Spatial Analysis of Solar Potential in Sydney

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Summary

There is significant potential for rooftop solar PV in Australia. Rooftop solar PV is a key energy technology because it is leading the transition to consumer uptake of low-carbon demand-side energy technologies, which are providing new opportunities for consumer engagement and new clean energy business models to emerge. However, there is a lack of good information in the public domain about the potential for rooftop solar to contribute to low-carbon electricity generation in Australia's cities. This type of information is important for policymakers and planners, and to encourage public support for rooftop solar.

This research uses the data and methodologies behind the APVI Solar Potential Tool http://pv-map.apvi.org.au/potential, developed by researchers at UNSW, to estimate the Solar Potential in the Sydney CBD. The report includes:

1. An assessment of PV Potential in Sydney CBD (bounded by the City of Sydney LGA)
2. An estimate of the potential impact of rooftop PV on local electricity consumption and emissions
3. Identification of rooftops with the largest PV potential (area available) in the CBD
4. Three case studies of PV Potential on landmark buildings in Sydney

The useable area suitable for PV deployment across Sydney's CBD (City of Sydney LGA) was calculated using two different methods. **The most conservative estimate of the two suggests the useable area suitable for rooftop PV deployment (the ratio between the area of PV panels that could be accommodated and the total roof area) is 25% corresponding to 393 MW of PV potential with an expected annual yield of 507 GWh. The equivalent CO_2 emission savings are 403 kt per year.**

The average of the two methods indicated that an area equal to 40% of the available roof surfaces could be used to accommodate PV, corresponding to 619 MW of potential PV capacity with an expected annual yield of 777 GWh. This equates to 22% of the 3,588 GWh of load in the CBD. The potential CO_2-equivalent emission savings from PV based on the average of the two PV potential estimation methods are 618 kt per year. There is an estimated 6.7 MW of existing PV capacity installed on rooftops in the City of Sydney LGA, around 1% of the potential capacity. Almost all of the electricity generation and emissions savings calculated would therefore be additional.

The breakdown across different suburbs is shown in Table 1 below.

Table 1: Summary of results categorised by suburb

Sydney City Suburbs	PV Capacity (MW)	PV Yield (GWh)
	Average	Average
All	619.25	777.12
Alexandria	109.57	143.39
Annandale	6.40	8.01
Barangaroo	0.27	0.34
Beaconsfield	4.84	6.05
Camperdown	20.59	25.53
Centennial Park	3.64	4.45
Chippendale	10.54	13.02
Darlinghurst	19.55	23.85
Darlington	8.15	10.22
Dawes Point	1.21	1.45
Eastlakes	3.15	3.99
Edgecliff	0.02	0.03
Elizabeth Bay	6.46	7.98
Erskineville	18.21	22.89
Eveleigh	9.23	11.46
Forest Lodge	7.92	9.79
Glebe	24.50	30.08
Haymarket	12.11	14.90
Kensington	4.83	5.88
Kingsford	0.03	0.04
Mascot	11.01	14.29
Millers Point	3.52	4.24
Moore Park	15.98	20.37
Newtown	18.60	22.80
Paddington	14.31	17.45
Port Jackson	1.58	1.91
Potts Point	12.96	16.00
Pyrmont	21.54	26.69
Redfern	25.94	31.82
Rosebery	47.40	60.08
Rushcutters Bay	2.34	2.88
St Peters	12.09	15.73
Surry Hills	30.65	37.67
Sydney CBD	47.52	57.57
The Rocks	3.41	4.19
Ultimo	18.16	22.59
Waterloo	33.10	42.10
Woollahra	0.46	0.56
Woolloomooloo	9.14	11.08
Zetland	18.32	23.77

The rooftops with the largest PV potential in Sydney have been mapped (Figure 1 below). More detailed images appear in Appendix C.

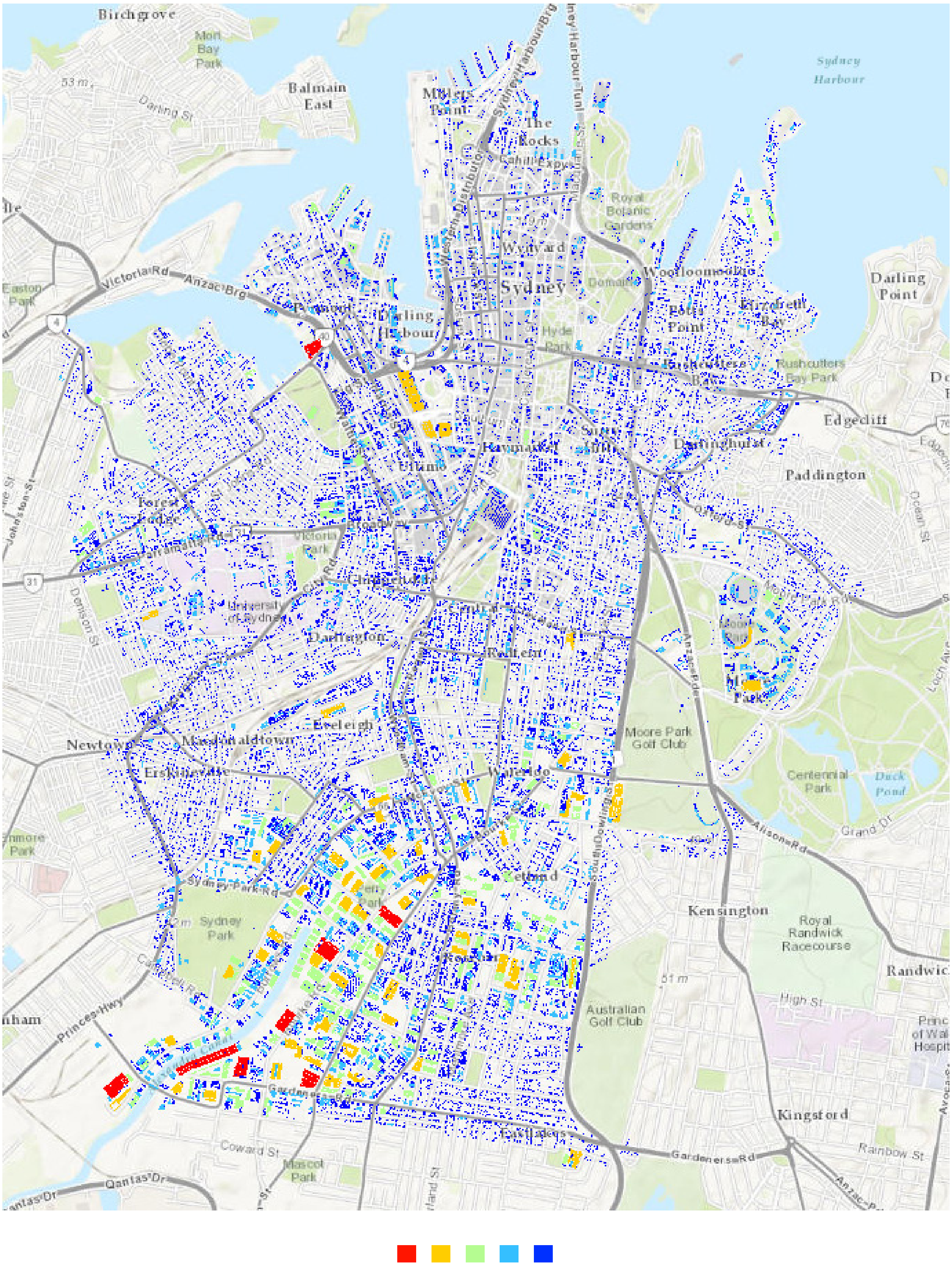

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Figure 1: Rooftops with Largest PV Potential in Sydney CBD

Case studies of specific landmark buildings including the Art Gallery of New South Wales, the Overseas Passenger Terminal (OPT) at Circular Quay and Central Station have been conducted.

Table 2 based on the data and visual imagery available shows that an area equivalent to just over half the building footprint of the 3 buildings is suitable for PV arrays. Both Central Station and the Overseas Passenger Terminal (OPT) have large areas of uncluttered and unshaded roof (although part of the OPT's footprint consists of roadway, reducing the % usable for PV), while the Art Gallery's irregular roof profile has a smaller but significant usable proportion.

Table 2: Potential productive roof area

Site	Building Footprint (m^2)	Array Area (m^2)	Array Area / Roof Area
Central Station	31403	19600	62%
Art Gallery NSW	8456	3158.4	37%
OPT	5760	2420.8	42%

Table 3 shows the array capacity and expected annual energy production for the potential PV arrays illustrated in Figure 2 -**Figure 4**.

Table 3: PV Capacity and Annual Energy Production

Site	PV Capacity (kW_{peak})	Annual Energy Production (w/o shading) (MWh/year)	Average Yield per kW PV installed (kWh/kW/day)	Annual Energy Production (adjusted) (MWh/year)
Central Station	3063	3902	3.49	3599
Art Gallery NSW	494	642	3.56	589
OPT	378	476	3.45	461

Table 4 presents the estimated carbon offsets for each system and shows that these three buildings could save an estimated 3.7 kilotonnes of carbon emissions each year and could supply the equivalent of 691 households, based on the average 2014 electricity demand of a New South Wales household (in 2014) being 6730 kWh [1].

Table 4: Carbon offset and household energy equivalents

Site	Expected Annual Energy Production (MWh/year)	Emissions Offset (Tonnes CO_2-e / year)	Average NSW household equivalent
Central Station	3599	2861	535
Art Gallery NSW	589	468	87
OPT	461	366	68
Totals	**4648**	**3695**	**691**

