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Analysis of Rooftop Solar Potential on Australian Residential Buildings

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Abstract

Deployment of rooftop photovoltaics (PV) is technically constrained by the availability of suitable roof space as well as by the ability of the distribution network to absorb exported generation. Although Australian rooftop PV installations are at record levels, deployment is uneven across different building types, with commercial, industrial and multi-occupancy residential buildings lagging behind the world-leading penetration on detached residential buildings. An understanding of the amount and distribution of usable rooftop space on different building classifications is therefore useful in guiding appropriate policy incentives to increase deployment, as well as in network planning. The APVI Solar Potential Tool (SunSPoT) contributes to this understanding by using 3D building models or LiDAR building elevation data, vegetation layers and weather data to calculate the rooftop solar potential of specific buildings. This method has been extended in a number of APVI reports to calculate the rooftop solar potential in some of Australia's major urban centres using both 3D building models and low-resolution LiDAR data.

In this study, we combine these methods with residential building classification data to determine utilisation factors (the proportion of a building's roof area that is usable for PV deployment) for different types of residential building. The potential PV capacity per dwelling and an estimate for the potential capacity per unit of floor area is also calculated for different classes of residential building. These results are combined with Australian Bureau of Statistics (ABS) census data to estimate the total residential potential for different dwelling types in each state or territory. National residential solar potential is estimated to be between 43GWp and 61GWp, of which 6.5% is on multi-occupancy buildings.

As well as the slope and orientation of the roof planes and the degree of shading from neighbouring buildings and trees, utilisation factors are also affected by the presence of rooftop obstructions (such as air-conditioning units, skylights, perimeter walls, access equipment) which are not always captured by 3D models or low-resolution LiDAR data. Using high-resolution aerial imagery, we visually assess the roofs of case study buildings to better understand the effect of these factors.

1. Introduction

Australia leads the world in deployment of distributed residential PV, with close to two million solar households and penetration levels reaching 40% of stand-alone houses in some areas (APVI 2018). Although 2018 has seen an increase in commercial scale PV deployment in Australia, the majority of installations are still on residential buildings, with new installations averaging 6kWp in size. Driven by a combination of increasing electricity prices and decreasing PV costs, the continuing increase in distributed generation has implications for the electricity system, particularly the management of the distribution network. Multi-occupancy buildings, often located in proximity to daytime-peaking commercial loads, may present opportunities for significant network benefits from PV deployment, as well as potential to address equity issues, such as exclusion of groups of consumers, including apartment dwellers and renters, from the benefits of distributed energy in the energy transition. An understanding of the scale and distribution of this residential rooftop potential can therefore inform network planning as well as facilitating targeted policies for PV deployment.

Assessment of residential solar potential is hampered by a lack of data about the country's residential building stock. The Australian Bureau of Statistics (ABS) five-yearly Census of Population and Housing (ABS 2016) includes information on the number of dwellings in each state, local government area (LGA) and post office area (POA), broken down by dwelling structure. For stand-alone houses, dwelling numbers are equal to building numbers, which, despite the diversity of house sizes, can be used, with an understanding of the housing stock, to estimate roof area and therefore solar potential. However, there are multiple attached dwellings in other types of residential buildings, such as multi-storey apartment buildings, and the number and geographical distribution of buildings is therefore difficult to extract from the census dwellings data. In recent years, ABS has also published statistics regarding numbers and categories of building development approvals (ABS 2018) and financial value of building completions which can help to reveal trends in multi-dwelling housing, but throws little light on the existing building stock. However, at a city level, some local councils collect more detailed building data which can be used to explore the relationship between solar potential and building characteristics.

The assessment of rooftop solar potential in Australia, as internationally, has been the subject of research for at least 20 years (Watt, Kaye et al. 1997). Space in this paper does not allow for a comprehensive review of the many methodologies applied to the problem. However, researchers from NREL have carried out such a review and used it as a basis for developing their own methodology (Lopez, Roberts et al. 2012, Melius, Margolis et al. 2013, Gagnon, Margolis et al. 2016). This method forms the basis for a number of APVI reports assessing the solar potential of Australian cities (e.g. (Copper, Roberts et al. 2017)) which are based on the dataset used for the APVI's Solar Potential Tool (SunSPoT)(APVI 2018).

In this paper, an analysis of the rooftop solar potential of buildings in the City of Melbourne has been conducted, and building census data provided by the City of Melbourne used to assess the usable roof area and potential PV capacity of different types of residential buildings in the LGA. Using ABS census data, these results have been extrapolated across the country. Assessment of visual imagery for a small number of case study buildings has been carried out in order to facilitate discussion of the accuracy of the methodology.

