Maximizing Performance: Determining the Relative Influence of Key Design Elements on the Performance of Grid Connected Solar Photovoltaic Systems in Geraldton, Western Australia.

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Declaration

I declare that this thesis is my own work, based on my own research, except where otherwise referenced. I further declare that this work has not previously been submitted to any other organization.

Signed

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Abstract

This paper investigates data collected from 17 recently installed grid connected solar PV systems in the town of Geraldton, Western Australia with the intention of determining the relative effects on performance of key design criteria. The influence of tilt, orientation, inverter efficiency, module efficiency and the sizing of the inverter are compared statistically to the performance of the systems over a three month period. The conclusion drawn from the data is that the most significant design elements are the tilt of the array and the orientation of the array and that shading can have significant effects on system output.

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Nomenclature and definitions

CEC efficiency	California Energy Council efficiency refers to the weighted efficiency of an inverter calculated in accordance with California Energy Council standards. It takes into consideration the performance of the inverter at different power levels, not just at its optimum output.
Significance F	The significance F value is the probability that the equation does not explain the variation, that is, any relationship indicated by the fit of the trendline is purely coinceidental.
P-value	The P value is the probability that a particular variable in a multiple regression does not explain the variation, and can be used as an indication of the significance of a particular variable in a multiple regression.

1. Introduction

The rapid growth of Grid Connected Solar Photo-Voltaic systems (GCSPV) in Australia has led to unprecedented competition at a retail level in this industry. In spite of this increase in competition the majority of systems are sold on the basis of their size, as indicated by the peak output of the panels, and their price. Little emphasis is placed on the overall efficiency of the system or its output, other than under the requirements to provide an estimate of system output laid out by the Clean Energy Council (2009).

The purpose of this paper is to consider the major factors that influence the performance of a GCSPV system, specifically in Geraldton Western Australia, and attempt to identify the relative effects of key design considerations on maximising the performance of a grid connect solar photovoltaic systems. This involved assessing the performance of different existing systems and attempting to identify statistical correlations between design factors and system performance using linear regression.

The paper begins with a review of literature on the subject, to highlight some of the factors that determine system output. This is followed by a description of the research design and the information gathered from the study along with the results of the study. An interpretation of the results then follows along with some suggestions of how this information impacts on system design.

2. Literature Review

2.1 Influence of Module Temperature on Annual Yield

The power output of a module is dependent on its operating temperature (Skoplaki and Palyvos 2009b) which is dependent on many factors including ambient temperature, orientation, tilt and wind speed (Skoplaki and Palyvos 2009a; Nakamura et al. 2001, 599). Nishioka (et al. 2003) points out that the output energy is heavily influenced by the module temperature and therefore the temperature coefficient of power is a significant aspect in system design, especially where systems will be subject to high temperatures.

An additional aspect of module temperature is that the lower output power resulting from higher operating temperatures may shift the array output outside the optimum range for the maximum power point tracker which in turn leads to less efficient operation of the inverter. A Japanese study of 100 residential systems (Sukiura et al. 2003) showed that the greatest losses of power were attributable to normal inverter losses, shading losses and losses resulting from high temperatures leading to the PV output being below the MPPT optimum range. Parretta et al. (1998) also concluded that of the loss mechanisms of reflection, spectral effects, low irradiance effects, temperature effects and polarisation effects the greatest reductions in module output were caused by the effects of temperature.

2.2 Influence of Tilt on Annual Yield

There are many experimental and theoretical studies that investigate the optimal tilt angle of solar collectors and solar panels in various locations and situations including Chang (2009), Chen et al. (2005), Li and Lam (2007), Modon et al. (2007), Nafeh (2004), Shu et al (2006, 402) and Tang and Wu (2004), Yakup and Malik (2001), and the majority of these studies conclude that the optimal tilt angle is the angle at which the greatest amount of solar radiation will be received over the year. Modelling by Hussein et al. (2004, 2450) showed that the optimum tilt angle for maximum annual yield in Cairo was anywhere between 20º and 30º. It is suggested that, through this range, increases in solar irradiation are balanced out by increases in module temperature and a corresponding drop in output. When the incident angle is small there may be greater reflection of solar irradiation which decreases module efficiency (Nakamura et al. 2001, 598). Although power is a function of irradiance, higher irradiance also results in higher panel temperatures, which have a detrimental effect on performance. The optimal angle for power output will therefore differ from the optimum angle for solar radiation (Beringer et al. (2011, 471; Shu et al 2006, 402; Nakamura et al. 2001, 598) However, Beringer et al. concluded from experiments in Germany that although modelling of systems indicated significant output variation depending on the tilt of the panels his experimental results showed values 10% smaller than those indicated in literature and shown by calculation of irradiances. The results of Beringer et al.'s experiment was that variations in tilt angle during summer did not vary the power output by more than 6%, and not more than 10% in winter. Hussein et al. (2004, 2450) also indicated that the annual output of a South facing module (Northern Hemisphere) would not be less than 95% of its maximum for tilt angles from 0º to 50º. This overview of articles indicates that, depending on region, tilt between 0º to 50º which would cover the range of tilt found in most ordinary roof mounted systems, may not have an influence greater than 10% on the annual energy yield.