Array Illustrations

Figure 2: Potential PV Array on Central Station

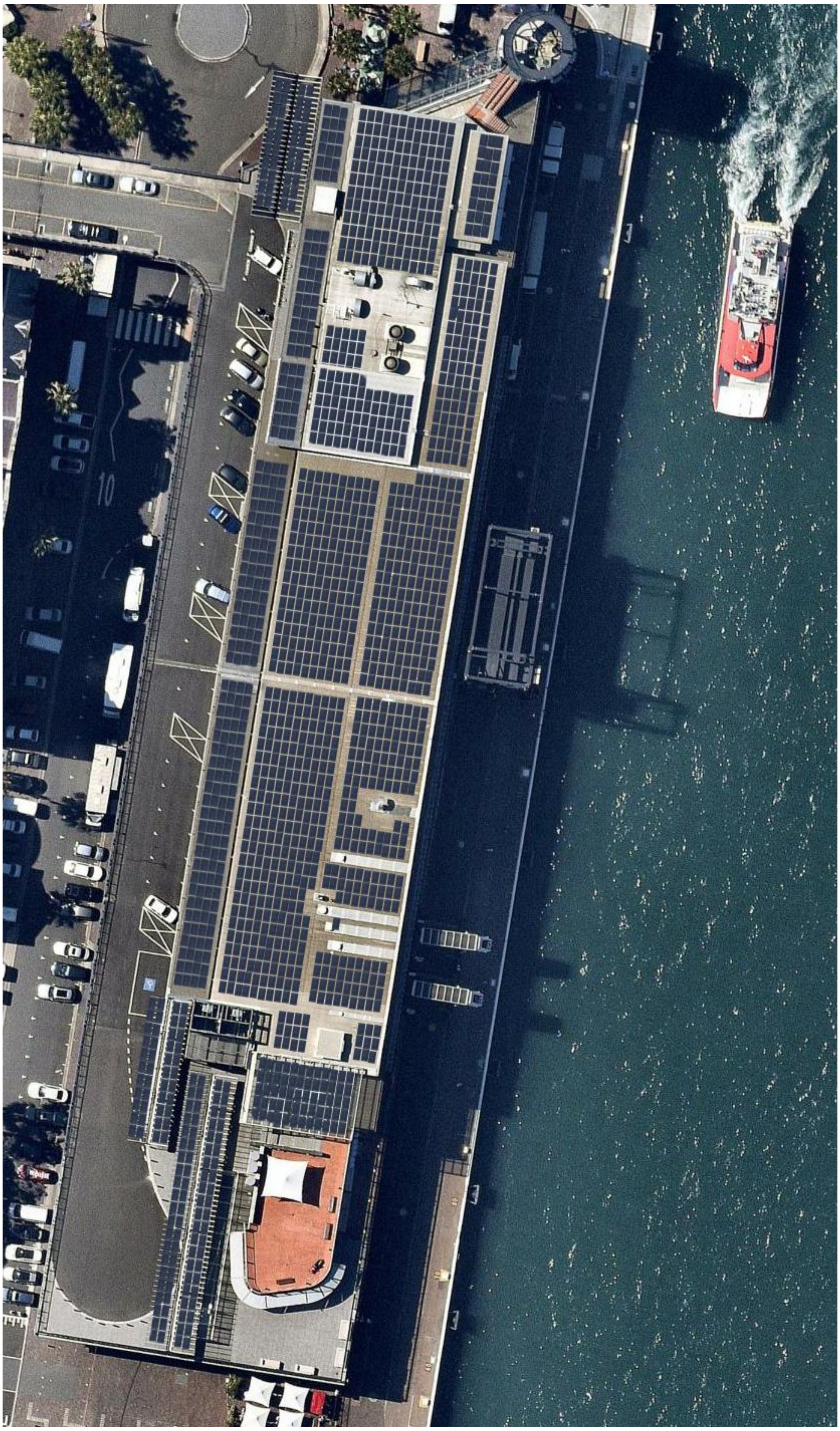


Figure 3: Potential PV Array on the Overseas Passenger Terminal

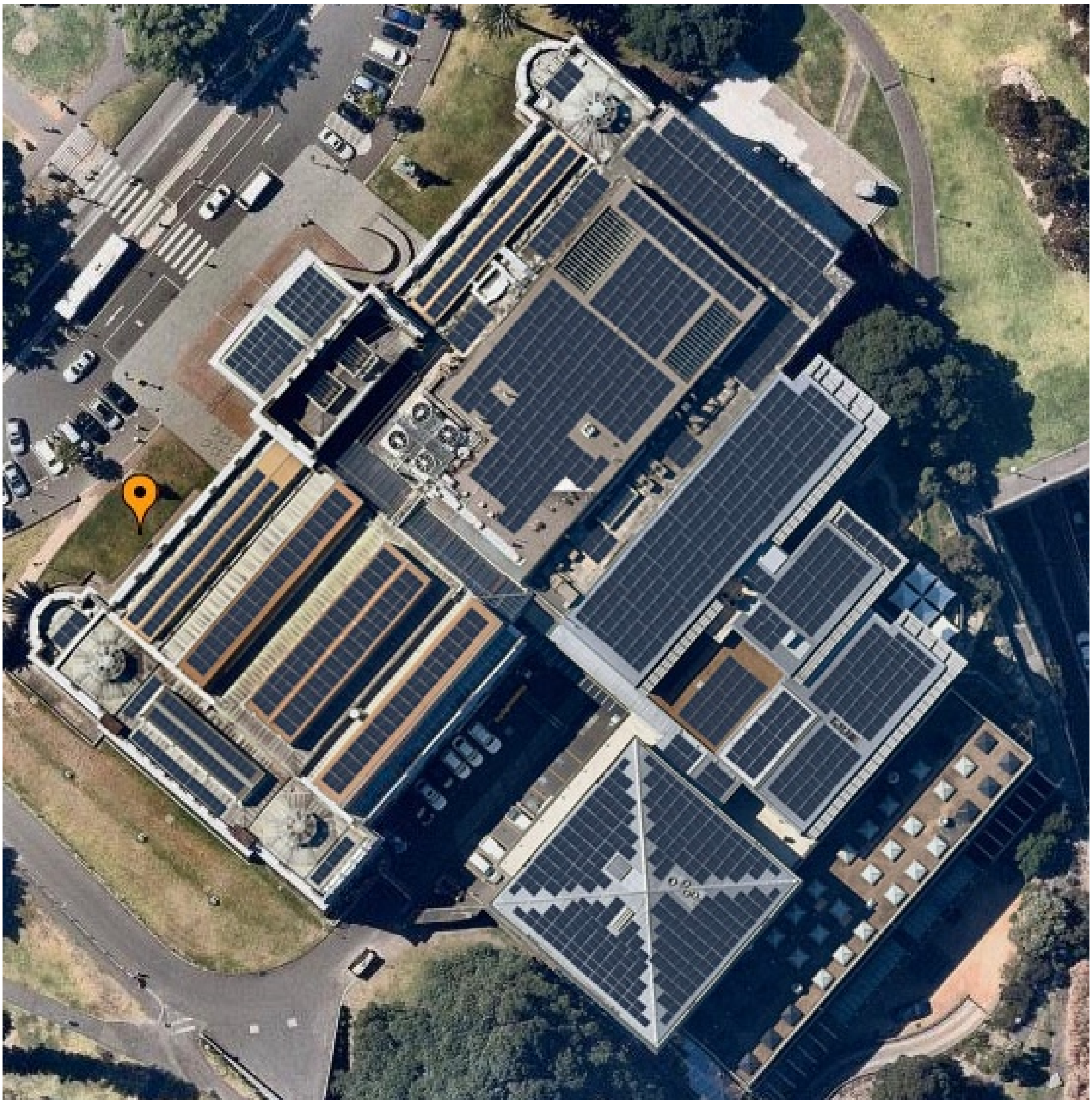


Figure 4: Potential PV Array on the Art Gallery of NSW

Introduction to the Solar Potential Tool

The APVI Solar Potential Tool (SPT) is an online tool to allow electricity consumers, solar businesses, planners and policymakers to estimate the potential for electricity generation from PV on building roofs. The tool accounts for solar radiation and weather at the site; PV system area, tilt, orientation; and shading from nearby buildings and vegetation.

The data behind the APVI SPT were generated as follows:

1. Three types of digital surfaces models (DSMs)[1] (3D building models, XYZ vegetation points and 1m ESRI Grids), supplied by geospatial company AAM, were used to model the buildings and vegetation in the areas covered by the map.
2. These DSMs were used as input to ESRI's ArcGIS tool to evaluate surface tilt, orientation and the annual and monthly levels of solar insolation falling on each 1m^2 unit of surface.
3. Insolation values output by the ArcGIS model were calibrated[2] to Typical Meteorological Year (TMY) weather files for each of the capital cities and against estimates of insolation at every 1 degree tilt and orientation from NREL's System Advisor Model (SAM).

At a city level, an insolation heatmap layer (Figure 5b) allows identification of the best roofs, while the shadow layer (Figure 5c) allows the user to locate an unshaded area on a rooftop. On a specific roof surface, an estimate of annual electricity generation, financial savings and emissions offset from installing solar PV can be obtained.

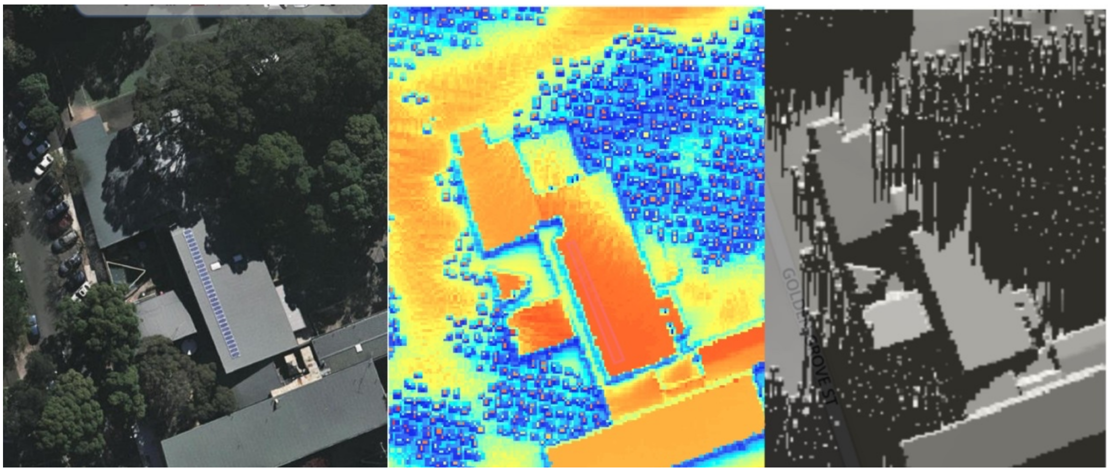


Figure 5: (a) Aerial photograph (b) Insolation heat map, (c) Winter shadow layer

This project expanded the data and methodologies behind the Solar Potential in order to estimate the Solar Potential in the Sydney CBD region.

[1] Digital surface models provide information about the earth's surface and the height of objects. 3D building models and vegetation surface models have been used in this work. The ESRI Grid is a GIS raster file format developed by ESRI, used to define geographic grid space.

[2] Calibration was required in order to obtain good agreement NREL's well-tested SAM model and measured PV data.

Assessment of the PV Potential in Sydney CBD

This section of the report details the methodology and the results of the geospatial analysis of PV potential across Sydney CBD.

Methodology

The assessment of the PV potential in Sydney's CBD, expanded on the initial work undertaken for the Sydney region of APVI's SPT. The analysis made use of the following data sources:

1. The three sources of input DSMs data from AAM; and
2. NSW LPI LiDAR data for Sydney North – 2013 dataset sourced NSW Land and Property Information.

The general steps in the methodology are illustrated in Figure 6. To test the sensitivity of the estimated PV potential two input data sources and two rooftop suitability methods were assessed. The two input data sources used to calculate the tilt, aspect, solar insolation and determine suitable roof planes were 1) the DSM and 3D building models from AAM and 2) the 2013 NSW LPI LiDAR data covering Sydney CBD. The two methods utilised to determine suitable rooftops were 1) based on a minimal level of surface insolation and 2) NREL's PV rooftop suitability method based on hillshade and surface orientation. Both methods also required a minimum contiguous surface area of $10m^2$ for a roof plane to be determined suitable. This limit was defined to ensure a minimum 1.5kW PV system for any plane defined as suitable.

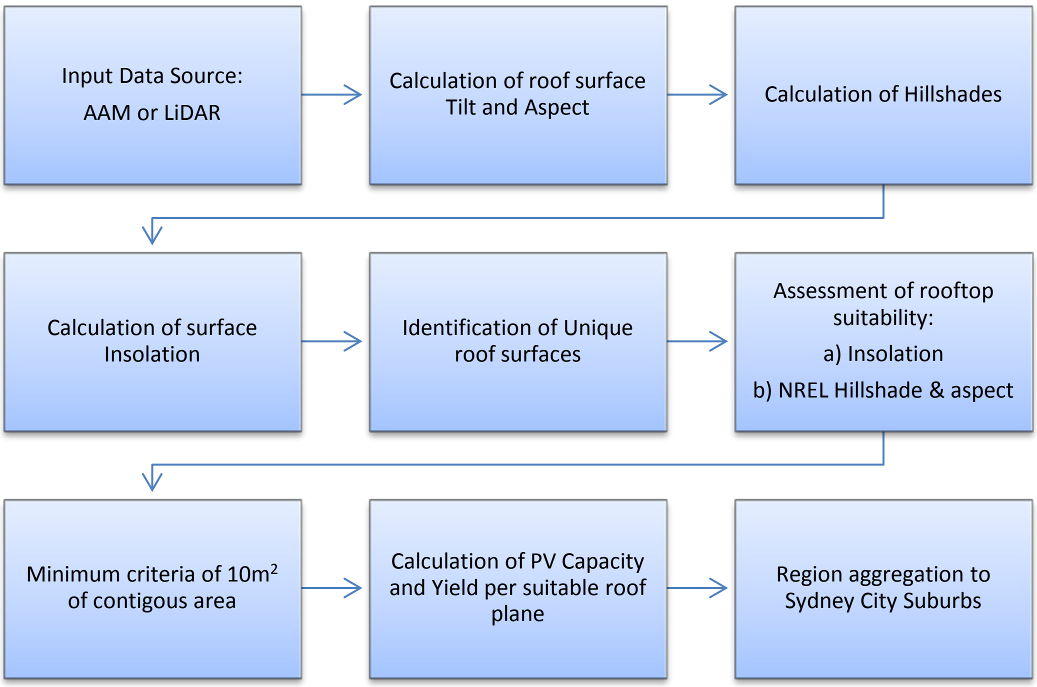


Figure 6: Major process steps for the calculation of rooftop PV potential

The regions covered by the analysis and the relevant suburbs used to classify the PV potential opportunities are shown in Figure 7.

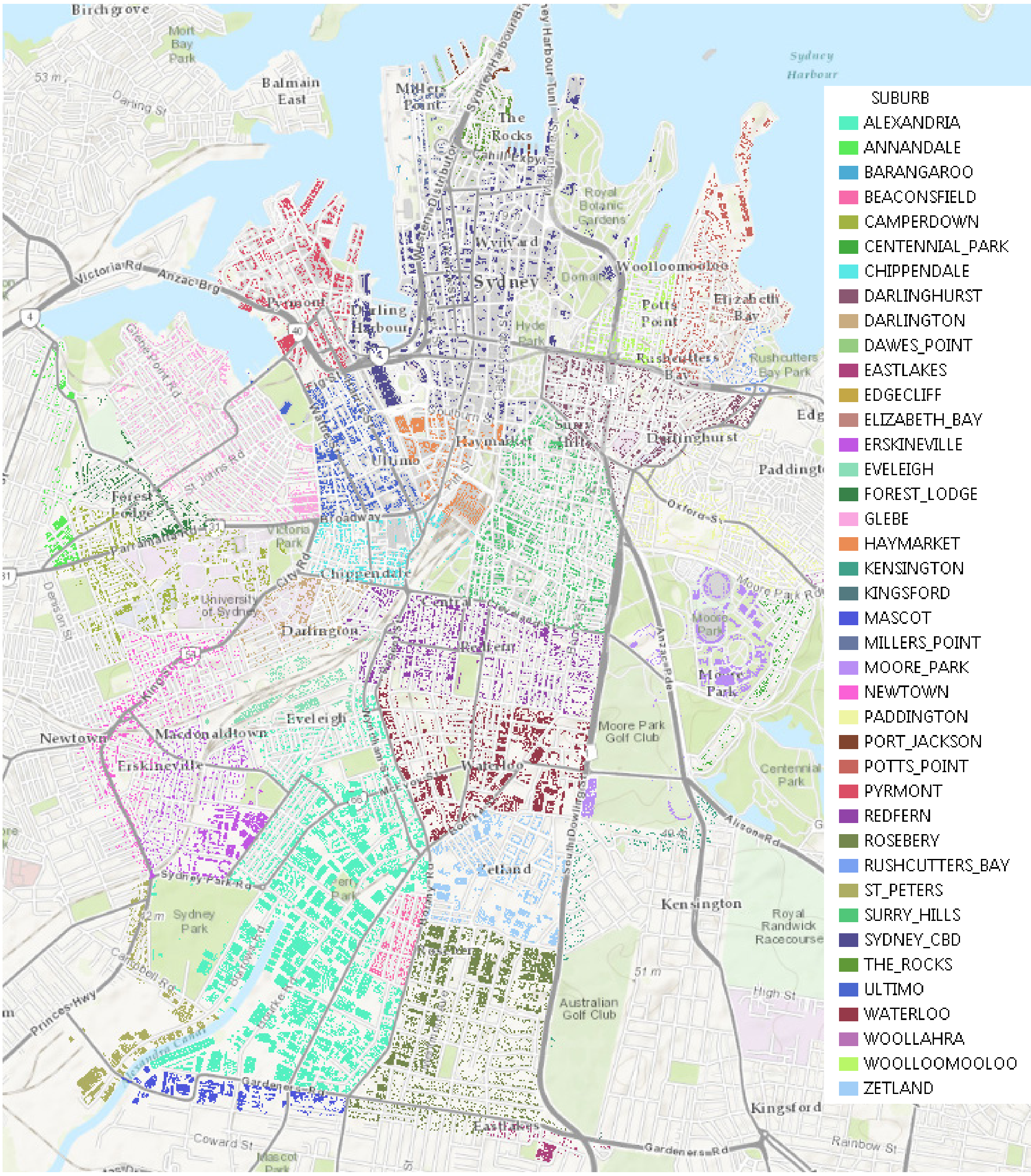


Figure 7: Sydney CBD Regions Covered by Analysis

Method 1: Insolation Limit

The first method utilised to determine suitable roof planes was based on a minimum level of insolation. The minimum value was set at an annual average insolation of **3.62 kWh/m²/day**. This limit was calculated as 80% of the expected level of annual insolation for a horizontal surface in Sydney, calculated as 4.53 kWh/m²/day, using the default TMY weather file for Sydney contained within the National Renewable Energy Laboratories (NREL) System Advisor Model (SAM). This limit was applied to the Solar Insolation Heat Map which was developed and calibrated as part of the APVI SPT methodology [2, 3].