2. Method

2.1. Calculation of usable area and solar potential

Figure 1 shows the major steps in the process. Steps 1 to 7 share the data and methodology behind the APVI's *SunSPoT* tool, as detailed in (Copper and Bruce 2014,2) and (Copper and Bruce 2014,1), which has also been used to assess the solar potential of major Australian cities as detailed in the relevant reports (Copper, Roberts et al. 2017). A brief description follows.

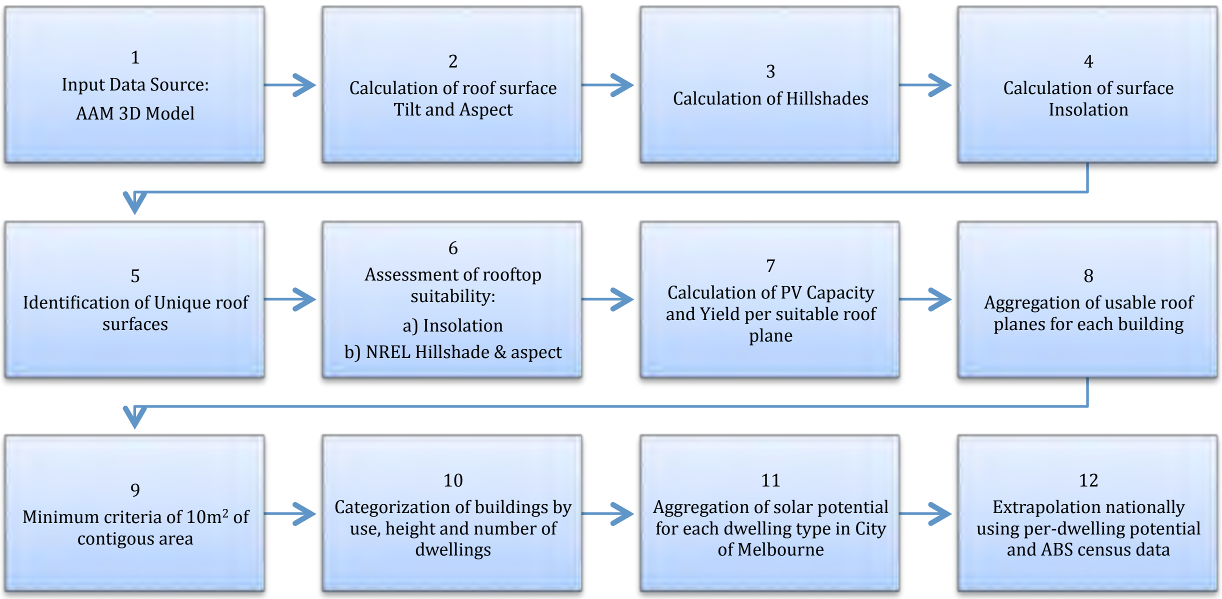

Figure 1. Major process steps for the calculation of rooftop PV potential (adapted from Copper, Roberts et al. 2017)

A 3D building model (built from photogrammetry and LiDAR data) and XYZ vegetation dot point, both supplied by geospatial company AAM, were combined to create a 1m^2 gridded raster-based digital surface model of the City of Melbourne. ESRI's ArcGIS tool was used to calculate tilt and orientation of the roof surfaces in the model, and ArcGIS's Area Solar Radiation tool was used to calculate monthly and annual values of solar radiation, considering shading from surrounding buildings and vegetation as well as from the building itself. These were then adjusted by a set of calibration factors which were determined via a validation analysis (Copper and Bruce 2014,1) against hourly modelling undertaken in NREL's System Advisor Model (SAM) (NREL 2010) using a Typical Meteorological Year (TMY) weather file. Two processes were then used to identify suitable planes for PV deployment: the first based on NREL's hillshade and surface orientation method (Melius, Margolis et al. 2013) and the second selecting areas exposed to 80% of the insolation incident on an unshaded horizontal surface. The NREL method used the ArcGIS hillshade tool to calculate shading on the roof planes for each hour on four days of the year (the equinoxes and solstices) and then find a metric for average sunlight availability. Roof planes were selected if they were exposed for sufficient hours to produce 80% generation on those four days, while excluding planes orientated between south-east and south-west (in the southern hemisphere) or between north-east and north-west in the northern hemisphere. The second method used annual daily average insolation (rather than the four days used in NREL's method) and allowed all orientations of roof surface if they were exposed to sufficient insolation. However, planes of under 10m^2 contiguous area were discarded for both methods. For each usable plane, potential PV system size (DC capacity) was calculated as per APVI's SPT methodology (Copper and Bruce 2014,1) using DC size factor and array spacing methodologies (Copper, Sproul et al. 2016) based on a generic 250W module with dimensions of 1m x 1.6m.