2.3 Influence of Orientation and Dust on Annual Yield

The orientation of a PV array also determines the amount of solar irradiation received. Normally a North facing panel (southern hemisphere) will receive the maximum amount of solar irradiation with variations in orientation leading to a decline in annual yield. However, as Mondol et al. (2007, 119) point out, where there are variations between the average morning and afternoon insolation the optimum orientation may not be directly North. Hussein et al. (2004, 2449) showed that in Cairo the higher water vapour content of the morning air means that modules facing East receive less solar irradiation than those facing West and therefore have a lower annual energy output. Mondol et al's (2007, 124) experiment in Northern Ireland showed that, where the tilt was optimal, variations in the orientation of up to 50º lead to a reduction in annual insolation of less than 5% in comparison to the optimum orientation. However, where the tilt was not optimal, but in the range of 0º to 50º, the drop in annual insolation, from its maximum value, could reach almost 10%.

Dust can have significant effects on the performance of solar PV panels (Goossens and Van Kerschaever 1999; Elminir et al. 2006; Jiang et al. 2011). Research in Egypt indicated that dust build up reduced the energy yield of solar PV cells by up to 17.4% per month over a seven month period (Elminir et al 2006. 3200). Goossens suggests (1999, 287) that significantly less dust accumulates on the leeside of hills and immediately downwind of “sharp topographic transitions”. This could indicate that the prevailing wind direction should be an additional consideration when installing systems in dusty areas such as Geraldton. In addition, Nakamura et al. (2001, 598) points out that panels installed on the horizontal plane gather more dirt than tilted panels and this affects their performance.

2.4 Influence of Inverter to Array Ratio on Annual Yield

Another cause of system losses or decreased system efficiency is an undersized inverter (Burger and Rüther 2006, 33-35). Burger and Rüther (2006, 44) found that where inverter sizing was based on mean hourly averages for irradiation peak values were missed which resulted in underestimation of solar irradiation peaks and undersizing of inverters, i.e. when the inverter nominal power is smaller than the peak output of the PV array. Many modern inverters reach maximum efficiency before they reach their nominal or maximum power and efficiency may be lower at full load (Burger and Rüther 2006, 33). This means that there is the potential for the PV system output to be greater than the inverter can manage, which results in energy losses. In addition, an inverter that runs close to its maximum output will have a much higher operating temperature and is more likely to instigate the inverters temperature control systems which may reduce the output power from its maximum value to its nominal value (Burger and Rüther 2006, 33-35). However, Mondol et al. (2006, 1527, 1538) shows that sizing ratios, and particularly under sizing, are less of an issue for high efficiency inverters as they tend to perform better under a partial load and concluded that a 42% variation in sizing ratio from the optimum ratio, which depends principally on the characteristics of the inverter and available insolation, only affected system performance by 2%.

3. Description of the Research Design

3.1 Data Collection

The investigation involved the collection of data from 20 grid connected solar PV systems in the town of Geraldton, Western Australia. A number of system owners were contacted and invited to participate in the study and the final selection of systems was based on the owners' willingness to participate.

The twenty systems were all located within 10km of each other and within three kilometers of the coast, ensuring that they were exposed to similar temperatures and solar radiation. Each system consisted of between one and four strings of commercial monocrystalline solar panels and a high efficiency inverter (inverter CEC efficiencies between 93.2% and 96.4%). Two systems, System R and System Q, involved two separate arrays with different orientations, one array to the East and one to the West. A third system, System M, involved two arrays on different tilts. These three systems took advantage of the two maximum power point trackers contained in the SMA 5000TL inverter and therefore data collected from these systems is the total production of the separate arrays. In this study the east/west orientation systems are treated as having an orientation of 90° and the average tilt of the two arrays is used for System M. The systems in the study were installed by four different companies. Where a location had more than one system the systems were treated as separate for the purposes of this study.

System data collection involved an initial site visit and system inspection. At this stage the tilt and orientation of the panels, the type of modules, and the type of inverter were noted and the panels were cleaned with fresh water. Data sheets for the modules were then obtained to determine the module specifications. During the site visit observations were made on the general condition of the system and any potential issues, such as shading.