Figure 9 presents an example application of the insolation limit in practice, displaying an aerial image (left), the insolation heat map (centre) and the classified insolation layer (right); classified as either above (white) or below (black) the insolation limit. As for each method in this report, a 10m² contiguous area was required for a roof plane to be determined suitable. Figure 10 presents the roof planes that were identified to meet both the insolation and 10m² contiguous area criteria for the example presented in Figure 9.

Figure 8 - Minimum distance from rooftop obstruction for 80% annual output

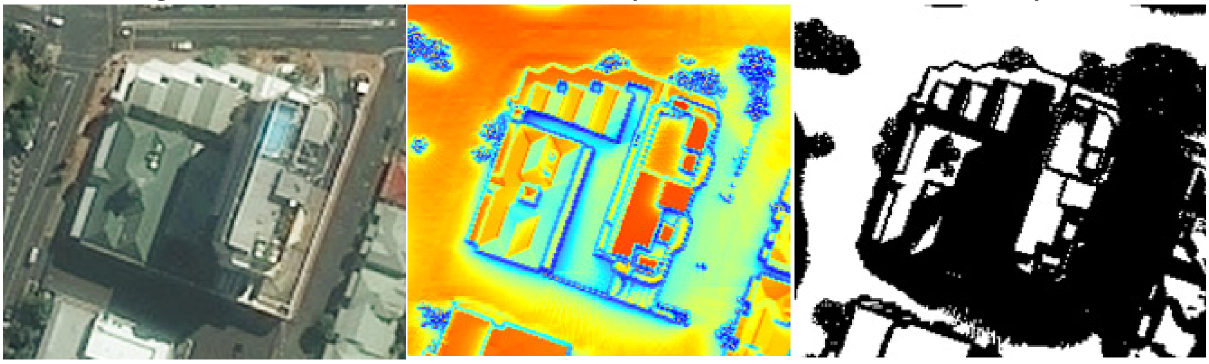


Figure 9: Example application of the Insolation limit. Areal image (left); Insolation heat map (centre); and classified Insolation layer (right)

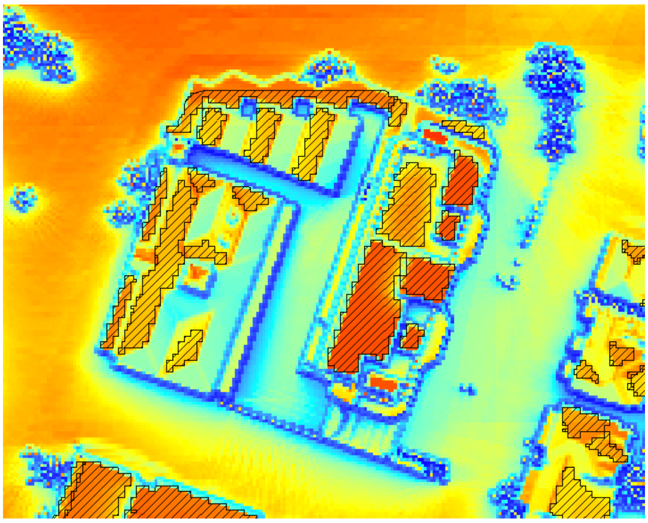


Figure 10: Example application of suitable planes (hatched areas) by the Insolation limit method.

Method 2: NREL's Hillshade and Orientation

The second method utilised to determine suitable roof planes was the method developed by NREL to assess the technical potential for rooftop PV in the United States [4]. NREL's method makes use of ArcGIS's hillshade function to determine the number of hours of sunlight received on each $1m^2$ of roof surface, across 4 representative days within a year i.e. the winter and summer solstices and the two equinoxes; similar to the shadow layers of APVI's SPT as illustrated in Figure 5.

To determine which areas met the shading criteria, NREL's method defines that roof surfaces must meet a minimum number of hours of sunlight. The limit for any location can be determined by calculating the number of hours a rooftop would need to be in sunlight to produce 80% of the energy produced by an unshaded system of the same orientation [4]. For the location of Sydney, the value was determined to be **19.58 hours** across the 4 representative days, i.e. a minimum of 4.9 hrs/day of sunlight across the year.

In addition to the hillshade limit, NREL's method also excludes roof planes based on orientation. In NREL's method all roof planes facing northwest through northeast (i.e. 292.5 - 67.5 degrees for northern hemisphere locations) were considered unsuitable for PV. For southern hemisphere locations the equivalent exclusion would be orientations southeast through southwest (i.e. 112.5 – 247.5 degrees) as per Figure 11. Again as for each method in this report, a $10m^2$ contiguous area is also required by NREL's methodology.

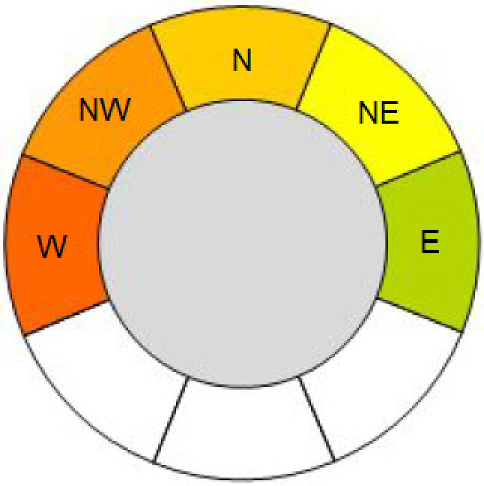


Figure 11: Rooftop azimuths included in final suitable planes for the Southern Hemisphere

Figure 12 presents an example application of NREL's hillshade and orientation limit in practice. For this particular example there is reasonable agreement between the surfaces determined as suitable for PV deployment from the two methods i.e. Figure 10 vs Figure 12. This is not always the case as evident in the example presented in Figure 13, which illustrates how the insolation limit method can define roof planes orientated southeast through southwest as suitable planes if the annual insolation meets the limit requirement.

Figure 12: Example application of the hillshade limit (left) with the suitable planes overlayed (right)

Figure 13: Comparison between roof planes defined as suitable by the insolation method (both - yellow) and NREL's hillshade and orientation method (Left – orange)

Input Data Source: AAM 3D Building Model vs. LiDAR data

The other variable that affected the sensitivity of the estimated PV potential was the input data source. Two input data sources were available for use in this analysis:

1. The DSMs and 3D building models from AAM, which were utilised to generate the APVI SPT,
2. NSW LPI LiDAR data for Sydney North – 2013 dataset sourced NSW Land and Property Information.

The application of the PV potential analysis was applied identically to both input data sources.

Generally, Figure 14 demonstrates that there is general agreement between the roof planes identified as suitable via the two input data sources. However the figure also illustrates how the analyses undertaken with the LiDAR data set excludes a greater proportion of roof surfaces.

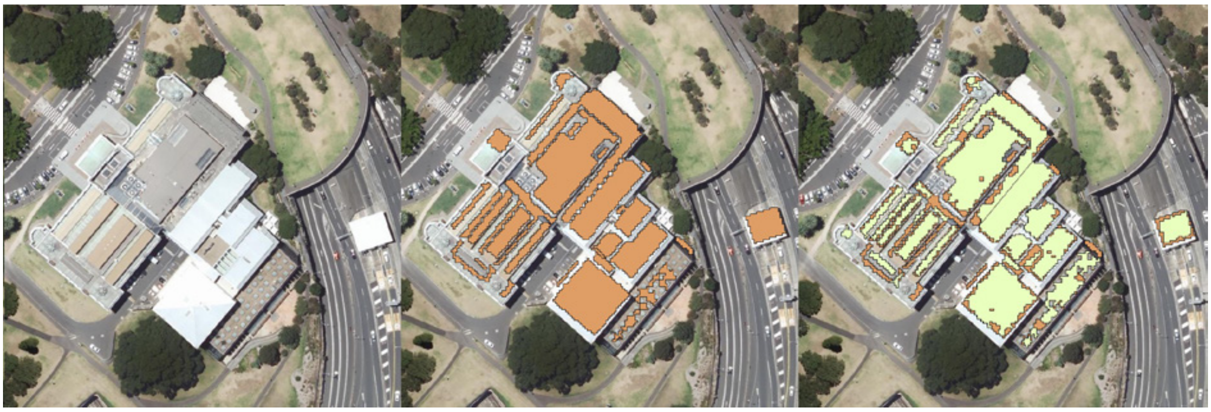


Figure 14: Example of good agreement between the two input data source for large buildings. Aerial image (Left), AAM 3D buildings with NREL method (centre); NSW LPI LiDAR with NREL method (Right)

Calculation of PV Capacity, Annual Yield and CO_2-e Emission Reductions

After suitable roof planes have been identified, the PV capacity and annual yield for each roof surface can be calculated. The DC PV capacity (otherwise known as system size) was calculated as per APVI's SPT methodology [2] using the DC size factor and array spacing methodologies [5]. The relevant equations for this method can be found here.

Generally, the method assumes a fixed DC size factor of **156.25 W/m^2** (i.e. a 250W module with dimensions of 1m x 1.6m) for flush mounted arrays, and a variable DC size factor for rack mounted PV arrays. For rack mounted arrays, the DC size factor is a function of the PV array tilt and orientation and the tilt and orientation of the underlying roof surface. Figure 15 presents the equivalent useable roof area, which is analogous to the DC size factor, for a 15 degree tilted north facing PV array in Sydney, as a function of the tilt and orientation of the underlying roof surface. For an absolutely flat roof, Figure 15 indicates a useable area of 70%, analogous to a DC size factor of 110 W/m^2. In comparison, NREL's method assumes a fixed ratio of module to roof area of 70% for flat roof surfaces.

As per NREL's method to calculate the PV potential in the United States [4], this analysis has assumed that rack mounted arrays will be installed on flat and relatively flat roof surfaces. For consistency with NREL's method, **flat roofs have been defined as roof surfaces with a tilt <= 9.5 degrees** and the **tilt angle of the rack mounted arrays were defined as 15 degrees**.

Similarly, for tilted roof surfaces > 9.5 degrees, **an additional module to roof area ratio of 0.98** was assumed in the NREL method to reflect 1.27cm of spacing between each module for racking clamps. This assumption was also applied in this study.

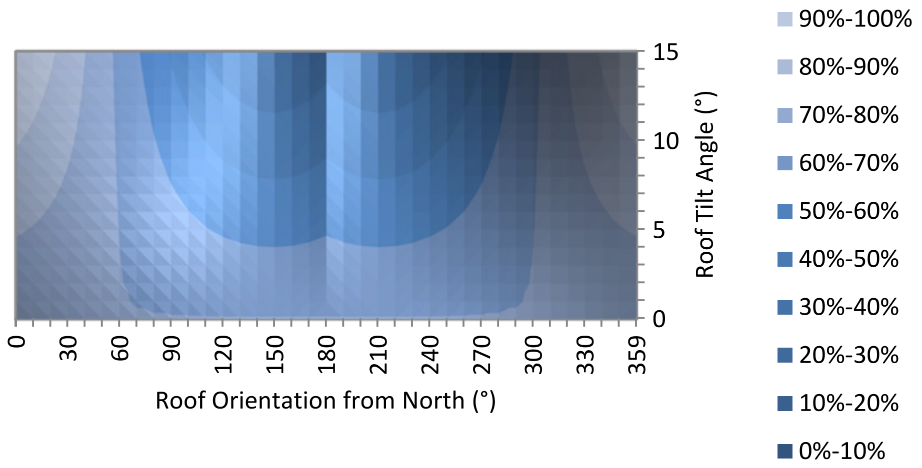


Figure 15: Percentage of useable roof area as a function of roof tilt and orientation for a 15 degree North facing array in Sydney

The PV yield was calculated using APVI's SPT methodology as detailed here. This method multiplies the calculated DC PV capacity by the average annual level of insolation calculated on the roof surface and by a **derating factor of 0.77**. The derating factor accounts for all the typical PV losses of temperature, soiling, wiring, mismatch, manufacturing module tolerance and inverter efficiency. This simplified method shows good agreement with detailed hourly PV performance simulations undertaken in NREL's SAM as illustrated in Appendix A.

