23rd International Congress on Modelling and Simulation, Canberra, ACT, Australia, 1 to 6 December 2019
mssanz.org.au/modsim2019

Orienting solar panels to minimise power shortfall

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Abstract: Solar panels on residential dwellings are typically installed facing the equator to maximise the energy collected. But the power generated by an equator-facing panel peaks at around midday, whereas residential loads typically have peaks in the morning and afternoon. By orienting panels in different directions it is possible to minimise the shortfall between load and generation. This benefits the end-user by decreasing the amount of electricity required to be imported, and the stability of the grid by decreasing the amount of variability between peak and low loads. We present a linear program for calculating the optimal panel orientations for a community of 29 individual dwellings, and for an apartment building with 42 apartments in Australia. In both cases, panels should initially be placed facing north-west to meet the afternoon loads. If more panel area is available, the optimal configuration has fewer panels facing north-west and more facing north-east and west.

This information has been used by a developer to design a renewable energy system for a retirement village.

Keywords: *Solar energy, aggregating demand, embedded network, optimisation*

1 INTRODUCTION

Over the last few decades the use of residential renewable generation sources has increased significantly in Australia, as it has globally (Australian PV Institute, 2017; IEA, 2016). This increase has been in response to factors including concern over the impacts of climate change, government rebates for renewable energy, falling prices for renewable energy technologies, and increasing energy prices. These changes, along with new technologies for customer metering, have led to the development of new models of electricity supply and pricing. For example, Green and Newman (2017) and Hicks and Ison (2011) discuss how citizen and community based power systems in an integrated grid are emerging in practice, Lehr (2013) focus on new regulatory models that can enable new utility business models, and Steriotis et al. (2018) highlight that smart grids and high penetrations of renewable energy necessitate the development of modern pricing schemes.

The changes also include embedded networks, which are increasingly being scrutinized for their current and potential incorporation into national or state electricity grids, and stand alone microgrids. Precincts with a single geographical location can aggregate individual household or apartment loads and act as one user. Such communities generally have three options in setting up their energy supply: operating as stand-alone systems (off-grid), whereby they supply, store and use their own locally generated electricity; staying connected to the grid and using 100% grid sourced electricity; or staying connected to the grid and using their own supply of locally generated electricity where possible and purchasing remaining requirements from the grid. In Australia, as with other countries with high radiance levels, residential renewable power generation is usually from solar panels. These precincts may contain photovoltaic (PV) systems with or without storage.

Here we look at how to increase the use of locally produced renewable energy by optimally matching residents electricity use with solar energy through panel placement only in an embedded network. The importance of self-consumption of rooftop photovoltaic generation has been increasingly recognised over the last few years. A good review of these studies can be found in Luthander et al. (2015) and Freitas and Brito (2019). Power generated by solar panels at any instant will generally not match the household load at that instant, even if the total annual energy generated matches the total annual energy load. Simultaneously matching on-site renewable energy generation with residential load by increasing the solar panel area and optimising the orientation of solar panels can decrease the amount of electricity required to be imported from the grid.

Other options to improve self-consumption are the inclusion of battery or other storage mechanisms, and demand side management (eg. load-shifting) (Luthander et al., 2015). Storage may be added to the PV system, but generally at high cost (Grantham et al., 2017). Currently, solar panels are relatively cheap and payback periods are short. For these reasons, matching local on-site renewable energy with household energy use without storage is considered useful, particularly in this uncertain era of transition from traditional centralised power stations to distributed energy sources.

A typical residential community load profile has a peak in the morning and a larger peak in the late afternoon/evening. Traditionally, PV panels are mounted facing the equator as this creates more energy per square metre of PV panels. However this orientation does not necessarily maximise the community self-use of the energy prior to the excess being exported to the wider grid. From the perspective of the wider grid, to which the local PV generation sources are connected, the onset of large amounts of residential solar being exported causes grid stabilisation issues due to the high variability between import and export peaks (Obi and Bass, 2016), which are exacerbated when many users in one area all produce high PV generation and import from the grid at the same time, also known as 'ramping' or the 'duck curve' (Denholm et al., 2015).

From the perspective of governing bodies, self-consumption helps reduce the peak import as electricity use increases with a rising population, which means less grid augmentation is required. This should also reduce electricity prices for the end-user. From the perspective of the end-user (the prosumer), while government subsidies (such as Feed in Tariffs) which were implemented to encourage the uptake of rooftop solar are now decreasing or disappearing altogether, the cost effectiveness of installing rooftop PV becomes more related to self-consumption, which avoids more expensive import costs. Once installed, the electricity generated and used by the prosumer has no cost.