2.2. Building classification

City of Melbourne building footprints from 2015 (City of Melbourne 2015) were used to divide the roof planes and allocate them to building identifiers, while discarding planes of less than 10m^2 area per building. Two datasets from the City of Melbourne 2017 Census of Land use and Employment (CLUE)

(City of Melbourne 2018) ('Building Information' and 'Residential Dwellings') were used to identify residential buildings according to predominant space use and categorise them by ABS dwelling types[1]. Aggregate values for gross floor area (GFA) (approximated by the product of total footprint area and number of floors above ground), usable area, insolation, PV potential and annual energy generation were calculated for each building. 154 outliers (1.6% of the dataset) with PV capacities of 20 kW per dwelling or above were removed from the dataset – predominantly either dwellings attached to non-residential buildings or new developments with incorrect dwelling numbers in the database. The remaining data were used to generate averages for utilisation factor (the % of total roof area that is usable for PV) and for PV potential per dwelling and per square meter of GFA.

2.3. Comparison with aerial imagery for case study buildings

The roofs of some case study buildings within the City of Melbourne were analysed using high resolution aerial imagery from nearmap.com (Nearmap Ltd. 2015). This visual analysis allowed the exclusion of roof surfaces with localised, building-specific obstructions or sources of shading below the resolution of the 3D model (including air vents, HVAC installations, etc.) or otherwise unsuitable for PV deployment. Details of the method can be found in (Copper, Roberts et al. 2017). Nearmap's Solar tool was used to design an array, by laying out 1.6m x 1.0m modules on the roof.

2.4. Application to Australia's residential housing stock

The average figures for PV system size (in kWp/dwelling), combined with data from the ABS censuses (ABS 2016) enumerating types of dwelling by State or Territory, were used to estimate the potential residential PV capacity for each type of dwelling in 2011 and 2016. The rate of increase of each dwelling type between the two census dates was projected forward to estimate dwelling numbers for 2018 and current solar potential for each state. PV potential was compared with the current installed capacity of PV system less than 10kW (as PV systems <10kW are generally assumed by the Australian PV industry to be residential systems). The data on PV systems was obtained from the Clean Energy Regulator's Small Scale renewable Energy Scheme (Clean Energy Regulator 2018) database, accessed through the APVI PV Postcode Tool.

3. Results

3.1. Residential solar potential of City of Melbourne

Table 1 shows the total usable area, potential PV capacity and annual generation aggregated across all the residential building roofs in the City of Melbourne, calculated using the two methods outlined in Section 2.1. This represents approximately 24% of the total rooftop PV potential in the LGA (Copper, Roberts et al. 2017) and nearly 50 times the approximately 2.1MW of small (under 10kWp) systems currently installed in the LGA (Clean Energy Regulator 2018).

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[1] The full list of ABS Dwelling Structures ('STRD') is: Separate House; Semi-detached, row or terrace house, townhouse etc. (with one storey / with two or more storeys); Flat or apartment (in a one or two storey block / in a three storey block / in a four or more storey block / attached to a house); Other dwelling (caravan / cabin or houseboat / improvised home, tent, sleepers out / house or flat attached to a shop, office, etc.).(ABS 2016)

Table 1. Total usable area, PV system size and energy generation for each residential building type in City of Melbourne

Dwelling Type	# Buildings	% with Flat Roof	80% Insolation method			NREL Method		
			Usable Area (Ha)	Potential Capacity (MWp)	Annual Energy (GWh)	Usable Area (Ha)	Potential Capacity (MWp)	Annual Energy (GWh)
House	7815	28%	32.6	48.8	56.7	30.8	46.2	53.8
Townhouse*	334	43%	5.3	8.0	9.5	4.9	7.5	8.8
1 or 2 storey apartment	339	32%	5.1	7.8	9.1	4.7	7.2	8.4
3 storey apartment	385	61%	8.4	13.0	15.5	8.2	12.6	15.0
4 or more storey apartment	553	86%	20.3	31.4	37.4	22.5	34.7	40.3
Total	**9426**		**71.7**	**109.1**	**128.2**	**71.1**	**108.2**	**126.3**