Of the 20 initial systems one system was withdrawn from the study as it was not possible to arrange an intermediate or final reading close enough to the dates of the other system readings. Another system was excluded as only data for some days was gathered and there was no initial or final reading. Two systems, Systems E and F, were commissioned after the start of the study due to Western Power delays. Data from these systems was included in the study but was excluded from the data analysis for Period 1. A fifth system, System G, was excluded from the data analysis stage as it was subject to partial shading. Shading and solar access was checked at the time of the system inspection and reviewed at subsequent data collection visits and this was the only system that was believed to be subject to shading. The data from this system was therefore used to compare it to an almost identical system at another location to illustrate the effects of shading on system performance.

Performance data was collected over a period of 103 days, from the 11th of May to the 22nd of August 2011. For all systems the performance data used was the output total in kWh as indicated by the inverter display. Readings were made at the beginning and end of the period, along with one or two intermediate visits depending on system access. As the systems were all privately owned, data collection was subject to the availability of access to the site which meant that data was collected less frequently than would have been ideal. The exact nature of the data collected depended on the type of system. Twelve of the systems included an SMA TL type inverter which incorporates data storage and Bluetooth connectivity. For these systems the data used was the data collected from the inverter at the end of the period, which included a production total for each day, a running total for production recorded every five minutes and an instant AC power output recorded every five minutes. The accuracy of data collected from the inverter would vary with the type of inverter. Three brands of inverter were included in the study. Xantrex inverters are used in systems G, H and I, a Conergy inverter is used in system N and all the other systems incorporate an SMA inverter. The user manual for the Xantrex inverters suggests an accuracy for the system lifetime energy value of plus or minus 5% (Energy Matters 2011). The SMA website (SMA 2011) suggests a value of plus or minus 3% of the inverter capacity, meaning that variations in accuracy could be greater at lower outputs. No figure was available for the Conergy inverter but it would seem to be reasonable to expect it to be in a similar range. The accuracy of the inverter data was not a factor that was included in the analysis of system performance. No downtime was reported for any of the systems during the analysis period. For the systems where detailed data was downloaded no system errors were recorded indicating no downtime for reasons other than insufficient solar radiation.

Daily global solar exposure data for Geraldton was taken from the Bureau of Meteorology website (BOM 2011a) and is based on satellite data. Temperature data was also collected from the Bureau of Meteorology website (BOM 2011b).

3.2 Data Analysis

The method of data analysis involved two distinct approaches. The first method was to calculate a performance ratio for each system over the period and to use linear regression to compare these system performance ratios to the major aspects of the system design. The linear regression was performed with Excel. The areas that were considered were the tilt and orientation of the panels, the temperature coefficient of maximum power for the panels, the efficiency of the panels and inverter and the ratio of the size of the PV array to the maximum AC output power of the inverter. This information is contained in Table 1.

The second method involved comparing the results of similar systems to see if differences in production were attributable to any particular difference in system design.

Table 1

System Name	Temperature coefficient of power (mpp) %/° C	Inverter	PV Panels to nominal AC output ratio	Inverter Efficiency (CEC %)	Module Type	Module Rating (W)	Module Efficiency	Number of Panels	PV Array Size (kWp)	Array Tilt (Degrees)	Orientation
A	-0.43	SB4000TL	1.18	96.4	CEEG-SST175	175	13.7	27	4.725	20	0
B	-0.43	SB3000TL	1.23	96.3	CEEG-SST175	175	13.7	21	3.675	20	0
C	-0.45	SB5000TL	1.14	96.5	Suntech 19JS 24 AD+	190	14.9	30	5.7	28	0
D	-0.45	SB5000TL	0.34	96.5	Suntech 19JS 24 AD+	190	14.9	9	1.71	28	0
E	-0.45	SB5000TL	1.06	96.5	Jing Ri 190	190	14.5	28	5.32	23	0
F	-0.45	SB5000TL	1.06	96.5	Jing Ri 190	190	14.5	28	5.32	23	0
G	-0.44	Xantrex 2.8	0.79	94	Conergy P185M	185	14.49	12	2.22	19	3
H	-0.44	Xantrex 2.8	0.79	94	Conergy P185M	185	14.49	12	2.22	19	357
I	-0.46	SB5000TL	1.05	96.5	Suntech STP 175S -24/ad	175	12.6	30	5.25	24	5
J	-0.46	SB5000TL	1.05	96.5	Suntech STP 175S -24/ad	175	12.6	30	5.25	24	5
K	-0.46	SB5000TL	1.05	96.5	Suntech STP 175S -24/ad	175	12.6	30	5.25	24	5
L	-0.44	Xantrex 5	1.04	95.5	Conergy P185M	185	14.49	28	5.18	20	345
M	-0.44	SB5000TL	1.18	96.5	Conergy P180M	185	14.1	32	5.92	14 / 19	345
N	-0.46	Conergy 5900	0.64	93.5	Conergy PP230M	230	14.13	14	3.22	9	342
O	-0.44	SB2500	0.96	93.2	Conergy P185M	185	14.49	13	2.405	24	40
P	-0.44	SB2500	0.96	93.2	Conergy P185M	185	14.49	13	2.405	24	310
Q	-0.46	SB5000TL	0.92	96.5	Conergy PP230M	230	14.13	20	4.6	23	270 / 90
R	-0.46	SB5000TL	0.92	96.5	Conergy PP230M	230	14.13	20	4.6	24	270 / 90