Importantly, of course, given much power in the wider grid is still sourced from non-renewable energy, decreasing the amount imported from the grid during times of low renewable energy production will typically decrease the amount of non-renewable energy used. Using locally generated renewable energy also decreases transmission losses and therefore decreases CO_2 emissions with every kilowatt used.

Tariff structures are based on government regulations and market forces and may change rapidly and radically.

Maximising self-consumption will, in general, limit exports during periods when overall demand on the grid is low and prices paid for exports are low, and minimise the energy required when demand is high and import prices are high.

This paper presents data, methodology and outputs of a model which minimises the shortfall between community load and PV generation by optimising the panel orientations. While it is apparent that facing some panels more eastward and westward will match the higher energy-use in households which often occurs during the morning and afternoon periods, due to the historical difficulty in obtaining detailed load use data, optimal panel placement has rarely been accurately designed, and designs using eastward and westward facing panels has not yet been confidently taken up by the industry. Awad and Gül (2018) show that at high latitudes in the northern hemisphere, a south west facing solar PV system can significantly improve the residential self-consumption compared to facing the panels towards the equator. Widén et al. (2009) also showed that using high latitude data, an east-west orientation of PV arrays was best for maximising self-consumption, albeit the effect of the optimisation was small. Our analysis uses detailed load data and matching detailed irradiance data and shows that optimal panel placement for self-consumption is never towards the equator.

The importance of using detailed data has been highlighted by Luthander et al. (2015) who summarise that sub-hourly data are needed to obtain a sufficiently accurate result. Times of extreme weather events (with high or low irradiance) will often cause correlating changes in energy use. Temporal and spatial matching of load and PV generation at high resolution will therefore provide a much more accurate idea of the amount being exported or imported in reality. This impacts upon; the wider grid in identification of the maximum peak import or export, policy which may be based upon the size of imports and exports, and the end-user if import prices are different to export prices. Here we have used matching 30 minute aggregated data.

In Section 2.2 we formulate the problem of calculating the best panel orientations as a linear program. Section 3 gives the results for various total panel areas.

2 METHOD

2.1 Load and solar generation data

We have used two sets of household load data for our analysis:

- half-hour load data from 29 separate dwellings at Lochiel Park in South Australia
- hourly load data from an apartment building in Bowden, South Australia, with 42 apartments.

Lochiel Park is a residential development designed by the South Australian government to be a 'model green village'. Each house was designed with a minimum 7.5-star NatHERS rating. The electricity use of each house is recorded every minute. We used aggregated half-hour data from 2015.

Bowden is an inner northern suburb of the city of Adelaide, in South Australia. In 2018, the South Australian government began work in Bowden to create the state's first higher density urban infill project, which includes a number of apartment blocks. All buildings meet 5 star Green Star As Built standards, which is a sustainability rating system launched in 2003 (Green Building Council Australia, 2019). We used hourly energy use data of the 42 apartments from 2016–2017.

Neither the Lochiel Park nor the Bowden dwellings are organised as embedded networks, but we have aggregated the load data as if they are.

One-minute solar radiation data for the load years was downloaded from the Australian Bureau of Meteorology (Australian Bureau of Meteorology, 2018). The timestamp of the radiation data was matched with the equivalent time and date of the residential load data, allowing an exact match between the time of residential energy use and PV output, on average, every half hour or hour. Solar panel output for various times and panel orientations was obtained from the solar radiation data using the 'SolaR' package (Perpiñán, 2012). We assumed 20% panel efficiency, and 25% losses due to dirt, temperature, power conversion and manufacturing tolerances. We assumed a standard roof pitch of 25 degrees, and considered panels facing east, north-east, north, north-west and west.

2.2 Mathematical formulation

The aim is to meet as much of the instantaneous load as possible using power generated from photovolatic panels.

The load at time t is $L(t)$. Photovoltaic panels can have one of five different orientations: east, north-east, north, north-west and west. Panels facing east generate $p_{\mathrm{e}}(t)$ watts per square metre at time t. The power from panels facing the other directions are p_{ne}, p_{n}, p_{nw} and p_{w}.