*The dwelling type 'Townhouse' includes terraced and semi-detached houses

Figure 2 shows the usable area normalized (left) by total roof area and (right) by number of dwellings. Note that the 80% insolation method gives slightly higher values, on average, likely because of the inclusion of low tilt, south-facing roofs that are excluded in the NREL method, whereas PV systems are commonly installed on near-flat roofs in Australia. The increase of usable roof area between houses, townhouses and low-rise apartments may be due to increasing proportion of flat roofs, or decrease in highly tilted roofs (and therefore south facing roof areas), while the slight decrease for high rise apartments is likely due to lift housings and other rooftop obstructions, but it is important to note the wide distribution of values for all dwelling types. It is unsurprising that the per-dwelling usable area is greater for houses than for apartments and lowest for high-rise apartments, although the variability is large and the sample sizes for apartment buildings relatively small (Table 1).

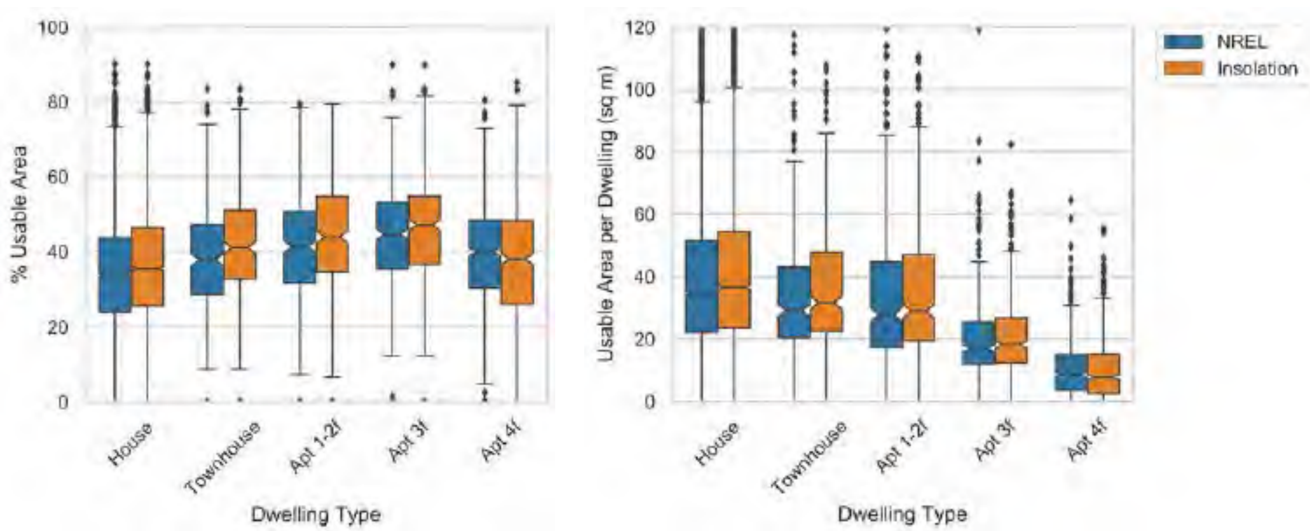


Figure 2. Percentage usable area (left) and usable area per dwelling (right) for residential dwellings in City of Melbourne

Table 2 shows the mean (and standard deviation) of usable area and potential PV capacity for each dwelling type in the City of Melbourne. On average, low-rise apartment buildings have a greater proportion of roof area available for PV deployment, perhaps because of a greater incidence of flat roofs (Table 1) and therefore less South-facing planes. The results show that, on average, high-rise apartments have approximately a quarter of the potential per-dwelling PV capacity of stand-alone houses (but note the large standard deviation (SD) compared to the mean, due to the variety of building heights, so that a usable area of 1.1m^2/dwelling is one SD below the mean). On average, three-storey apartment buildings have twice that, and one- or two-storey apartment buildings have similar potential per-dwelling capacity to townhouses, semi-detached and terraced houses.

Residential electricity demand increases with dwelling occupancy and with space heating and cooling loads, both of which are related to gross floor area (GFA). Table 2 gives approximate average GFA for dwellings (based on the product of building footprint and number of floors) for each dwelling type (but note that these include internal walls and common areas) and PV potential per square meter of GFA.