Table 1: Key Design Criteria

3.2.1 Method 1

Performance data was collected for most systems on day 50 and day 103. The data was therefore divided into two periods, Period 1, power generated between the 11th of May and the 30th of June, and Period 2, power generated between the first of July and the 22nd of August. This data is displayed in Table 2, overleaf.

The performance of the systems was compared with a Performance Ratio. The purpose of the performance ratio is to relate the actual performance of the system to the level of energy available to the system. The standard method for calculating the Performance Ratio is to relate the actual annual energy yield from the system to the ideal energy yield. This ideal energy yield is calculated on the plane of array (Clean Energy Council 2009, IEC; International Electrotechnical Commission, 1998). The performance ratio used in this study differs significantly from this standard measure. As specific incident radiation data was not gathered for each system it was decided to use the global solar radiation on a horizontal surface as a benchmark for available radiation rather than estimating radiation on the tilted surfaces.

The performance ratio was therefore calculated as follows:

$$PR = \frac{\text{Actual system output (kWh)}}{\text{Size of PV array (kW) x Total Global solar radiation on a horizontal surface (kWh)}}$$

As tilted arrays would receive more solar radiation than a horizontal surface it is possible for this ratio to be greater than 1.

Table 2

System Name	Period 1 11/05/2011 - 30/6/2011 Number of Days	Global Solar Radiation on a horizotal surface period 1 (kWh)	Period 1 Production (kWh)	Period 1 Production PR	Period 2 1/7/20110 - 22/08/2011 Number of Days	Global Solar Radiation on a horizotal surface Period 2 (kWh)	Period 2 Production	Period 2 Production PR	Global Solar Radiation on a horizotal surface Total	Total Period Number of Days	Total Production (kWh)	Total Production PR
A	50	185.1	906.161	1.036	52	196.9	982.623	1.056	382.0	102	1888.784	1.046
B	50	185.1	696.003	1.023	52	196.9	758.471	1.048	382.0	102	1454.474	1.036
C	50	185.1	1213.813	1.150	53	196.9	1305.999	1.164	382.0	103	2519.812	1.157
D	50	185.1	363.312	1.148	53	196.9	390.727	1.161	382.0	103	754.039	1.154
E	28	97.7	501.138	0.964	53	196.9	1072.257	1.024	294.6	81	1573.395	1.004
F	28	97.7	501.184	0.964	53	196.9	1074.577	1.026	294.6	81	1575.761	1.005
G	NA	185.1	NA	NA	NA	196.9	NA	NA	382.0	103	619.000	0.730
H	50	185.1	360.000	0.876	53	196.9	418.000	0.956	382.0	103	778.000	0.917
I	50	185.1	1100.000	1.132	53	196.9	1195.200	1.156	382.0	103	2295.200	1.144
J	50	185.1	1080.700	1.112	53	196.9	1173.300	1.135	382.0	103	2254.000	1.124
K	50	185.1	1085.100	1.117	53	196.9	1180.300	1.142	382.0	103	2265.400	1.130
L	NA	185.1	NA	NA	NA	196.9	NA	NA	382.0	103	1898.000	0.959
M	50	185.1	869.461	0.793	53	196.9	988.148	0.848	382.0	103	1857.609	0.821
N	50	185.1	554.000	0.929	53	196.9	650.000	1.025	382.0	103	1204.000	0.979
O	50	185.1	425.000	0.955	53	196.9	493.000	1.041	382.0	103	918.000	0.999
P	50	185.1	411.000	0.923	53	196.9	475.000	1.003	382.0	103	886.000	0.964
Q	50	185.1	643.251	0.755	53	196.9	741.659	0.819	382.0	103	1384.910	0.788
R	50	185.1	616.631	0.724	53	196.9	713.435	0.788	382.0	103	1330.066	0.757

Table 2: Production and Performance Ratio Data

In order to analyse the data, individual characteristics needed to be isolated. The first step in this process was to gather together all the north facing systems. For the purpose of this selection a North facing system was defined as any system whose orientation did not deviate by more than 15 degrees from true north. This group consisted of 12 systems.