The problem is to determine how much area of photovolatic panels to have facing in each direction so that as much load as possible is met by the generated power. The total generated power at time t is

$$p(t;a) = a_{\mathrm{e}}p_{\mathrm{e}}(t) + a_{\mathrm{ne}}p_{\mathrm{ne}}(t) + a_{\mathrm{n}}p_{\mathrm{n}}(t) + a_{\mathrm{nw}}p_{\mathrm{nw}}(t) + a_{\mathrm{w}}p_{\mathrm{w}}(t) \tag{1}$$

where $a = (a_{\mathrm{e}}, a_{\mathrm{ne}}, a_{\mathrm{n}}, a_{\mathrm{nw}}, a_{\mathrm{w}})$ and $a_{\mathrm{e}} \geq 0, \ldots, a_{\mathrm{w}} \geq 0$ represent the installed areas facing each of the five directions. The *shortfall* at time t is

$$s(t;a) = \max\{0, L(t) - p(t;a)\}. \tag{2}$$

If the load exceeds the generated power at some instant then the shortfall is the difference between the load and the generated power; if the generated power exceeds the load then there is no shortfall.

The total shortfall over some time interval $[0,T]$ will be

$$S(a) = \int_{t=0}^{T} s(t;a)dt. \tag{3}$$

If loads and powers are calculated at discrete times t_i then the total shortfall is

$$S(a) = \sum_i s(t_i;a). \tag{4}$$

We wish to minimise the total shortfall S, but in general we will have a limit A on the total area of panels available. The problem is

$$\text{minimise } S(a) \tag{5}$$

subject to the constraint

$$a_{\mathrm{e}} + a_{\mathrm{ne}} + a_{\mathrm{n}} + a_{\mathrm{nw}} + a_{\mathrm{w}} \leq A. \tag{6}$$

There may also be limits on the areas available for panels in each direction:

$$a_{\mathrm{e}} \leq A_{\mathrm{e}}, \quad a_{\mathrm{ne}} \leq A_{\mathrm{ne}}, \quad a_{\mathrm{n}} \leq A_{\mathrm{n}}, \quad a_{\mathrm{nw}} \leq A_{\mathrm{nw}}, \quad a_{\mathrm{w}} \leq A_{\mathrm{w}}. \tag{7}$$

This problem cannot be solved using standard Linear Programming (LP) solvers because the objective function is nonlinear due to equation (3) being nonlinear. The problem can be linearised by replacing equation (2) with pairs of constraints

$$s(t;a) \geq L(t) - p(t;a) \tag{8}$$

$$s(t;a) \geq 0. \tag{9}$$

The fact that we are minimising the total shortfall S will guarantee that the solution will have $s(t;a) = L(t) - p(t;a)$ for all times t where $L(t) \geq p(t;a)$. This formulation introduces an extra pair of constraints for each time, but can still be solved using standard LP solvers even with half-hourly times for a year. The final LP formulation is

$$\text{minimise } \sum_i s_i \tag{10}$$

subject to

$$s_i \geq 0 \tag{11}$$

$$a_{\mathrm{e}}p_{\mathrm{e}i} + a_{\mathrm{ne}}p_{\mathrm{ne}i} + a_{\mathrm{n}}p_{\mathrm{n}i} + a_{\mathrm{nw}}p_{\mathrm{nw}i} + a_{\mathrm{w}}p_{\mathrm{w}i} + s_i \geq L_i \tag{12}$$

$$a_{\mathrm{e}} + a_{\mathrm{ne}} + a_{\mathrm{n}} + a_{\mathrm{nw}} + a_{\mathrm{w}} \leq A \tag{13}$$

$$a_{\mathrm{e}} \leq A_{\mathrm{e}} \tag{14}$$

$$a_{\mathrm{ne}} \leq A_{\mathrm{ne}} \tag{15}$$

$$a_{\mathrm{n}} \leq A_{\mathrm{n}} \tag{16}$$

$$a_{\mathrm{nw}} \leq A_{\mathrm{nw}} \tag{17}$$

$$a_{\mathrm{w}} \leq A_{\mathrm{w}} \tag{18}$$

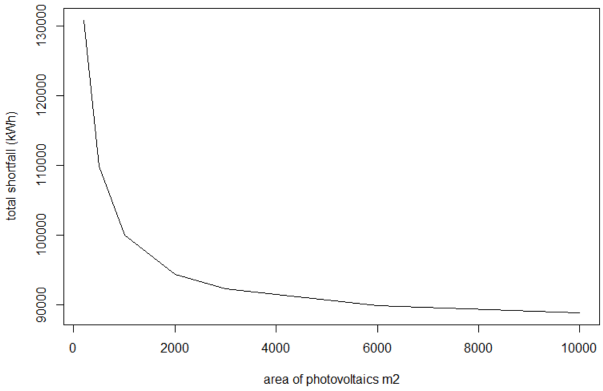

Figure 1. Shortfall reduces as total panel area increases.

with variables $a_{\mathrm{e}}, a_{\mathrm{ne}}, a_{\mathrm{n}}, a_{\mathrm{nw}}, a_{\mathrm{w}}$ and s_i to be determined.