Table 2. Mean (standard deviation) usable area and PV potential per dwelling in City of Melbourne by dwelling type

Dwelling Type	% Usable Area	Usable Area (m^2) per dwelling	PV (kWp) per dwelling	GFA (m^2) per dwelling	PV per GFA (Wp/m^2)
House	34.5% (15.0%)	40.3 (25.0)	6.0 (3.8)	171 (102)	39.2 (22.7)
Townhouse	39.6% (13.5%)	35.5 (21.4)	5.4 (3.3)	177 (112)	34.1 (18.1)
1 or 2 storey apartment	42.1% (15.1%)	34.9 (24.5)	5.3 (3.7)	153 (102)	36.1 (16.0)
3 storey apartment	45.3% (13.1%)	20.8 (13.2)	3.2 (2.0)	138 (107)	24.0 (7.0)
4 or more storey apartment	37.2% (15.4%)	10.3 (9.2)	1.6 (1.4)	178 (138)	10.1 (7.3)

The variability of percentage usable area and potential PV capacity per dwelling for each dwelling type are shown in Figure 3. For all dwelling types, median percentage usable area is higher for flat roofs than pitched roofs, while three storey apartments with flat roofs have a narrower distribution than all other categories.

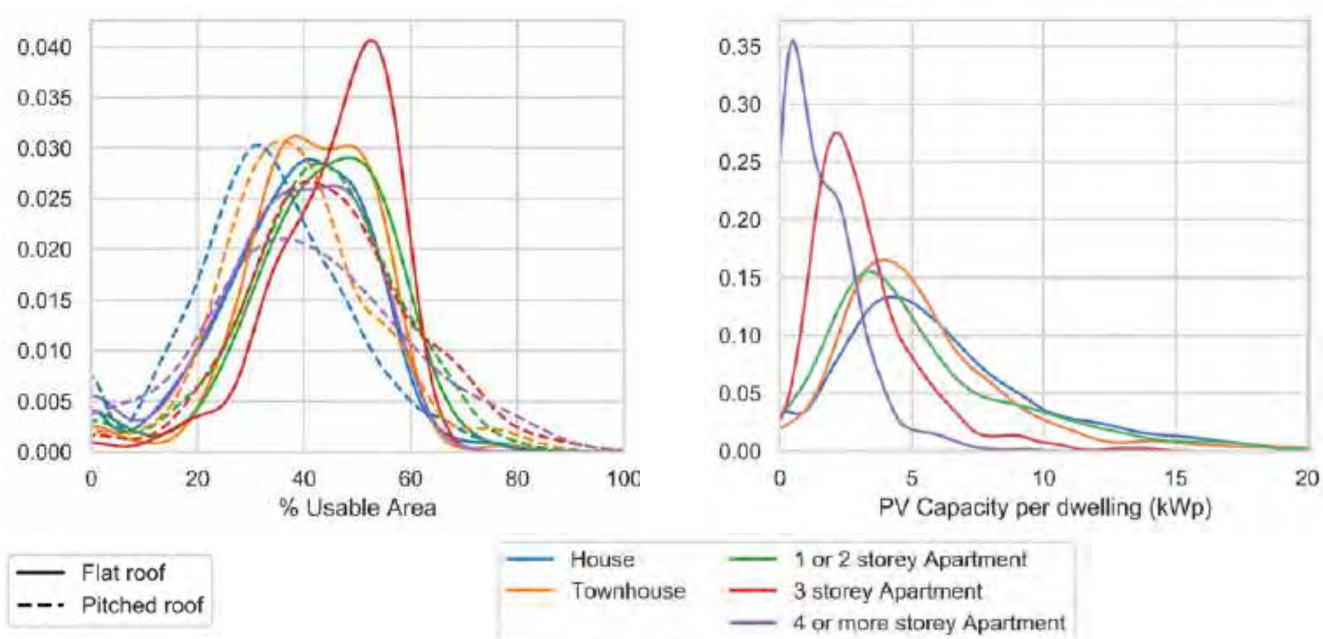


Figure 3. Percentage usable area by dwelling type and roof form (left), and mean PV potential (kWp/dwelling) by dwelling type (right)

3.2. Observations from analysis of case studies

Figure 4 shows images of the usable planes (calculated using the 80% insolation method) for four case study buildings (selected to demonstrate specific constraints), along with images showing PV arrays arranged on the roof using Nearmaps. For all these buildings, there are constraints revealed by the visual imagery that are not accounted for in the GIS analysis, and which reduce the potential PV capacity of the roofs, as shown in Table 3.