The potential contribution of rooftop PV generation to electricity load in the Sydney CBD area was assessed by comparison to the annual energy consumption seen by Ausgrid in the City of Sydney LGA (Table 5), the same area over which rooftop PV potential was modelled. The total annual demand for the LGA in 2015-16 was 3,588 GWh.

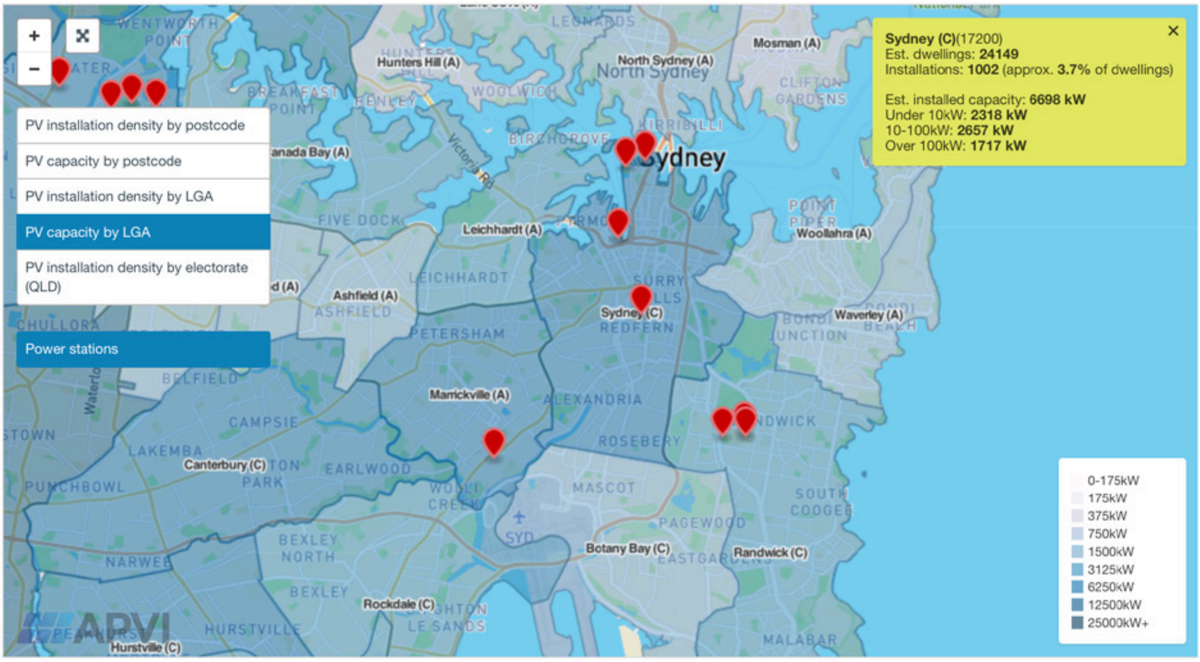
Table 5: Load Data for the City of Sydney

Customer Group	Demand (MWh)
Residential	408,669
Commercial	770,078
Large Commercial	2,409,442
Total	3,588,189

Source: Ausgrid's 2015-16 Summary Community Electricity Report

In order to assess the potential for additional rooftop PV in the Sydney CBD, and associated emissions reductions and electricity savings, data on existing PV capacity in the City of Sydney LGA area from the APVI Solar Map was used (Figure 17). This data is sourced from the Clean Energy Regulator's database of PV systems registered under the Renewable Energy Target scheme, which is a near complete record of PV systems installed in Australia. The total existing PV capacity is estimated to be around 6.7 MW, made up of around 1000 PV systems. This includes several large PV systems at the Sydney Theatre Company, Barangaroo, Australia Post Strawberry Hills, and the Sydney Renewable Power Company, with a total of 1.7 MW capacity. These are shown as red pointers in Figure 17.

Figure 16: PV Capacity in the City of Sydney LGA



Source: APVI Solar Map

Finally, the annual CO_2-equivalent emission reductions are calculated by multiplying the estimated annual yield by an appropriate emissions factor for New South Wales as sourced from the 2016 National Greenhouse Account Factors. The relevant value for New South Wales was **0.84 kg CO_2-e/kWh which is reduced by 0.045 kg CO_2-e/kWh to account for the embodied carbon emissions from the manufacture, installation, operation and decommissioning of the PV systems**. The value of 45 g CO_2-e/kWh of electricity produced was sourced from the PV LCA Harmonization Project results found in [6], which standardised the results from 13 life cycle assessment studies of PV systems with crystalline PV modules, assuming system lifetimes of 30 years.

Results

Table 6 presents a summary of the results of the rooftop suitability assessment for the Sydney CBD. Results are presented for the average and standard deviation (Std) of the sensitivity analysis undertaken by assessing the two input data sources and the two calculation methodologies. A comprehensive breakdown of the results by method and input data source are presented in Appendix B.

The conservative estimate suggests the useable area suitable for rooftop PV deployment (the ratio between the area of PV panels that could be accommodated and the total roof area) is 25% corresponding to 393 MW of PV potential with an expected annual yield of 507 GWh. The equivalent CO_2 emission savings are 403 kt per year. These values were calculated using the LiDAR data as the input data source in conjunction with NREL’s hillshade and orientation method.

The average of the two methods indicated that an area equal to 40% of the available roof surfaces could be used to accommodate PV, corresponding to 619 MW of PV potential with an expected annual yield of 777 GWh, with corresponding potential CO_2-equivalent emission savings of 618 kt per year.

The average estimate of PV generation (777 GWh) equates to around 22% of the 3,588 GWh of load in the CBD area. There is an estimated 6.7 MW of existing PV capacity installed on Sydney CBD rooftops, around 1% of the potential capacity. Almost all of the electricity generation and emissions savings calculated would therefore be additional.

The rooftops with the largest PV potential in Sydney have been mapped (Figure 17 below). More detailed images appear in the appendix.

Table 6: Summary of results categorised by the Sydney City Suburbs

Sydney Suburb	Percentage Useable Area		Capacity (MW)		Yield (GWh)	
	Average	Std	Average	Std	Average	Std
All	39.64%	14.39%	619.25	224.83	777.12	270.05
Alexandria	49.57%	10.30%	109.57	22.77	143.39	27.95
Annandale	35.94%	11.28%	6.40	2.01	8.01	2.36
Barangaroo	53.72%	19.01%	0.27	0.10	0.34	0.12
Beaconsfield	43.60%	15.18%	4.84	1.68	6.05	2.00
Camperdown	37.92%	13.96%	20.59	7.58	25.53	9.09
Centennial Park	30.48%	12.25%	3.64	1.46	4.45	1.75
Chippendale	38.62%	16.52%	10.54	4.51	13.02	5.45
Darlinghurst	32.44%	14.57%	19.55	8.78	23.85	10.43
Darlington	38.40%	17.11%	8.15	3.63	10.22	4.38
Dawes Point	31.38%	9.94%	1.21	0.38	1.45	0.45
Eastlakes	53.64%	21.43%	3.15	1.26	3.99	1.52
Edgecliff	44.87%	16.56%	0.02	0.01	0.03	0.01
Elizabeth Bay	48.04%	31.79%	6.46	4.27	7.98	5.17
Erskineville	40.56%	12.10%	18.21	5.43	22.89	6.50
Eveleigh	40.96%	15.23%	9.23	3.43	11.46	4.02
Forest Lodge	35.43%	13.23%	7.92	2.96	9.79	3.55
Glebe	30.52%	10.34%	24.50	8.30	30.08	9.82
Haymarket	36.73%	17.11%	12.11	5.64	14.90	6.66
Kensington	35.69%	11.36%	4.83	1.54	5.88	1.81
Kingsford	36.93%	10.67%	0.03	0.01	0.04	0.01
Mascot	59.19%	16.24%	11.01	3.02	14.29	3.75
Millers Point	34.49%	15.64%	3.52	1.60	4.24	1.85
Moore Park	45.39%	10.74%	15.98	3.78	20.37	4.58
Newtown	31.14%	15.19%	18.60	9.07	22.80	10.75
Paddington	30.27%	11.82%	14.31	5.59	17.45	6.63
Port Jackson	45.62%	20.52%	1.58	0.71	1.91	0.83
Potts Point	39.30%	17.02%	12.96	5.61	16.00	6.72
Pyrmont	40.59%	18.41%	21.54	9.77	26.69	11.71
Redfern	38.74%	14.28%	25.94	9.56	31.82	11.37
Rosebery	48.34%	12.53%	47.40	12.28	60.08	14.75
Rushcutters Bay	35.87%	19.36%	2.34	1.26	2.88	1.51
St Peters	50.60%	12.04%	12.09	2.88	15.73	3.49
Surry Hills	34.79%	16.43%	30.65	14.47	37.67	17.41
Sydney CBD	28.89%	17.95%	47.52	29.52	57.57	34.74
The Rocks	27.14%	12.15%	3.41	1.53	4.19	1.81
Ultimo	37.69%	15.24%	18.16	7.34	22.59	8.81
Waterloo	49.98%	19.09%	33.10	12.64	42.10	15.50
Woollahra	25.76%	11.65%	0.46	0.21	0.56	0.24
Woolloomooloo	39.87%	18.85%	9.14	4.32	11.08	5.13
Zetland	50.18%	17.57%	18.32	6.41	23.77	7.91

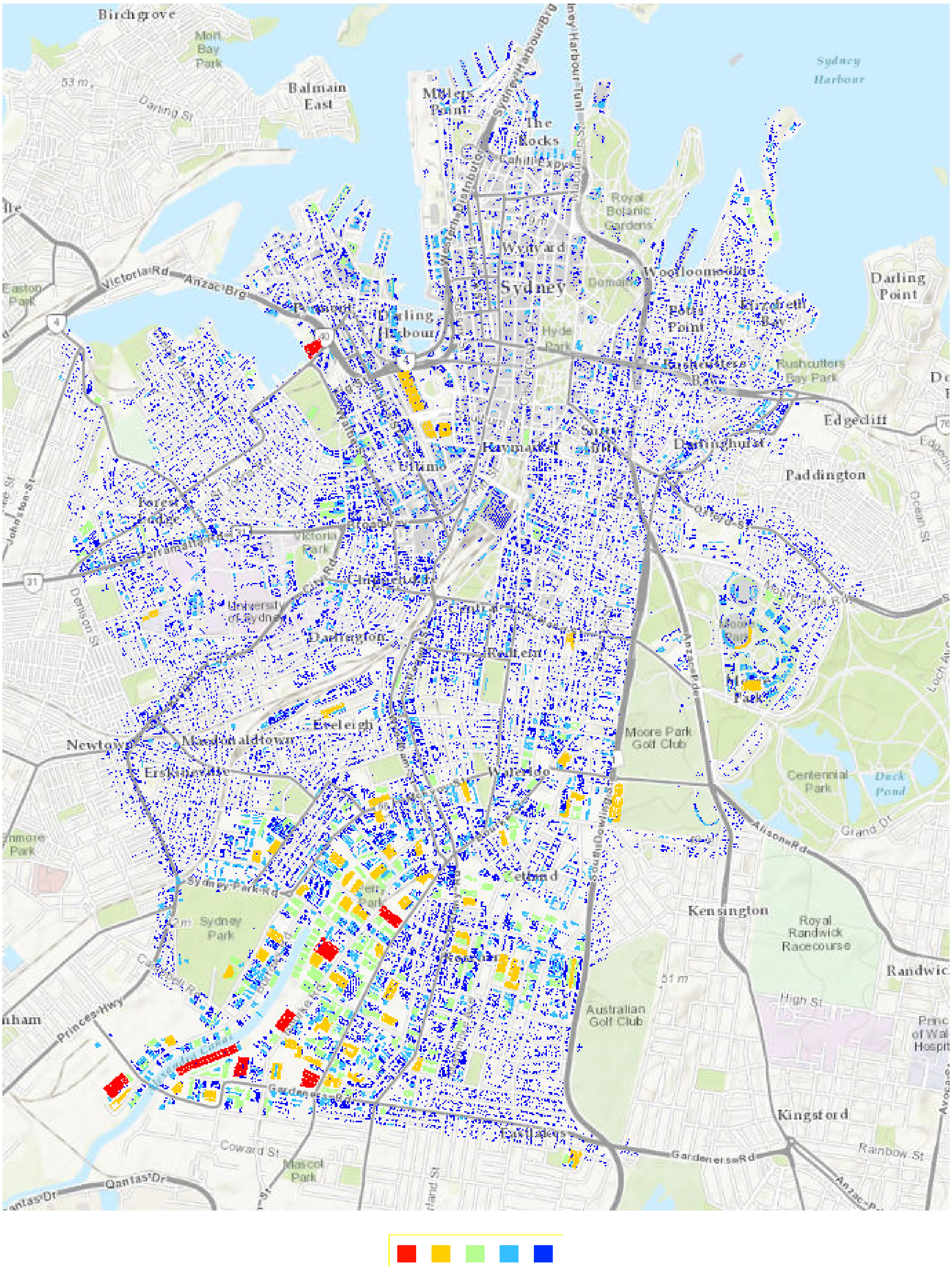


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Figure 17: Rooftops with Largest PV Potential in Sydney CBD

Case Studies of Landmark Buildings

This section of the report details the methodology and the results for a detailed assessment of the PV potential for 3 landmark Sydney buildings: the Art Gallery of New South Wales, Central Station, and the Overseas Passenger Terminal at Circular Quay. Apart from being well-known public buildings, these were selected for their varied roof profiles in order to demonstrate the solar potential of disparate types of building.