The linear programs were implemented and solved using R.

3 RESULTS OF OPTIMISING PANEL ORIENTATIONS

3.1 Separate dwellings

The linear program to solve the problem for the separate dwellings at Lochiel Park has 5 panel orientations and a shortfall every half hour for a year, giving a total of 17 523 decision variables. The optimal configuration was calculated for various total panel areas ranging from 200 m^2 (typically four panels per dwelling) up to an unrealistic 10 000 m^2.

As the total area of PV to be used in the model increases, the configuration of panels which minimises the shortfall changes. This optimisation model does not constrain the area allowed in any direction. Table 1 shows the orientation of panels that minimises the shortfall for a given total area of PV.

For the 29 separate dwellings at Lochiel Park, typical roof area available in the precinct for PV panels may be between 400 m^2 (roughly eight panels per dwelling) and 1000 m^2 (roughly 21 panels per dwelling). Table 1 shows that the initial panel placement to minimise shortfall is north-west. However, as the area of PV increases beyond 300 m^2, panels are removed from this orientation and placed initially west and north-east. Orientations for realistic roof areas are generally north-east, north-west and west, and never north or east.

Figure 1 shows how the shortfall reduces as the total solar panel area increases. The shortfall cannot reduce below 87 MWh, which is the energy used during the night. With 1000 m^2 of panels, the reduction in shortfall is about 73% of the theoretical maximum reduction.

Table 1. PV area (m^2) at each orientation when using from 200 to 10 000 m^2 of total PV area to minimize the shortfall using Lochiel Park data.

Max Panel Area (m^2)	Area PV East	Area PV North-east	Area PV North	Area PV North-west	Area PV West	Shortfall (kWh)
200	0	0	0	200	0	127 847
300	0	4	0	296	0	117 880
400	0	85	0	176	139	111 795
500	0	153	0	88	259	107 585
700	0	235	0	0	465	102 439
1000	0	326	0	0	674	98 426
2000	644	0	0	0	1356	93 508
10 000	7751	0	0	0	2249	88 790

Table 2. Shortfalls (kWh) for 500, 700 and 900 m^2 of PV panels using optimised panel placement (the first line in each section) followed by various constrained panel placements.

Max Panel Area (m^2)	Area PV East	Area PV North-east	Area PV North	Area PV North-west	Area PV West	Shortfall (kWh)
500	0	153	0	89	259	107 585
500	250	0	0	0	250	108 585
500	0	0	0	0	500	109 528
500	0	500	0	0	0	116 277
700	0	235	0	0	465	102 439
700	0	0	0	0	700	104 284
700	350	0	0	0	350	102 980
900	0	301	0	0	599	99 462
900	0	300	300	300	0	101 233
900	0	0	900	0	0	103 181

Table 3. Optimal panel orientations for given areas between 200 to 20 000 m^2 of PV panels, to minimize the shortfall between load and generation in apartments using 2016–17 energy data. The shortfall is for two years.

Max Panel Area (m^2)	Area PV East	Area PV North-east	Area PV North	Area PV North-west	Area PV West	Shortfall (kWh)
200	0	0	0	200	0	103 322
400	0	1	0	261	138	97 562
500	0	23	0	289	188	96 236
700	0	51	0	0	649	94 551
1000	0	148	0	0	852	93 124
2000	849	0	0	0	1151	91 100
10000	1177	0	0	0	1054	90 849
20000	1177	0	0	0	1054	90 849

The model tells us the optimum area of PV panels to place in each direction, but is the difference in shortfall significant if the panels are placed sub-optimally? This may be useful information for precinct developers as they often need to take into consideration other unrelated factors which influence rooftop angles. For a typical precinct of around 20 to 30 dwellings, the available rooftop space for PV arrays may be around 500 m^2 to 900 m^2. Table 2 presents the shortfall for sub-optimally placed panels, compared to optimised panel placement. The increase in shortfall is small. For example, for 500 m^2 of panels, the increase in shortfall when restricting the panels to the north-east and west is 490 kWh per year (including all 29 houses), which is an increase of only 0.1%. If panel orientation is restricted to 250 m^2 panels east and 250 m^2 west, the additional shortfall is 1%. Putting all panels west results in a 2% increase in shortfall, whereas placing them all north-east results in an 8% increase in shortfall.