Table 3. PV potential of case studies using 80% insolation method and visual analysis

	Dwelling / Roof Type		PV capacity kWp (80% insolation)	PV capacity kWp (Visual analysis)	Nearmap array as % of theoretical potential	Notes
(a)	Townhouse	Slope	11.0	10.3	93%	Some loss of potential on SW facing roof from roof vents
(b)	Apt - 3F	Slope	76.5	55.8	73%	Loss of potential from air vents and tree shading
(c)	Apt - 3F	slope	74.4	74.5	100%	Loss of potential from skylights, shading but may have additional potential compared to usable planes
(b)	Apt - 4+F	Flat	225.8	15.0	7%	Most potential lost through large HVAC obstruction and roof garden.

For sites (a), (b) and (c), usable area is reduced by air vents and skylights on the roof space. Note that the 3D model was not built for the purpose of analysing rooftop solar, so does not capture these small roof features and is therefore likely to result in an overestimate of the solar potential. For the APVI report on Melbourne's solar potential (Copper, Roberts et al. 2017), repeating the analysis using LiDAR data gave an average value for usable area of 31.3%, compared to 44.3% using the 3D model, although that method may *under*estimate the total potential (and note that a smaller difference was observed for other Australian cities). The visual assessments for case studies (a), (b) and (c) are consistent with that range.

For (b) and (c), there is also additional shading from proximate trees, but the discrepancy between the two results may be due to the time difference the vegetation data used to create the raster layer and the visual imagery[2]. However, for site (c), the loss of usable area is compensated by additional roof areas available for PV deployment that are excluded by the resolution of the polygons defining the usable planes[3], so the two methods produce similar results.

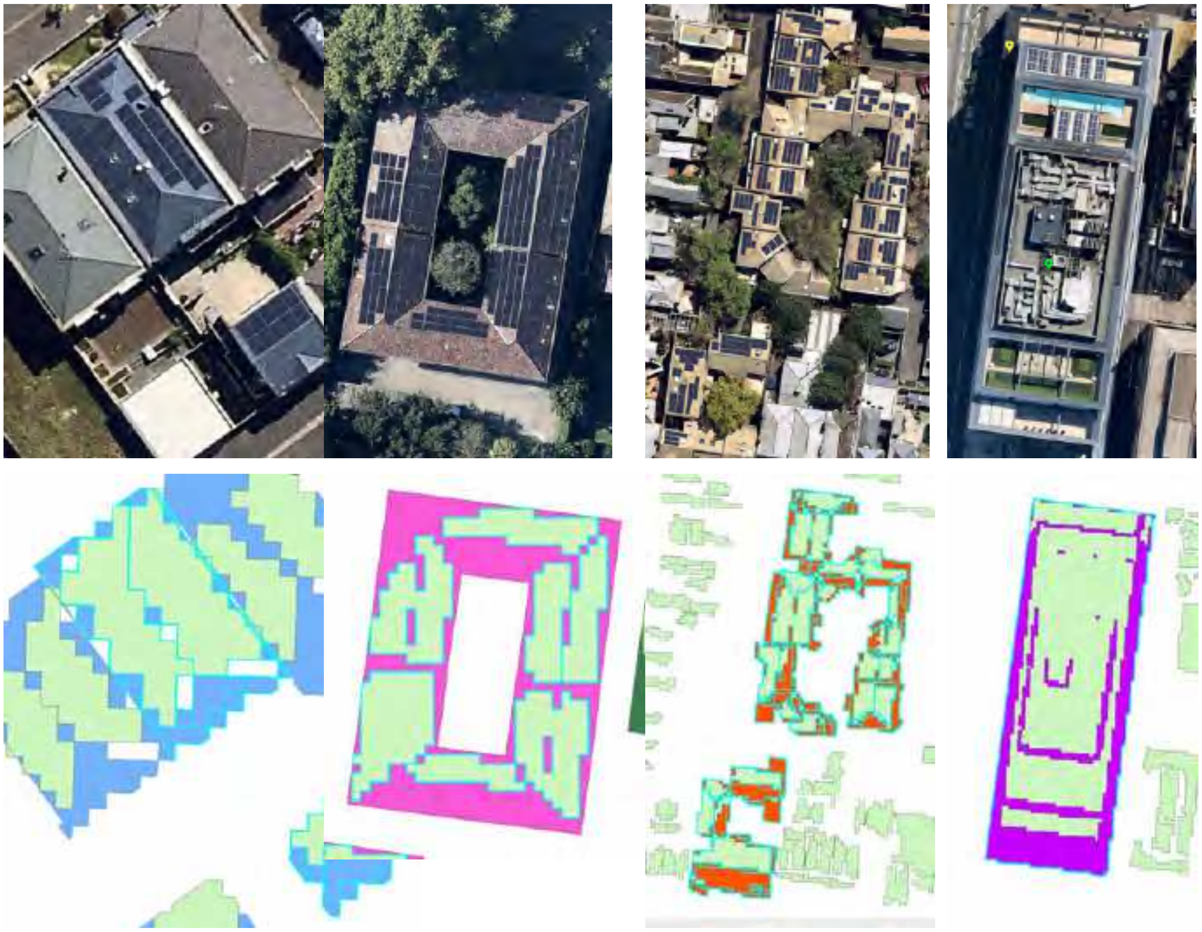
Site (d), however, was chosen to demonstrate a less common issue where the roof is largely occupied by public areas (roof garden, pool, terraces) and HVAC equipment, with the results that very little of the theoretical usable area can be used for PV deployment, unless additional structures such as shade structures were erected.