Methodology

The case studies were assessed by combining GIS analysis with a visual assessment of the building roof profiles using aerial imagery, in order to account for rooftop obstructions and other building-specific anomalies below the resolution of the AAM and Lidar data. The sensitivity of the results was tested against the building level outputs of the 4 methodologies described above.

Assessment of Roof Area

An initial assessment of developable roof planes was made by applying *Method 1* above to the AAM Building Model. This method and dataset identifies continuous areas greater than $10m^2$ receiving 80% of the annual insolation for an unshaded horizontal surface (3.62 $kWh/m^2/day$) and was chosen as it gives the largest area of the 4 approaches to serve as a basis for further refinement.

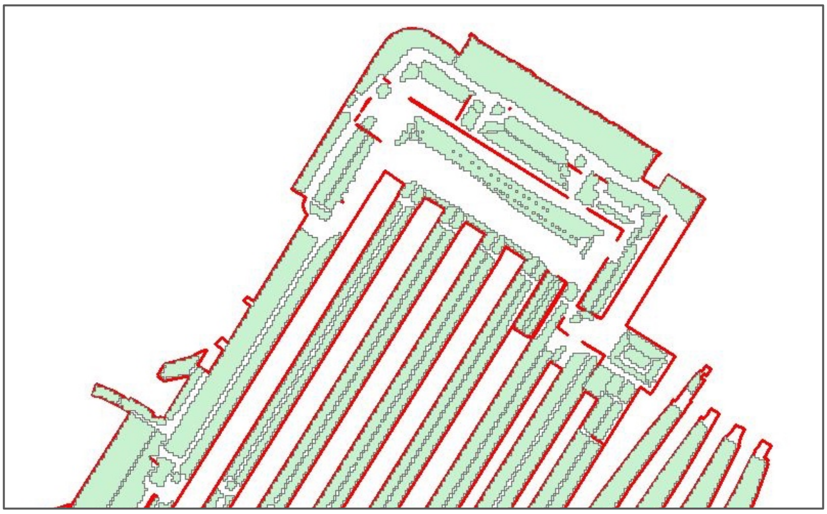

Figure 18: Developable Planes with > 3.62KWh/m^2/day

The roof surfaces were then assessed visually, using imagery from multiple sources: aerial plan view images from *Nearmap* and *Google Earth,* multiple viewpoint aerial imagery from *Nearmap*, and photographs sourced from the internet. Unsuitable surfaces (roadways, roof terraces, platforms, skylights, etc.) were identified and excluded from the usable roof area, as shown in Figure 19

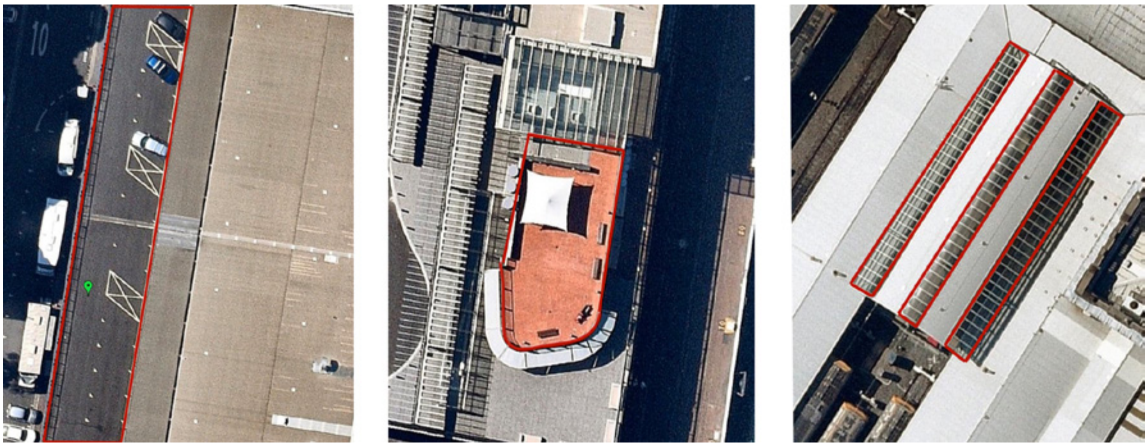

Figure 19: Examples of unsuitable surfaces (a) roadway, (b) public terrace, (c) skylights

Small rooftop obstructions, perimeter walls, overhead gantries, etc. below the resolution of the GIS data were identified and their height estimated using multiple viewpoint aerial imagery. (see Figure 20)

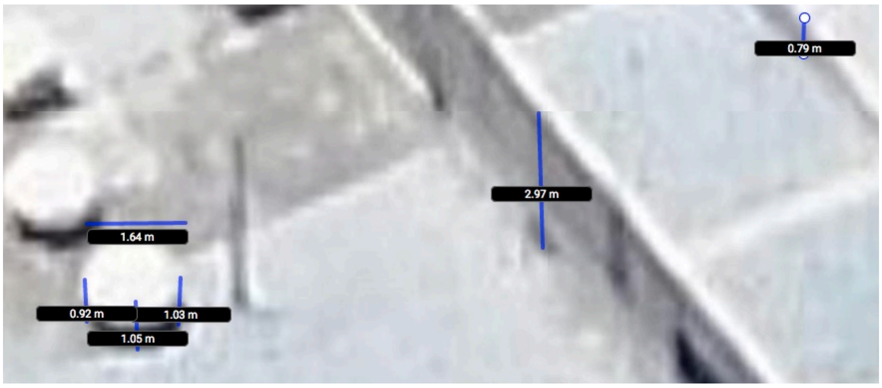

Figure 20: Estimation of rooftop obstructions

The shading on a PV module at a range of distances from obstructions of different heights was modelled using the 3D shading calculator in NREL's System Advisor Model (SAM) and the impact on annual output for a horizontal PV panel in Sydney (using the Sydney RMY weather file from Energy Plus[7]) was calculated. Figure 21 shows the results for a small range of distances and wall heights. Using this data, additional roof area proximate to rooftop obstructions was excluded if annual output was estimated to be less than 80% of an unshaded horizontal panel.

As Australia has no regulation for minimum access pathways through and around rooftop PV installations, the proportion of roofspace allocated for these will depend on the installer's requirements for installation and maintenance. For this analysis, a 1m wide perimeter was allowed around arrays, except those on easily accessible low-level surfaces. For all the buildings, the arrangement of arrays around the roof architecture created additional 'natural' access pathways.

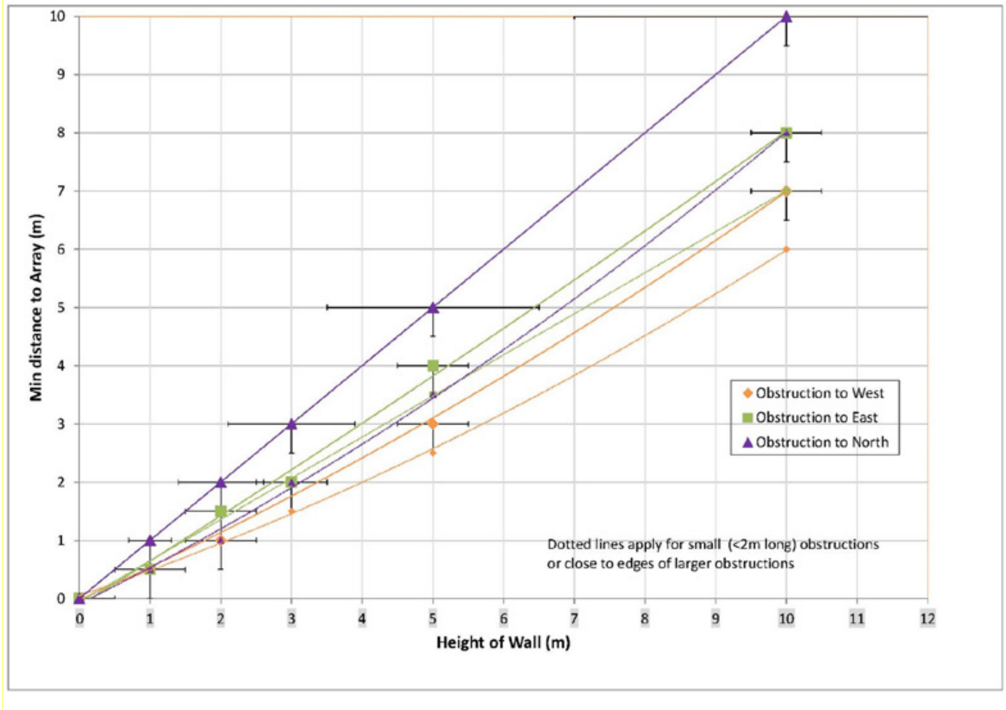

Figure 21: Nearest distance to obstruction to give 80% annual output

Calculation of Array Size and PV Capacity

Nearmap's Solar Tool was used to arrange 1.6m x 1.0m PV panels on the usable roofspace. The slope of each roof plane was determined from the GIS building slope layer. For sloping roofs, the panels were positioned flush with the roof in order to avoid self-shading and maximise generation. For flat roofs, panels were orientated towards North (i.e. between 045°and 315°) at a tilt angle of 5°. Although this arrangement causes individual PV panels to operate at sub-optimal efficiency, it enables PV installation over a greater proportion of the roof than a rack-mounted arrangement, and so maximises total generation capacity from a given roof area. The power capacity of each array was calculated using a nominal output of 250W per module (equivalent to a DC size factor of 156.25 W/m^2).

Calculation of Annual Yield and Sensitivity Analysis

An initial value for the predicted annual energy output of each sub-array was calculated for appropriate orientation and tilt using SAM's PVWatts model and a derate factor of 0.77, and these were summed to give the output for each building. Although roof planes with significant shading have already been excluded, this value does not take account of shading (other than self-shading due to orientation and tilt).

The PV capacity and annual yield were compared with values given by the four methodologies above - hillshade and insolation limit using AAM and Lidar datasets.

The specific yield (in kWh/kW/day) was calculated for each of the arrays, and these compared with the specific yield given by the four methodologies. A conservative estimate of the annual output of each array, accounting for shading losses, was calculated by applying the lowest of these values for specific yield to each array capacity.

Calculation of Emissions Offset

The potential CO_2-e emissions reductions from the modelled PV systems on the 3 landmark buildings were calculated by multiplying the indirect (Scope 2) emissions factor for consumption of electricity purchased from the grid in New South Wales (0.84 kg CO_2-e/kWh[8]) by the expected annual energy generation from the system, and subtracting the estimated embodied carbon emissions from the manufacture, installation, operation and decommissioning of the PV system (0.045kg CO_2-e /kWh[6])

Results

Table 7 shows the potential roof area available for PV installation on each building, based on the data and visual imagery available. For comparison, it also shows the areas of "developable planes" calculated by the 4 methodologies discussed above.

The table shows that just over half the footprint area of the 3 buildings is suitable for PV arrays. Both Central Station and the Overseas Passenger Terminal (OPT) have large areas of uncluttered and unshaded roof (although part of the OPT's footprint consists of roadway, reducing the % usable for PV), while the Art Gallery's irregular roof profile has a smaller proportion unshaded.

Table 7: Available roof areas by different methodologies

Site	**Building Footprint (m2)**	**Potential Array Area from visual assessment (m2)**	**Array Area / Footprint**	**3D Model Insolation limit**	**3D Model Hillshade**	**Lidar Insolation limit**	**Lidar Hillshade**	**Average of 4 Methods**
Central Station	31403	**19600**	62%	24642	16796	18640	14665	**18686**
Art Gallery NSW	8456	**3158**	37%	4442	4457	4082	3884	**4216**
OPT	5760	**2421**	42%	3011	3008	2367	2310	**2674**
Totals	**45619**	**25179**	**55%**	**32095**	**24260**	**25089**	**20859**	**25576**

The potential array areas determined by visual analysis sit within the range of developable planes determined by the 4 methodologies above. Figure 22 shows the developable planes on the OPT by each methodology. In general, for large flat roofs, the methods using the Lidar data appear to slightly underestimate the usable area by breaking up large areas of usable roof into smaller roof planes. Conversely, the 3D model methodologies may slightly overestimate usable areas as they do not consider small obstructions, localised shading issues, access pathways and the physical arrangement of rectangular panels on irregularly shaped roof planes. Overall, the visual analysis gives good agreement with the average value of the 4 methods, except for the Art Gallery where additional roof areas have been excluded because of potential access and installation issues caused by the complex rooftop geometry.