3.2 Apartments

The optimisation process outlined in Section 2.2 was also run using the Bowden energy data with 2016–17 irradiance data to find the optimal panel placements that minimise the shortfall. This linear program has 17 008 decision variables (5 panel orientations, and a shortfall every hour for two years, with a few missing hours). The results are presented in Table 3, and show, similarly to the Lochiel Park data, that optimal panel placement is initially north-west, and then north-east and west as the permissible area for PV increases. The amount of energy used at night is 91 MWh.

Notice also that the 42 apartments use less energy that the 29 individual dwellings. The average annual load for an apartment is 1770 kWh, whereas the average annual load for a Lochiel Park dwelling is 6030 kWh.

4 Conclusions

The models developed in this paper use real and detailed residential electricity loads, and matching solar irradiation data, to reveal insights into best panel placement to optimise the use of renewable energy in both separate residential dwellings and apartments.

Household loads generally have morning and evening peaks, whereas solar power peaks during the middle of the day. For both the individual dwellings and the apartments that we studied, panels oriented north-west gave the greatest initial reduction in the shortfall between generation and load. As the total area of solar panels available is increased, panels are removed from the north-west and added to the west and north-east. For realistic total panel areas, panels were never oriented east or north.

The apartments use about a third of the energy of the separate dwellings, because of the smaller sizes, and the benefits of extra insulation from being adjacent to one another.

The information on how to orient solar panels to minimise power shortfall is useful to groups developing housing, and has been used to design a renewable energy system for a retirement village with 24 dwellings. Future work will incorporate energy storage into the model.

Acknowledgements

This research was funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative. The authors also thank the residents of Lochiel Park for their ongoing support and engagement.

References

Australian Bureau of Meteorology (2018). Climate data online.

Australian PV Institute (2017). Australian PV Institute website. `http://pv-map.apvi.org.au`.

Awad, H. and M. Gül (2018). Load-match-driven design of solar pv systems at high latitudes in the northern hemisphere and its impact on the grid. *Solar Energy 173*, 377 – 397.

Denholm, P., M. O'Connell, G. Brinkman, and J. Jorgenson (2015, 11). Overgeneration from solar energy in california. a field guide to the duck chart.

Freitas, S. and M. Brito (2019). Non-cumulative only solar photovoltaics for electricity load-matching. *Renewable and Sustainable Energy Reviews 109*, 271 – 283.

Grantham, A., P. Pudney, L. A. Ward, D. Whaley, and J. Boland (2017). The viability of electrical energy storage for low-energy households. *Solar Energy 155*, 1216 – 1224.

Green, J. and P. Newman (2017). Citizen utilities: The emerging power paradigm. *Energy Policy 105*, 283 – 293.

Green Building Council Australia (2019). Green star rating scheme. `https://new.gbca.org.au/green-star/`.

Hicks, J. and N. Ison (2011). Community-owned renewable energy (cre): Opportunities for rural australia. *Rural Society 20*(3), 244–255.

IEA (2016). Medium-term renewable energy market report 2016. Technical report, International Energy Agency.

Lehr, R. L. (2013). New utility business models: Utility and regulatory models for the modern era. *The Electricity Journal 26*(8), 35 – 53.

Luthander, R., J. Widén, D. Nilsson, and J. Palm (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy 142*, 80 – 94.

Obi, M. and R. Bass (2016). Trends and challenges of grid-connected photovoltaic systems – a review. *Renewable and Sustainable Energy Reviews 58*, 1082 – 1094.

Perpiñán, O. (2012). solaR: Solar radiation and photovoltaic systems with R. *Journal of Statistical Software 50*(9), 1–32.

Steriotis, K., G. Tsaousoglou, N. Efthymiopoulos, P. Makris, and E. Varvarigos (2018, June). Development of real time energy pricing schemes that incentivize behavioral changes. In *2018 IEEE International Energy Conference (ENERGYCON)*, pp. 1–6.

Widén, J., E. Wäckelgård, and P. D. Lund (2009). Options for improving the load matching capability of distributed photovoltaics: Methodology and application to high-latitude data. *Solar Energy 83*(11), 1953 – 1966.