The optimum tilt for a fixed array was assumed to be equal to the latitude angle. The latitude in Geraldton is 28 degrees, 45 minutes, therefore the optimum tilt angle was selected as 29 degrees. All the arrays studied were tilted at an angle lower than this optimum tilt angle. As the period of investigation was between May and August it straddled the period where the sun's declination at noon would have been in a position ideally suited to a system at the optimum tilt angle. A lesser tilt would therefore be presumed to have a detrimental effect on the array's performance at this time of year. For the analysis, the tilt angles were defined by their angle of deviation from the optimum tilt angle. A number of linear regressions were performed relating the PR for Period 1, Period 2 and the Total Period for the systems in this group against the six main criteria. Further multiple linear regressions were performed on this group to assess combinations of design factors that the preceding models indicated were significant.

The second grouping was based on the tilt and included all systems with a tilt not deviating by more than 6 degrees from the optimum tilt. The figure of six degrees was chosen to ensure that the grouping incorporated more than half the total number of systems. This group included 11 systems. The PR for these systems across Period 1, Period 2 and the Total Period was compared to the six main design criteria by linear regression.

3.2.2. Method 2

This method involved comparing the output of these similar systems with significant differences in performance to see if there were any indications of what factors were responsible for different levels of output.

4. Results

4.1 Method 1

4.1.1 North Facing Group

The results of the linear regressions performed for the north facing group of systems for Periods 1 and 2 and the Total Period appear below in Tables 3, 4 and 5 respectively. A regression model combining factors for the north facing systems was also performed, as shown in Table 6.

Table 3: Linear Regression of PR for Period 1 against Design Factors for North Facing Systems

	R Square			Coefficients		Range of Values Considered
		Standard Error	Significance F	Intercept	X Variable	
Deviation from North	0.3866	0.1072	0.0738	1.1033	-0.0164	0° to 15°
Tilt Deviation	0.7822	0.0639	0.0015	1.2268	-0.0290	1° to 12°
Temperature Coefficient of Maximum Power	0.2872	0.1156	0.1370	-0.4235	-3.2352	-0.43 to -0.48%/°C
Array / Inverter Ratio	0.0434	0.1339	0.5908	1.1390	-0.0958	0.34 to 1.23
Inverter Efficiency	0.2502	0.1186	0.1703	-6.4372	0.0778	94% to 96.5%
Panel Efficiency	0.0562	0.1330	0.5391	1.4800	-0.0318	12.6% to 14.9%

Table 4: Linear Regression of PR for Period 2 against Design Factors for North Facing Systems

	R Square			Coefficients		Range of Values Considered
		Standard Error	Significance F	Intercept	X Variable	
Deviation from North	0.2715	0.0902	0.1002	1.0993	-0.0114	0° to 15°
Tilt Deviation	0.7440	0.0535	0.0006	1.2203	-0.0248	1° to 12°
Temperature Coefficient of Maximum Power	0.3272	0.0867	0.0659	-0.3006	-3.0165	-0.43 to -0.48%/°C
Array / Inverter Ratio	0.0672	0.1021	0.4414	1.1703	-0.1039	0.34 to 1.23
Inverter Efficiency	0.1356	0.0983	0.2652	-3.6908	0.0494	94% to 96.5%
Panel Efficiency	0.0853	0.1011	0.8396	1.5126	-0.0323	12.6% to 14.9%

Table 5: Linear Regression of PR for total period against Design Factors for North Facing Systems

	R Square	Standard Error	Significance F	Coefficients		Range of Values Considered
				Intercept	X Variable	
Deviation from North	0.2949	0.0938	0.0681	1.0831	-0.0104	0° to 15°
Tilt Deviation	0.7540	0.0554	0.0002	1.2171	-0.0270	1° to 12°
Temperature Coefficient of Maximum Power	0.3315	0.0913	0.0501	-0.4544	-3.3123	-0.43 to -0.48%/°C
Array / Inverter Ratio	0.0577	0.1084	0.4518	1.1504	-0.1071	0.34 to 1.23
Inverter Efficiency	0.2038	0.0996	0.1407	-5.1672	0.0646	94% to 96.5%
Panel Efficiency	0.1059	0.1056	0.3021	1.5871	-0.0392	12.6% to 14.9%

Table 6: Linear Regression of PR for total period against Multiple Design Factors for North Facing Systems

