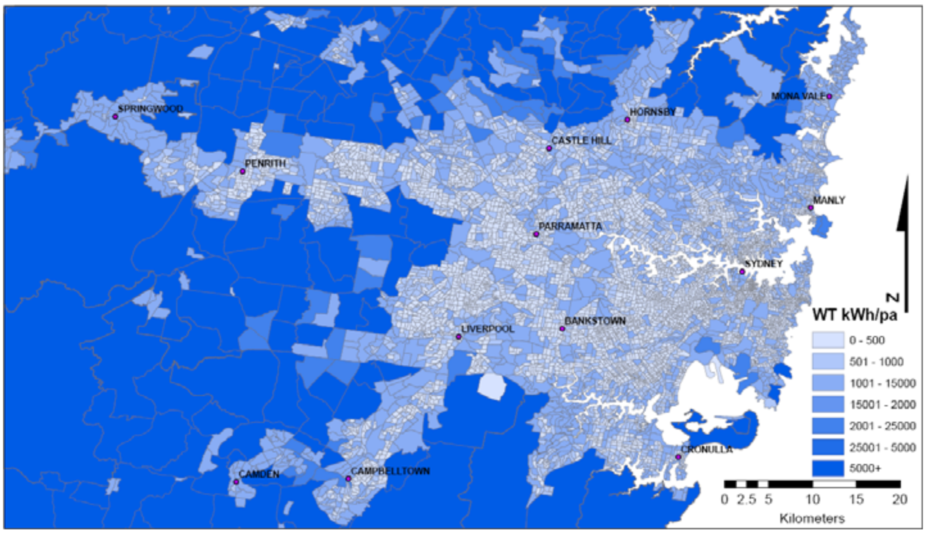

Figure 3. Electricity production of wind turbines by collection district, Greater Sydney region

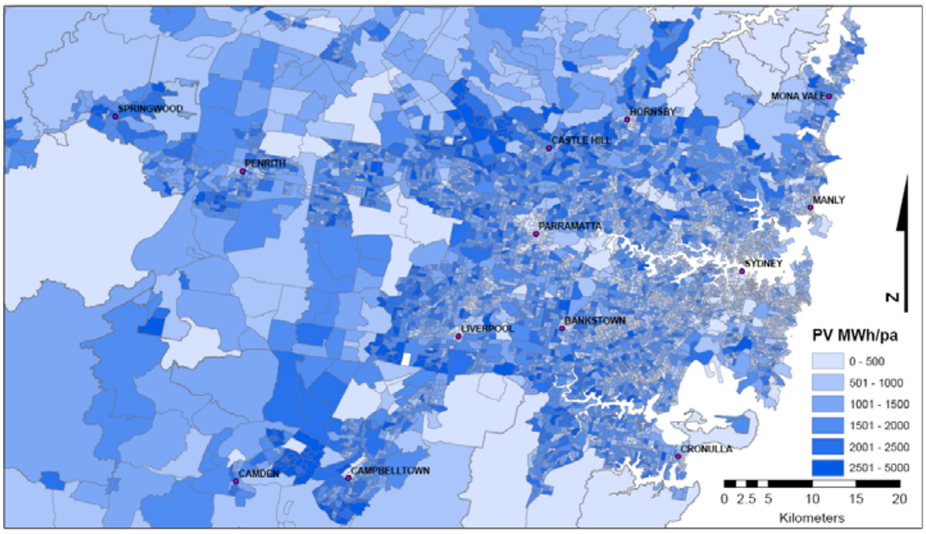

Figure 4. Electricity production of solar photovoltaic by collection district, Greater Sydney region

5.2. Comparison of socially acceptable and economically feasible capacities

As noted in the previous subsection, the physical potential of wind and solar PV is constrained by land use and building stock. However, the deployment of these technologies will arguably also be further constrained by social acceptance and economic feasibility. Table 1 summarises the physical, social and economic potential for wind and residential solar PV electricity generation in the Sydney Region. Recall that the estimate of socially acceptable potential was derived by scaling down the estimates of physical potential by ‘propensity to adopt’, whereas the calculation of the economic potential estimate was not constrained by that of physical potential.

Table 1. The physical, social and economic potential for wind and solar PV electricity generation in the Greater Sydney region

	Physical Potential (GWh)	Socially Acceptable Potential (GWh)	Economically Feasible (GWh)
Wind	29	18	0
Solar PV	6,900	5,900	3,300

Table 1 suggests that based on the methodology used and under the assumptions noted in Section 4, it is economic factors that provide the tightest constraints on the deployment of these renewable technologies rather than social acceptance factors and physical limitations imposed by competing land use or available roof space. The most notable feature of Table 1 is that small scale wind is not economic relative to other electricity generation technologies. This is mainly due to the low average capacity factor of around 3% for the Greater Sydney region.

6. DISCUSSION AND CONCLUSIONS

In this paper, we used GIS methods to estimate the potential of a subset of renewable electricity generation technologies in the Greater Sydney region. The work to date indicates that there exists significant physical potential for residential solar PV due to consistency of the solar resource and the dominance of one-storey detached dwellings in the residential building stock across the region. In contrast, the potential for wind is hampered by land use constraints. Solar PV is also more socially acceptable compared to wind. However, it appears to be economic feasibility that limits the deployment prospects for these technologies. Despite these findings, the results should be interpreted with caution.

For example, our results for the physical potential of wind may also be skewed due to the performance characteristics of the wind turbine we selected. Given the estimated average wind speed over the Greater Sydney region of around 3 m/s, selection of a different wind turbine may marginally increase output depending on the choice of model. Furthermore, it is possible that smaller-scale wind turbines under development for mounting directly onto built structures compared to traditional tower-mounted horizontal axis wind turbines may be more efficient in low wind speeds, more socially acceptable, more cost effective and less subject to competing land use constraints.

It is also possible that solar PV output may have been overestimated. For example, TAPM does not factor in shading from vegetation or adjacent buildings. Although detailed data on the effects of shading are not available, Watt et al. (1999) have estimated the impact of shading upon rooftop PV output to produce only a 2% drop. In addition, small scale convective cloud may not be well represented by TAPM even when operating at 2 km resolution leading to a marginal over prediction in shortwave radiation.

In some respects however, the physical potential for solar PV has been underestimated as we have not examined commercial and industrial roof space. This is potentially a significant resource and these end-users may be more able to economically justify deployment than residential end-users.

Future work will investigate the sensitivity of these results and extend the analysis to other stationary energy technologies and regions of Australia.

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