Additionally, although the insolation method discards roof planes of less than 10 m^2, constrains system size to integer quantities of (250Wp, 1.6m x 1.0m) modules, and includes a PV occupancy factor of

[2] The AAM vegetation points dataset was collected in 2010 while the data for the 3D model was from 2012 and the Nearmaps visual imagery is from 2018.

[3] The jagged edges of the usable plane polygons is an artefact of using a 1m^2 gridded raster. A finer resolution of the raster can be created using the 3D building model inputs but processing is highly resource-intensive.

98% for flush mounted panels, it does not account for fitting rectangular panels onto irregularly shaped roof planes, which results in additional loss of usable area, particularly near roof edges, making the effect likely more significant for smaller roof planes.



(a) (house) (b) (3 storey apt) (c) (3 storey apt) (d) (13 storey apt)

Figure 4. Case study buildings showing (top) arrays designed using aerial imagery and (bottom) usable roof planes by 80% insolation method (shown green)

3.3. Residential solar potential by state

Based on the results presented in Table 3, the estimated total (including existing) potential residential PV capacity for each dwelling type in 2011 and 2016 is calculated by state in Table 4 and, along with estimated 2018 potential and installed capacity, in Figure 5, though, as noted above, the 3D model analysis may overestimate usable roof area. Dwelling numbers, and therefore potential capacity, are increasing for all dwelling types in all states except for '1 and 2 storey apartments' but the very large increases in 'Semi-detached, row or terrace house, townhouse etc.' may include dwellings previously classified as apartments. Amongst apartments, the biggest increases are in buildings of four storeys and above, with the lowest potential per-dwelling capacity, but the potential capacity on three-storey apartment buildings also increased significantly, particularly in VIC and QLD.

Table 4. Estimated total potential PV capacity (MWp) by dwelling type and state 2016 (2011), % change

	NSW	VIC	QLD	WA	SA	TAS	ACT	NT
House	12019 (11770) 2%	10992 (10449) 5%	8855 (8365) 6%	4953 (4539) 9%	3546 (3473) 2%	1266 (1203) 5%	640 (621) 3%	328 (305) 8%
Townhouse	2009 (1652) 22%	1930 (1183) 63%	1151 (831) 39%	839 (561) 50%	619 (425) 46%	77 (68) 14%	159 (116) 37%	57 (47) 22%
1 or 2 storey apartment	914 (987) -7%	689 (1008) -32%	518 (643) -20%	155 (257) -39%	215 (295) -27%	62 (82) -24%	31 (35) -12%	37 (43) -14%
3 storey apartment	626 (561) 2%	204 (165) 24%	216 (176) 23%	54 (52) 4%	18 (15) 14%	5 (4) 11%	29 (23) 25%	9 (8) 14%
4 or more storey apartment	429 (326) 32%	195 (109) 79%	139 (102) 37%	41 (30) 36%	13 (11) 17%	2 (1) 28%	19 (10) 96%	10 (5) 84%

Using the 3D model analysis, the total residential potential PV capacity in Australia in 2018 is estimated to be 61GWp (ten times the capacity of existing sub-10kW installations), of which 4.0GWp of potential is on apartment buildings. It would be instructive to repeat the analysis using LiDAR data which might be expected to exclude more of the small roof obstructions. Applying the relationship between the results from the two datasets averaged across all buildings in the LGA (Copper, Roberts et al. 2017) (as discussed in Section 3.2) would suggest the total potential residential PV capacity to be in the range 43GWp - 61GWp.