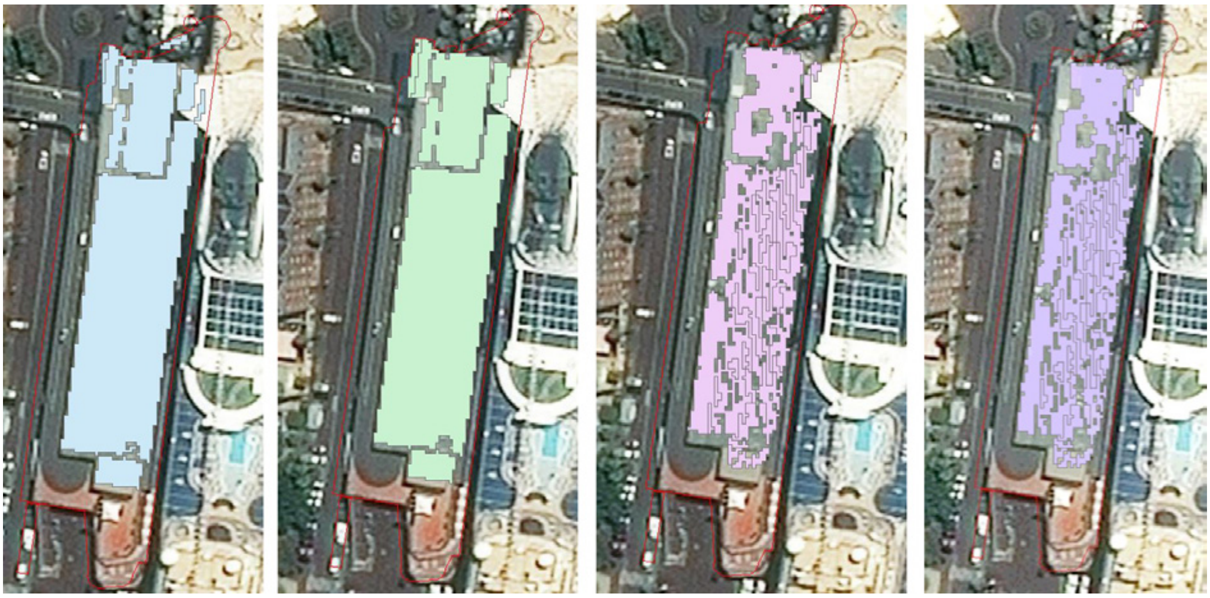

Figure 22: Developable Planes of OPT using 4 methodologies. a) 3D-model & insolation limit, b) 3D-model & hillshade, c) Lidar & insolation limit, d) Lidar & hillshade

Table 8 shows the projected array capacity and expected annual energy production for the potential PV arrays illustrated in Figure 2 – 4 above and Figure 23 – 25 below.

(As this assessment was carried out remotely, there may be additional physical, structural and aesthetic constraints on the available roof area that have not been considered here. The PV arrays shown and the results in the tables are indicative of the solar potential of these roofs but do not constitute a concrete proposal or system design.)

Table 8: PV Capacity and Annual Energy Production

Site	PV Capacity (kW_{peak})	Annual Energy Production (w/o shading) (MWh/year)	Average Yield across developable planes (kWh/kW/day)	Annual Energy Production (adjusted) (MWh/year)
Central Station	3063	3902	3.49	3599
Art Gallery NSW	494	642	3.56	589
OPT	378	476	3.45	461

Table 9 shows the potential PV capacity and Table 10 shows the annual yield calculated by each of the 4 methodologies above, and using 2 installation approaches for 'flat' (<9.5° slope) roofs: flush mounting (with minimum 5° tilt) and North-facing frame mounting at 15° tilt. Greater yield is obtained on flat roofs by flush-mounting but at the cost of a larger PV array and lower yield per kW of PV installed. Both the PV capacity and yield obtained by the visual assessment show good agreement with the average values calculated by the 4 methodologies above for flush mounted panels, except for the restrictions on the Art Gallery mentioned above.

Table 9: Case Study PV Capacity (kW) – comparison of methodologies

	Flush Mounted						Frame Mounted				
Site	**Visual Assessment**	3D Model - Insolation	3D Model - Hillshade	Lidar - Insolation	Lidar - Hillshade	**Average Flush**	3D Model - Insolation	3D Model - Hillshade	Lidar - Insolation	Lidar - Hillshade	**Average Frame Mounted**
Central Station	**3063**	3918	2658	2915	2285	**2944**	3565	2280	2324	1636	**2451**
Art Gallery NSW	**494**	688	688	629	598	**650**	479	485	401	373	**435**
OPT	**378**	467	466	364	355	**413**	258	256	267	227	**252**
Totals	**3935**	**5072**	**3811**	**3907**	**3237**		**4302**	**3022**	**2993**	**2236**	

Table 10: Case Study Annual Yield (MWh) – comparison of methodologies

	Flush Mounted							Frame Mounted				
Site	**Visual Assessment / SAM** (w/o shading)	**Visual Assessment / SAM** (adjusted for shading)	3D Model - Insolation	3D Model - Hillshade	Lidar - Insolation	Lidar - Hillshade	**Average Flush**	3D Model - Insolation	3D Model - Hillshade	Lidar - Insolation	Lidar - Hillshade	**Average Frame Mounted**
Central Station	**3902**	**3599**	4604	3188	3446	2733	**3493**	4267	2832	2852	2083	**3008**
Art Gallery NSW	**642**	**589**	823	821	755	720	**780**	617	623	532	499	**568**
OPT	**476**	**461**	569	567	443	433	**503**	350	347	341	299	**334**
Totals	**5019**	**4648**	**5996**	**4576**	**4644**	**3885**		**5234**	**3802**	**3725**	**2881**	

Table 11 presents the estimated carbon offsets for each system and shows that these three buildings alone could save an estimated 3.7 kilotonnes of carbon emissions each year and could supply the equivalent of 691 households, based on the average 2014 electricity demand of a New South Wales household (in 2014) being 6730 kWh [1].

Table 11: Carbon offset and household energy equivalents

Site	Expected Annual Energy Production (MWh/year)	Emissions Offset (Tonnes CO_2-e / year)	Average NSW household equivalent
Central Station	3599	2861	535
Art Gallery NSW	589	468	87
OPT	461	366	68
Totals	**4648**	**3695**	**691**