	R Square	Standard Error	Sign. F	Coefficients			P Value for Intercept	P Value for x Variable 1	P Value for x Variable 2
				Intercept	x1 Variable	x2 Variable			
Tilt (x1) and Inverter Efficiency (x2)	0.7618	0.7089	0.0016	-0.1356	-0.0257	0.0140	0.9578	0.0013	0.6003
Tilt (x1) and Deviation from North (x2)	0.7667	0.0568	0.0014	1.2135	-0.0249	-0.0025	0.0000	0.0021	0.5021
Tilt (x1) and Temp. Coefficient of Maximum Power (x2)	0.7801	0.0552	0.0011	0.7126	-0.0241	-1.0749	0.1792	0.0020	0.3282
Tilt	0.7540	0.0554	0.0002	1.2171	-0.0270				

4.1.2 Optimum Tilt Array Group

The results of the linear regressions performed for the optimum tilt group of systems for Periods 1 and 2 and the Total Period appear below in Tables 7, 8 and 9 respectively.

Table 7: Linear Regression of PR for Period 1 against Design Factors for Optimum Array Tilt

				Coefficients		
	R Square	Standard Error	Significance F	Intercept	X Variable	Range of Values Considered
Deviation from North	0.7970	0.0727	0.0002	1.0932	-0.0038	0 to 90°
Tilt Deviation	0.3074	0.1342	0.0767	1.2081	-0.0469	1 to 6°
Temperature Coefficient of Maximum Power	0.0960	0.1534	0.3538	-0.4182	-3.0843	-0.44 to -0.48%/C
Array / Inverter Ratio	0.0033	0.1610	0.8668	1.0340	-0.0408	0.34 to 1.14
Inverter Efficiency	0.0327	0.1586	0.5946	-0.9936	0.0207	93.2% to 96.5%
Panel Efficiency	0.0806	0.1547	0.3977	1.6533	-0.0471	12.6% to 14.9%

Table 8: Linear Regression of PR for Period 2 against Design Factors for Optimum Array Tilt

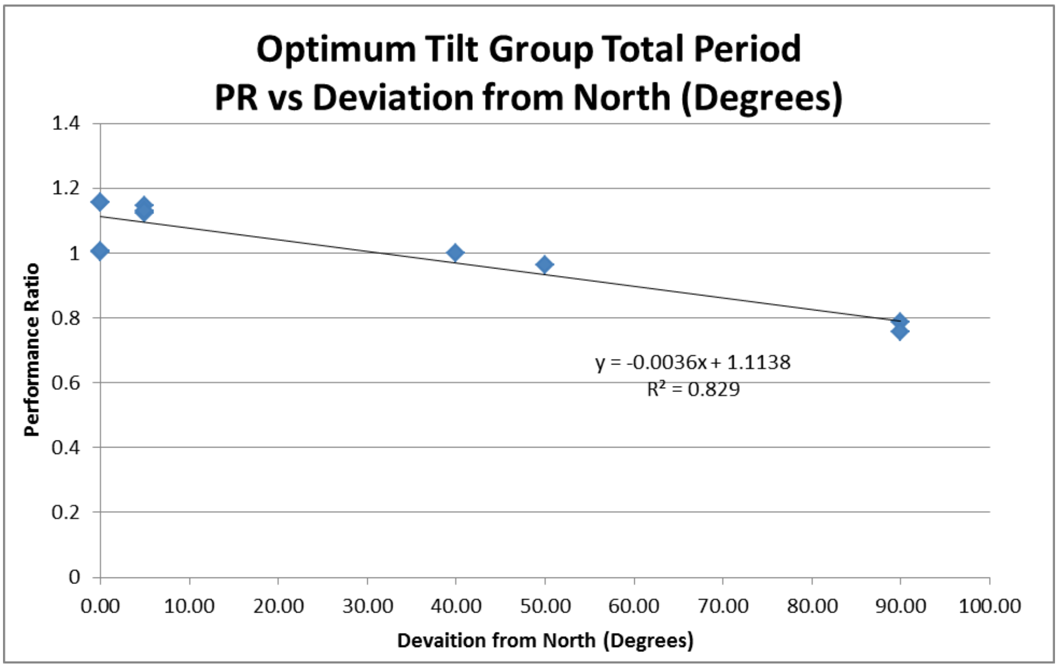
	R Square	Standard Error	Significance F	Coefficients		Range of Values Considered
				Intercept	X Variable	
Deviation from North	0.8150	0.0603	0.0001	1.1280	-0.0033	0 to 90°
Tilt Deviation	0.2570	0.1209	0.1115	1.2111	-0.0373	1 to 6°
Temperature Coefficient of Maximum Power	0.0567	0.1362	0.4806	0.0970	-2.0617	-0.44 to -0.48%/C
Array / Inverter Ratio	0.0008	0.1402	0.9329	1.0587	-0.0178	0.34 to 1.14
Inverter Efficiency	0.0052	0.1399	0.8324	0.3493	0.0072	93.2% to 96.5%
Panel Efficiency	0.0649	0.1357	0.4498	1.5554	-0.0367	12.6% to 14.9%