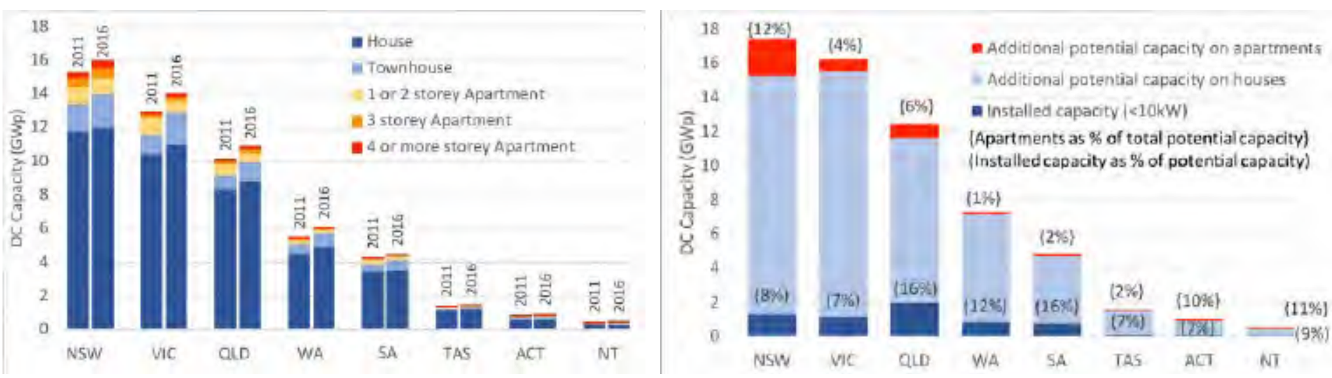


Figure 5. Estimated residential solar potential by state:
(l) by dwelling type for 2011 and 2016
(r) projected for 2018 showing existing capacity

The potential capacity on apartment buildings in NSW is more than twice that in QLD and three times VIC and exceeds the total existing residential capacity in the state.

4. Discussion and Conclusion

This study has used a novel approach to estimate Australia's residential solar potential for all dwelling types by calculating per-dwelling potential for the building stock in City of Melbourne LGA and extrapolating nationally using ABS census data.

The small number of case studies analysed visually suggest the method may overestimate potential by excluding the constraints due to small rooftop obstructions and the shape of roof planes. Visual analysis of a large number of buildings for each dwelling type would be useful to determine average adjustment factors to account for these effects. The quantity of small obstructions is building-specific but likely to be affected by the age of buildings (included in the CLUE dataset for 38% of buildings) as well as by dwelling type and roof form, while potential losses due to fitting modules to irregularly shaped roof planes is likely to be a factor of the size of the planes. These factors could be used to categorise buildings and calculate average adjustment factors. Conversely, the roofs of houses in City of Melbourne are likely to be smaller than the national average, which could result in an overestimate of the per-dwelling potential capacity. It would therefore be useful to repeat the analysis using 3D models and building data from suburban or rural areas.

Planned future work includes applying the analysis to high resolution LiDAR data and (as in the APVI solar potential reports) comparing the results with the 3D model data to estimate upper and lower bounds for the potential, as well as assessing further case-studies to determine how completely the LiDAR analysis captures small localised obstructions. Applying the average results from a previous analysis (Copper, Roberts et al. 2017) suggests the national residential potential to be in the range 43GWp - 61GWp, of which 6.5% (2.9GWp - 4.0GWp) is on multi-occupancy buildings.

Moreover, for some flat-roofed buildings, the use of roof space for other purposes, including roof gardens and terraces, reduces PV potential and is hard to detect through analysis of 3D building models. There may be potential to automate analysis of aerial imagery to detect some of these features. Collection of data regarding rooftop facilities would also be a useful addition to any future building census. Additionally, it should be noted that least-cost PV installations do not always allow for efficient use of the whole roof space, and that economically optimal sizing of systems often utilises only a proportion of the usable area but may exclude other areas from future installation. Paradoxically, as the penetration of rooftop PV increases, the total potential PV capacity may therefore be decreased, although the effect is likely to be counteracted by the ongoing growth of the building stock.

A detailed understanding of rooftop PV potential and its distribution geographically and by building type has application for federal, state and local governments to design incentives for PV deployment, for not-for-profit PV advocates and for network planners. In particular, where potential PV capacity is spatially aligned with distribution network locations having daytime capacity constrictions, there may be opportunities to utilise targeted PV incentives to defer the cost of network upgrades. Additionally, the scale of the potential opportunity on multi-occupancy buildings suggests value in exploring the barriers to apartment PV deployment and in incentivising developers and strata bodies to install PV on apartment buildings, and this is the subject of ongoing study by the authors.

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