Before & After Illustrations

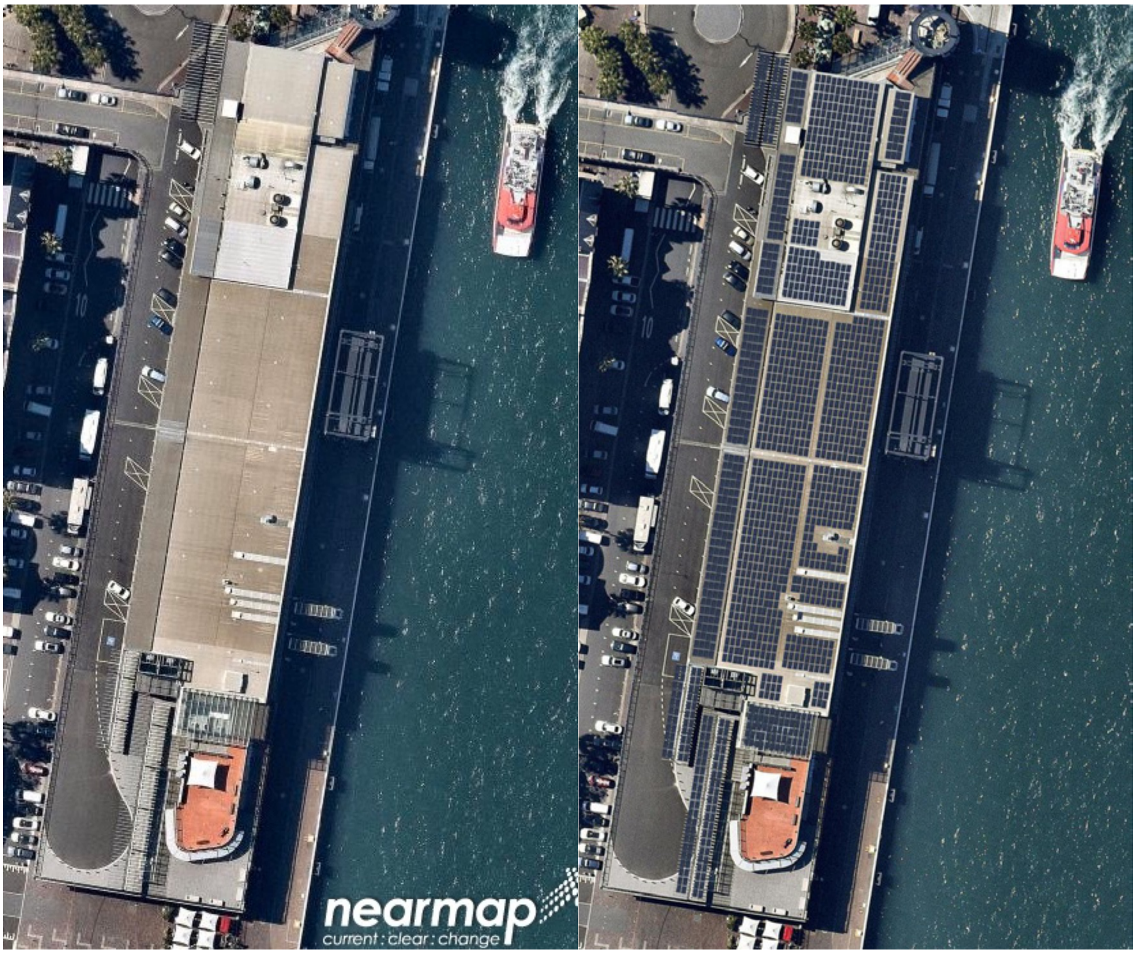

Figure 23: Overseas Passenger Terminal, now and with a possible PV array

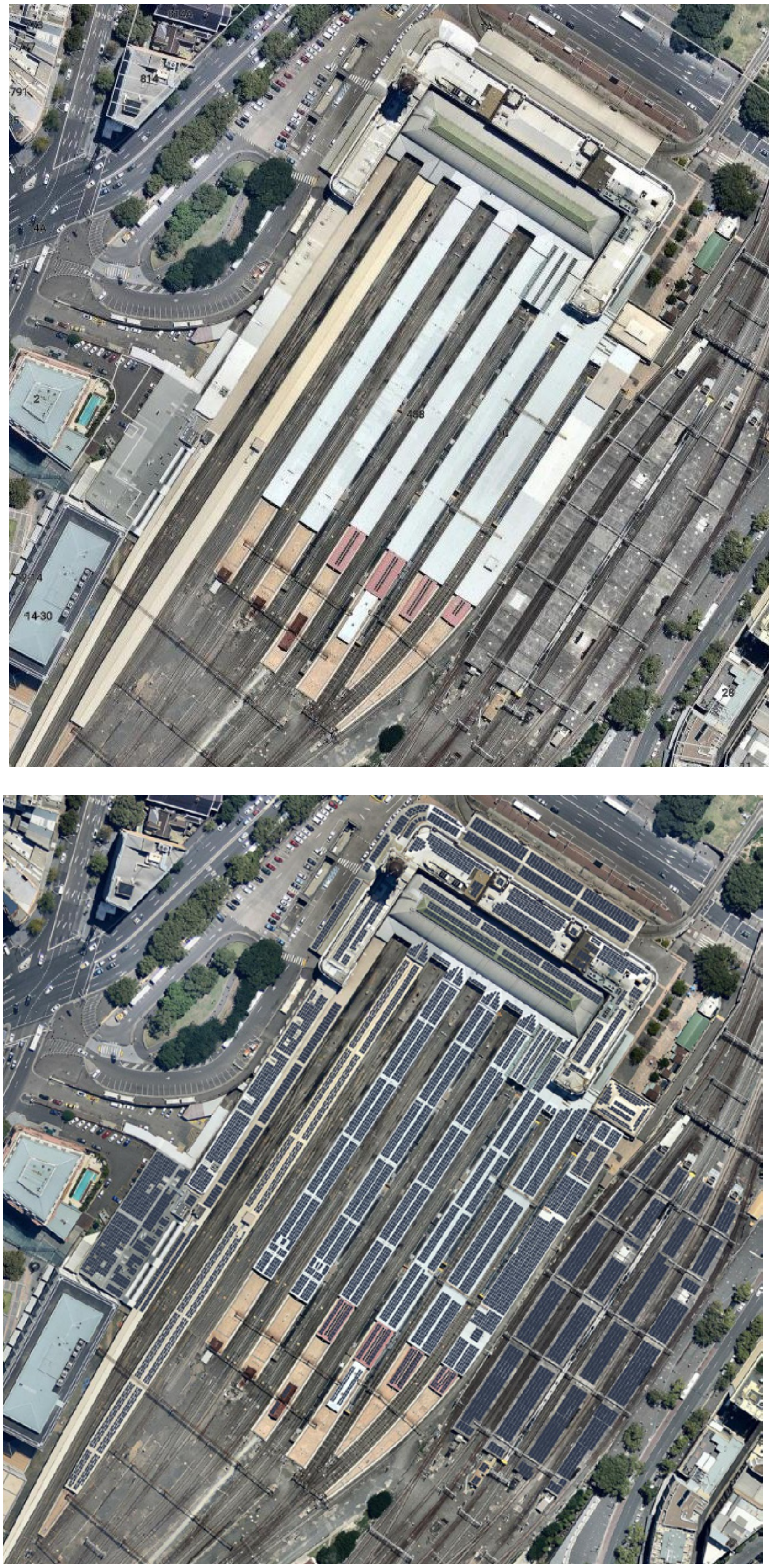

Figure 24: Central Station, now and with a possible PV array

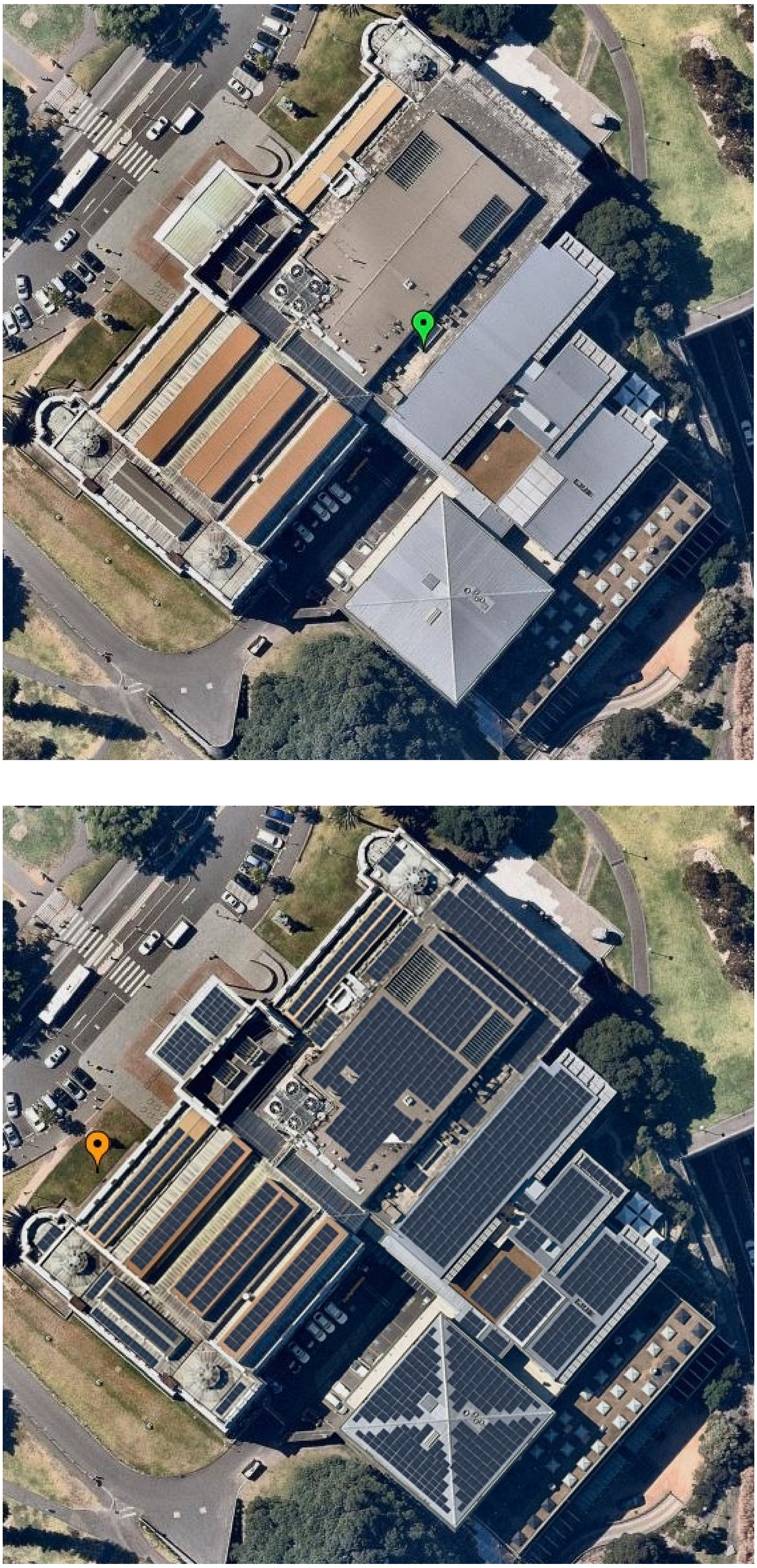

Figure 25: Art Gallery of NSW, now and with a possible PV array

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1. Acil Allen Consulting, *Electricity Benchmarks final report v2 - Revised March 2015*. 2015, Australian Energy Regulator.
2. Copper, J.K. and A.G. Bruce. *APVI Solar Potential Tool - Data and Calculations*. 2014; Available from: http://d284f79vx7w9nf.cloudfront.net/assets/solar_potential_tool_data_and_calcs-2dc0ced2b70de268a29d5e90a63432d7.pdf.
3. Copper, J.K. and A.G. Bruce. *Validation of Methods Used in the APVI Solar Potential Tool*. 2014; Available from: http://apvi.org.au/solar-research-conference/wp-content/uploads/2015/04/1-Copper_APVI_PVSystems_PeerReviewed.pdf.
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5. Copper, J.K., A.B. Sproul, and A.G. Bruce, *A method to calculate array spacing and potential system size of photovoltaic arrays in the urban environment using vector analysis.* Applied Energy, 2016. **161**: p. 11-23.
6. Hsu, D.D., et al., *Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation.* Journal of Industrial Ecology, 2012. **16**: p. S122-S135.
7. *Energy Plus Weather Data - Southwest Pacific Region*. Available from: https://energyplus.net/weather-region/southwest_pacific_wmo_region_5/AUS%20%20.
8. Department of Environment and Energy, *National Greenhouse Accounts Factors*. 2016.

Appendix A – Comparison between APVI SPT Simple PV Performance Method vs. Detail Hourly Simulation of PV Performance in NREL's System Advisor Model

Figure 26 presents a comparison between the calculated annual yields using APVI SPT simplified method versus detailed hourly simulations of PV performance using NREL's SAM PVWatts module with default settings. The results highlight the similarity in the calculated values, and demonstrate how the annual yield can be calculated using a simplified methodology, which requires as input only the annual or monthly averages of surface insolation in kWh/m^2/day. The simplified APVI SPT methodology enables geospatial calculation of yield for each identified roof surface.

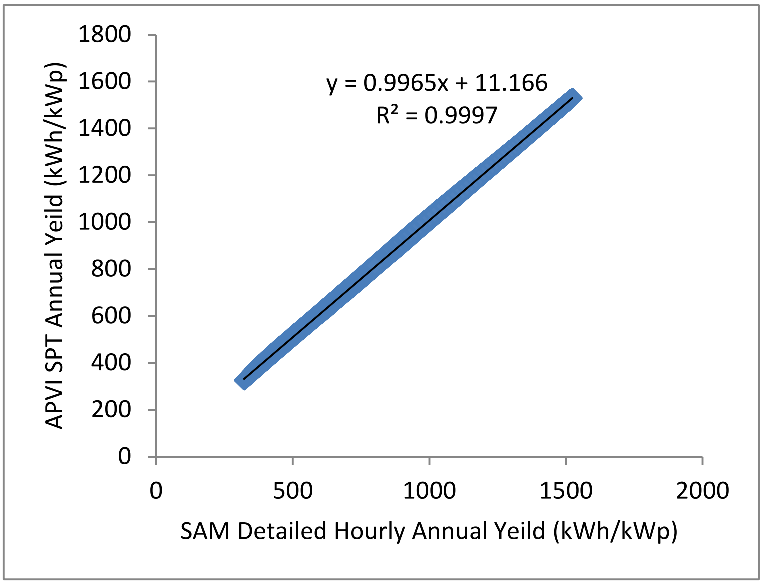


Figure 26: Correlation between APVI SPT simplified method to calculate annual yield from annual average insolation vs. detailed hourly simulations of PV performance from NREL's SAM. Results presented for each 1 degree combination of tilt (0-90°) and orientation (0-360°).

Table 12: Detailed results of rooftop suitability calculated using AAM DSM and 3D buildings

Sydney Suburb		Method 1 - Insolation Limit (3.62 kWh/m2/day) - 3D Buildings				Method 2: NREL Hillshade E/NE/N/NW/W (19.58) - 3D Buildings			
	Total Area (ha)	Developable (ha)	% Useable	Capacity (MW)	Yield (GWh)	Developable (ha)	% Useable	Capacity (MW)	Yield (GWh)
All	999.71	541.40	54.16%	845.94	1046.63	496.37	49.65%	775.59	968.73
Alexandria	141.46	86.07	60.84%	134.49	173.32	78.34	55.38%	122.40	160.18
Annandale	11.40	5.59	49.04%	8.74	10.72	4.69	41.09%	7.32	9.16
Barangaroo	0.32	0.22	69.36%	0.35	0.44	0.23	70.84%	0.36	0.44
Beaconsfield	7.10	4.36	61.32%	6.81	8.34	3.59	50.54%	5.61	7.05
Camperdown	34.75	18.02	51.87%	28.16	34.52	16.58	47.72%	25.91	32.04
Centennial Park	7.64	3.26	42.65%	5.09	6.15	3.00	39.19%	4.68	5.76
Chippendale	17.47	9.44	54.02%	14.74	18.02	9.02	51.62%	14.09	17.40
Darlinghurst	38.57	18.10	46.91%	28.28	34.14	16.52	42.82%	25.81	31.37
Darlington	13.59	7.65	56.31%	11.96	14.74	6.74	49.57%	10.52	13.15
Dawes Point	2.47	1.07	43.21%	1.67	1.98	0.87	35.20%	1.36	1.64
Eastlakes	3.75	2.85	76.00%	4.46	5.56	2.54	67.76%	3.97	5.02
Edgecliff	0.03	0.02	59.30%	0.03	0.04	0.02	59.11%	0.03	0.04
Elizabeth Bay	8.60	6.44	74.92%	10.07	12.34	6.55	76.15%	10.23	12.56
Erskineville	28.74	15.39	53.55%	24.04	29.79	13.69	47.63%	21.39	26.82
Eveleigh	14.42	8.83	61.21%	13.79	16.74	6.20	42.98%	9.68	12.20
Forest Lodge	14.31	7.10	49.58%	11.09	13.53	6.23	43.50%	9.73	12.06
Glebe	51.38	21.70	42.24%	33.91	41.02	18.39	35.80%	28.74	35.41
Haymarket	21.09	11.51	54.55%	17.98	21.93	10.14	48.09%	15.85	19.21
Kensington	8.66	4.14	47.84%	6.47	7.77	3.66	42.27%	5.72	7.01
Kingsford	0.05	0.02	47.90%	0.04	0.05	0.02	39.21%	0.03	0.04

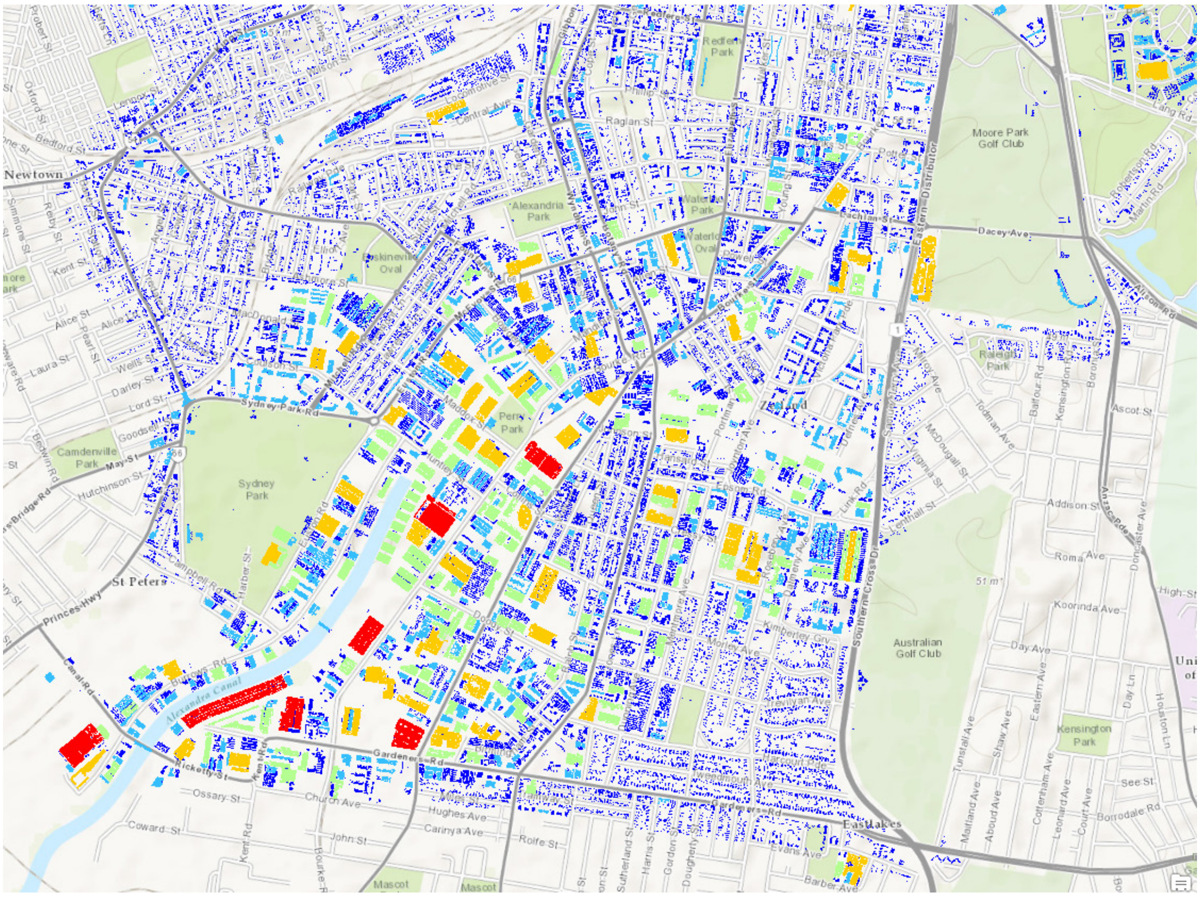
Mascot	11.90	9.02	75.74%	14.09	18.07	8.37	70.31%	13.08	16.91
Millers Point	6.53	3.03	46.45%	4.74	5.65	3.23	49.45%	5.05	6.01
Moore Park	22.54	13.17	58.44%	20.58	25.86	11.16	49.51%	17.44	22.27
Newtown	38.23	18.50	48.38%	28.90	34.78	14.98	39.19%	23.41	28.83
Paddington	30.27	12.98	42.89%	20.28	24.42	11.36	37.53%	17.75	21.68
Port Jackson	2.22	1.55	69.90%	2.43	2.87	1.21	54.45%	1.89	2.31
Potts Point	21.10	11.39	53.97%	17.79	21.72	11.38	53.94%	17.78	21.86
Pyrmont	33.97	20.00	58.89%	31.26	38.17	18.28	53.81%	28.56	35.32
Redfern	42.85	22.77	53.14%	35.58	43.08	20.79	48.53%	32.49	39.88
Rosebery	62.75	39.30	62.63%	61.41	76.67	34.23	54.54%	53.48	67.76
Rushcutters Bay	4.17	2.12	50.83%	3.31	4.02	2.26	54.24%	3.54	4.34
St Peters	15.29	10.00	65.39%	15.63	19.95	8.29	54.18%	12.95	16.92
Surry Hills	56.37	28.31	50.21%	44.23	53.89	26.84	47.61%	41.94	51.42
Sydney CBD	105.26	43.83	41.64%	68.48	83.23	49.48	47.01%	77.31	91.78
The Rocks	8.05	3.11	38.62%	4.85	5.89	2.94	36.53%	4.59	5.60
Ultimo	30.84	16.05	52.05%	25.08	30.78	15.27	49.52%	23.86	29.57
Waterloo	42.38	29.69	70.07%	46.40	58.19	26.39	62.26%	41.23	52.38
Woollahra	1.15	0.45	38.89%	0.70	0.83	0.37	31.92%	0.57	0.69
Woolloomooloo	14.66	8.55	58.32%	13.36	16.00	7.87	53.66%	12.29	14.95
Zetland	23.37	15.80	67.61%	24.68	31.48	14.70	62.90%	22.97	29.65