Table 9: Linear Regression of PR for Total Period against Design Factors for Optimum Array Tilt

	R Square	Standard Error	Significance F	Coefficients		Range of Values Considered
				Intercept	X Variable	
Deviation from North	0.8290	0.0620	0.0001	1.1138	-0.0036	0 to 90°
Tilt Deviation	0.2737	0.1277	0.0986	1.2076	-0.0411	1 to 6°
Temperature Coefficient of Maximum Power	0.0727	0.1443	0.4228	-0.1215	-2.4929	-0.44 to -0.48%/C
Array / Inverter Ratio	0.0014	0.1498	0.9132	1.0443	-0.0247	0.34 to 1.14
Inverter Efficiency	0.0183	0.1485	0.6920	-0.3598	0.0144	93.2% to 96.5%
Panel Efficiency	0.0695	0.1446	0.4335	1.5888	-0.0406	12.6% to 14.9%

5. Interpretation of Results

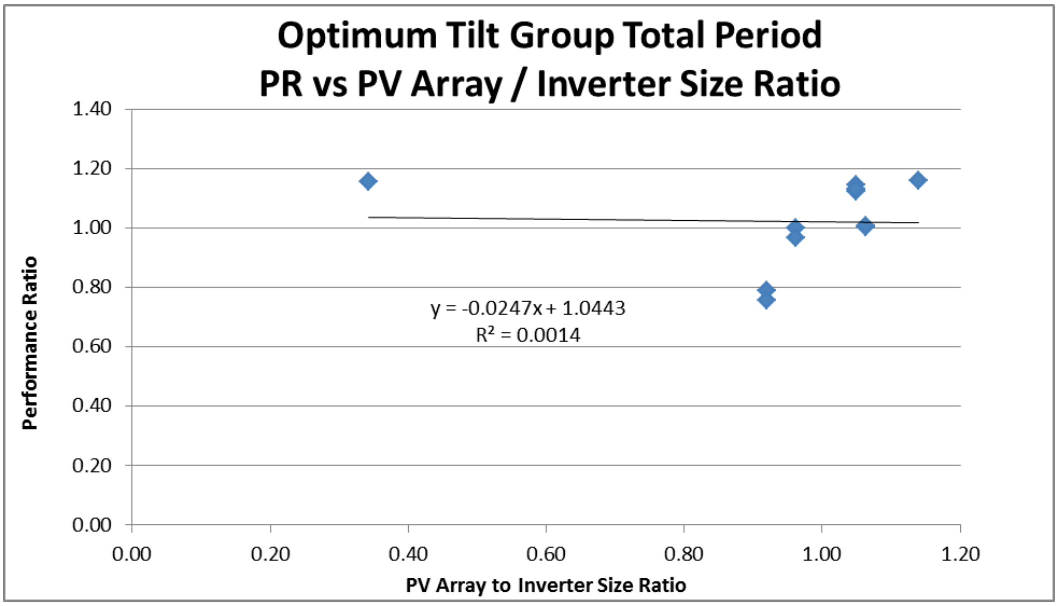
In order to understand the significance of the results it may be easier to consider a couple of results in the form of a graph, as a regression analysis can be viewed as a description of a graph. Graph 1, below, shows a significant result. This is one of the results for the optimum tilt group, a scatter chart of the performance ratio against the deviation from north. The trend line shows the general relationship between the two sets of data. It can be clearly seen that all the points are relatively close to the line and are in general agreement with the line. The equation for the line gives the slope of the line, this is the x variable coefficient in the results table, and the Y intercept, which is produced in the regression analysis but has not been included in our results. The R square value explains what portion of the variation in data is explained by this relationship. In this case, the R Square value of .829 indicates that the relationship as described by the equation explains 82.9 % of the variation.



Graph 1: A significant result.

The significance F value is the probability that the equation does not explain the variation, that is, any relationship indicated by the fit of the trendline is purely coinceidental. For this reason it is important that for a result to be regarded as significant, the significane F value must be below 0.1. The P value is the probability that a particular variable in a multiple regression does not explain the variation, and can be used as an indication of the significance of a particular variable in a multiple regression. Where there is only one variable, the significance F value will be equal to the P value for the x variable.