Table 13: Detailed results of rooftop suitability calculated using Sydney North 2013 LiDAR dataset from NSW LPI

Sydney Suburb	Method 1 - Insolation Limit (3.62 kWh/m2/day) - LiDAR				Method 2: NREL Hillshade E/NE/N/NW/W (19.58) - LiDAR			
	Developable (ha)	% Useable	Capacity (MW)	Yield (GWh)	Developable (ha)	% Useable	Capacity (MW)	Yield (GWh)
All	296.26	29.64%	462.91	586.05	251.25	25.13%	392.57	507.06
Alexandria	61.49	43.47%	96.09	126.18	54.60	38.60%	85.31	113.90
Annandale	3.39	29.76%	5.30	6.67	2.72	23.87%	4.25	5.50
Barangaroo	0.13	39.58%	0.20	0.25	0.11	35.09%	0.18	0.23
Beaconsfield	2.47	34.82%	3.87	4.86	1.97	27.72%	3.08	3.96
Camperdown	9.90	28.49%	15.47	19.27	8.20	23.60%	12.82	16.30
Centennial Park	1.69	22.06%	2.63	3.22	1.38	18.01%	2.15	2.69
Chippendale	4.66	26.66%	7.28	9.00	3.88	22.20%	6.06	7.66
Darlinghurst	8.63	22.36%	13.48	16.49	6.81	17.65%	10.64	13.39
Darlington	3.55	26.10%	5.54	7.01	2.94	21.63%	4.59	5.96
Dawes Point	0.66	26.64%	1.03	1.23	0.50	20.45%	0.79	0.97
Eastlakes	1.42	37.94%	2.23	2.86	1.23	32.87%	1.93	2.52
Edgecliff	0.01	31.23%	0.02	0.02	0.01	29.85%	0.02	0.02
Elizabeth Bay	1.92	22.33%	3.00	3.76	1.61	18.76%	2.52	3.24
Erskineville	9.67	33.67%	15.12	19.06	7.88	27.41%	12.31	15.89
Eveleigh	4.89	33.91%	7.64	9.48	3.71	25.73%	5.80	7.42
Forest Lodge	3.83	26.77%	5.99	7.40	3.13	21.86%	4.89	6.18
Glebe	12.52	24.38%	19.57	24.04	10.10	19.66%	15.78	19.85
Haymarket	5.04	23.90%	7.88	9.87	4.30	20.40%	6.72	8.58
Kensington	2.56	29.59%	4.00	4.86	2.00	23.08%	3.12	3.88
Kingsford	0.02	38.31%	0.03	0.04	0.01	22.31%	0.02	0.02
Mascot	5.69	47.76%	8.88	11.59	5.11	42.96%	7.99	10.58
Millers Point	1.47	22.51%	2.30	2.81	1.28	19.55%	2.00	2.48
Moore Park	8.82	39.12%	13.78	17.60	7.77	34.47%	12.14	15.73
Newtown	7.95	20.80%	12.42	15.32	6.19	16.20%	9.67	12.26

Paddington	6.81	22.49%	10.64	12.98	5.49	18.15%	8.59	10.71
Port Jackson	0.75	33.95%	1.18	1.42	0.54	24.17%	0.84	1.05
Potts Point	5.67	26.88%	8.86	11.02	4.73	22.40%	7.39	9.39
Pyrmont	9.18	27.03%	14.35	17.94	7.68	22.61%	12.00	15.35
Redfern	12.63	29.47%	19.73	24.26	10.21	23.82%	15.95	20.05
Rosebery	25.84	41.18%	40.38	51.39	21.99	35.04%	34.35	44.50
Rushcutters Bay	0.88	21.12%	1.38	1.72	0.72	17.29%	1.13	1.45
St Peters	6.97	45.54%	10.88	14.15	5.70	37.28%	8.91	11.88
Surry Hills	12.83	22.77%	20.05	24.73	10.48	18.58%	16.37	20.65
Sydney CBD	14.47	13.75%	22.61	28.21	13.87	13.18%	21.68	27.08
The Rocks	1.47	18.28%	2.30	2.85	1.22	15.11%	1.90	2.41
Ultimo	8.17	26.50%	12.77	16.02	6.99	22.68%	10.93	13.98
Waterloo	15.49	36.55%	24.20	30.97	13.15	31.04%	20.55	26.85
Woollahra	0.21	18.48%	0.33	0.40	0.16	13.76%	0.25	0.31
Woolloomooloo	3.90	26.62%	6.10	7.40	3.07	20.90%	4.79	5.96
Zetland	8.60	36.81%	13.44	17.69	7.80	33.39%	12.19	16.25

Appendix C – Detailed Maps of Rooftops with Large Solar Potential



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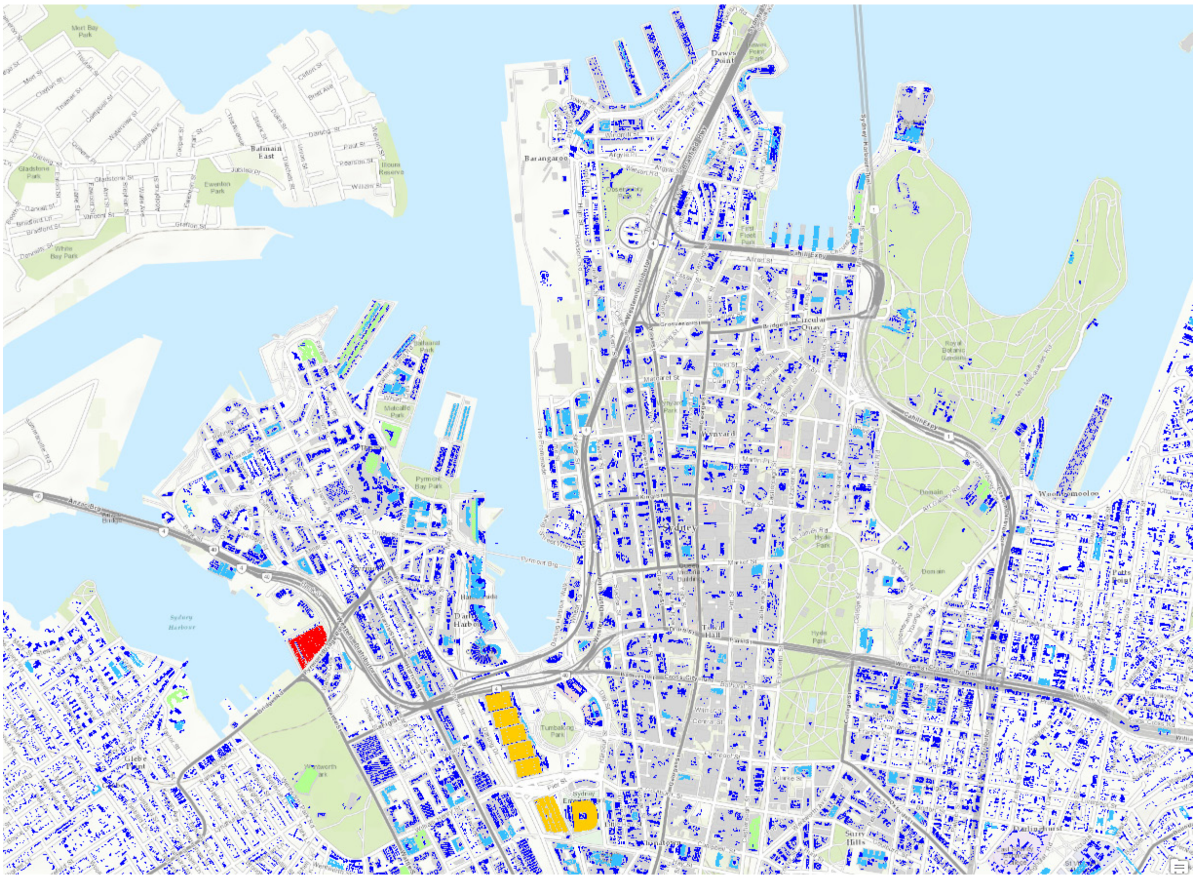
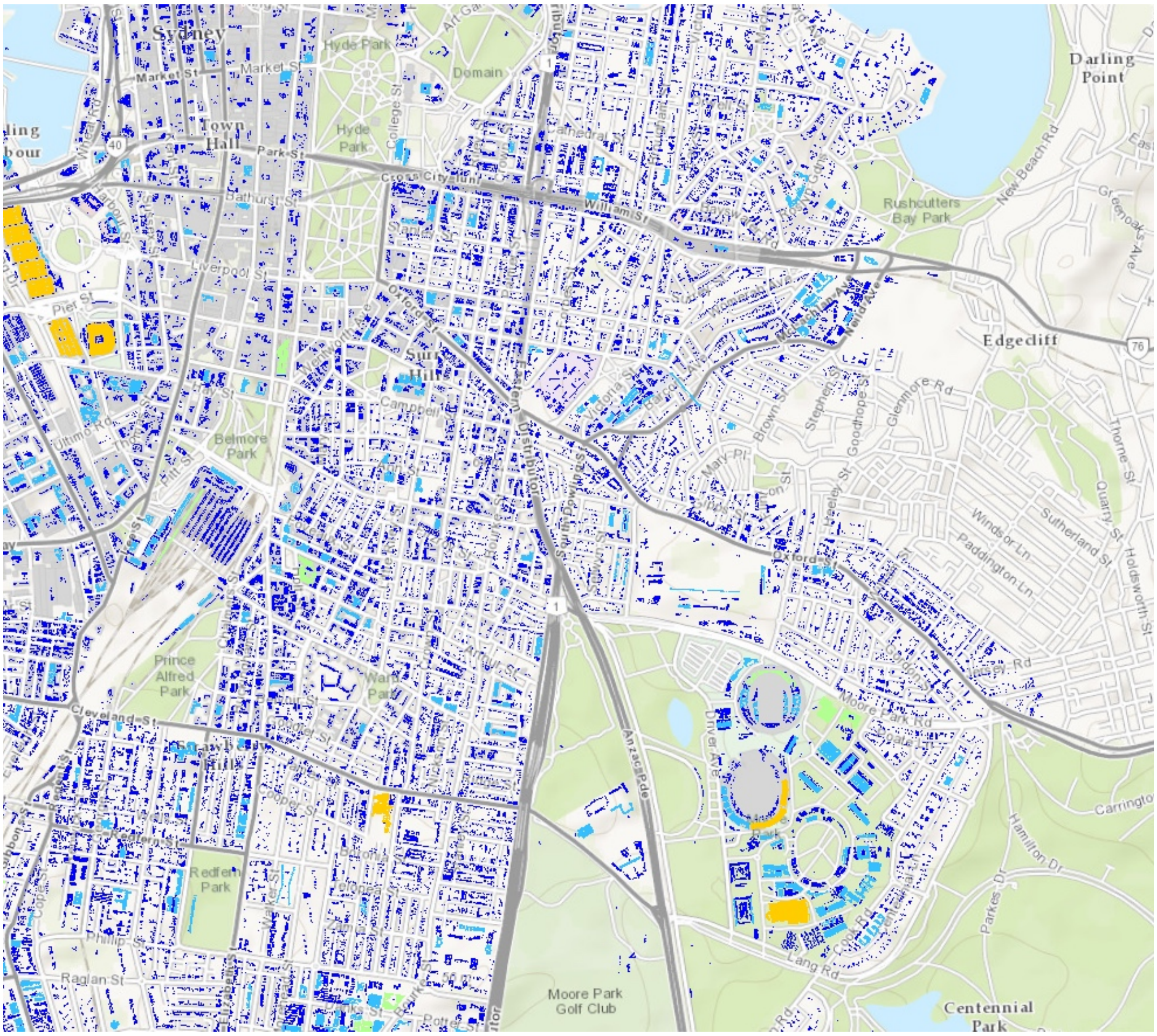


high - med - low


Sydney
Market St
Town Hall
Park St
Hyde Park
Domain
College St
Bathurst St
Liverpool St
Pier St
Ultimo Rd
Belmore Park
Campbell St
Oxford St
Surry Hills
Prince Alfred Park
Cleveland St
Redfern Park
Phillip St
Raglan St
William St
Rushcutters Bay Park
New Beach Rd
Darling Point
Edgecliff
Glenmore Rd
Brown St
Moore Park Rd
Anzac Pde
Driver Ave
Lang Rd
Moore Park Golf Club
Centennial Park
Parkes Dr
Hamilton Dr
Windsor Ln
Paddington Ln
Sutherland St
Quarry St
Thorne St
Holdsworth St
Carrington

high - med - low