Graph 2, below, shows a non-significant relationship. That is, a relationship where there does not appear to be a relationship between x and y. The points are further away from the line and the line does not illustrate the variation in the performance ratio. This non-significant relationship is indicated by the high signifincance F value in the regression results table of 0.9132.



Graph 2: A non-significant result

The criteria applied to the interpretation of the regression analysis performed in this study were that the model under consideration was considered significant if the significance F value was less than 0.1 and a variable was considered significant if the P value was less than 0.1. When there is an only one design criterion in the model the P Value for the X variable is equal to the Significance F value. Where this is the case only the Significance F value is shown.

5.1 North Orientation Group

The results of the linear regressions performed on the Period 1 data for the north facing group of systems showed that only the results for tilt and deviation from north had significance F values below the 0.1 threshold. The lowest significance F value was for tilt, which was well below the 0.1 threshold. The R square value was 0.78, indicating that this model accounts for 78% of the variation in performance ratio over this period.

The Period 2 results were slightly different with only the tilt and temperature coefficient F significance values being below the 0.1 threshold. The R square value for the tilt was 0.74 for this period. The F significance for the variable determined by the regression performed on the temperature coefficient data for this period indicated that this result was also significant.

The results for the total period for the north facing systems showed significance F values below the 0.1 threshold for deviation from north, tilt and temperature coefficient of maximum power. The greatest R square value was 0.754 for the tilt.

A number of multiple regressions were performed on the significant design characteristics from the analysis of the total period using pairs of criteria, the results of which can be seen in Table 6. Although the R square values were higher than for the regressions performed involving tilt alone, the P values for the second variable were all above the 0.1 threshold. The model involving just the tilt was therefore decided to be the most significant model.

5.2 Optimum Tilt Group

The results of the linear regressions performed on the Period 1 data for the optimum tilt group of systems showed that only the results for tilt and deviation from north had significance F values below the 0.1 threshold. The lowest significance F value was for deviation from north. The P values for both models were well below the 0.1 threshold and the R square value for deviation from north was 0.797 suggesting that this model accounted for almost 80% of the variation in performance ratio over period 1.

The Period 2 results were slightly different with only the deviation from north F significance value falling below the 0.1 threshold. This regression analysis returned low P values, below 0.0001, and a R square value of 0.815.

The results for the total period for the optimum tilt systems showed significance F values below the 0.1 threshold for deviation from north and tilt with P values within the accepted range. The largest R square value for this group was 0.829 for deviation from north, with the R square for tilt being 0.273.

5.3 Method 2

The most obvious pair of similar systems with different performance was Systems G and H. Systems G and H both consist of 12 185 Watt Conergy P185M Panels and a Xantrex 2.8GT inverter. The systems were located approximately 2km apart, both were on roofs with a pitch of 19 degrees and with an orientation less than 5 degrees away from true north. The only visible significant difference between systems G and H was shading. At the time of the site visit in May partial shading from the neighbor's trees was affecting two of the panels in System G. The percentage and time of shading was difficult to determine as the trees were thin and subject to frequent and large movement from the wind. Unfortunately intermediate data was not available for System G as the system could not be accessed as the owner was away on holiday. However, the difference in output over the three month period is an average of 1.5 kWh a day, or a loss of 20% of potential production and appears to be attributable to the shading.

6. Significance of Results

6.1 Deviation from North and Tilt

The high R square results for the deviation from north and deviation from optimum tilt across all periods indicate that these are the two most significant factors affecting system performance. Consideration of the equations derived from the coefficients for these regressions give an indication of the relative importance of these two factors. Looking at the Total Period results for the north facing systems, the derived coefficient of x for deviations from the optimum tilt is -0.027. The coefficient for deviations from

North in the Total Period results for the optimum tilt group is -0.0036. The x variable is an order of magnitude smaller than the variable for the tilt which indicates that a one degree variation in the tilt has a much more significant effect on system performance than a similar variation in orientation.

6.2 Temperature Coefficient of Maximum Power

The linear regression analysis for the north facing systems in Period 2 and the Total Period showed that this model accounted for did not show a significant relationship between the Performance Ratio of the systems and the Temperature Coefficients of maximum power, with the exception of a borderline indication for the Period 2 data in the north facing group. Although the effect of the temperature coefficient of power on system performance is significant, the total variation in the temperature coefficients of power across all the systems was only 0.05%/°C. In the case of module temperatures 40°C in excess of the standard test conditions this variation would only amount to a 2% variation in output as a result of variations in the temperature coefficient of maximum power. In addition, this study occurred during the spring period and the maximum temperature recorded in Geraldton during this period was 31.7°C (BOM 2011b). Using the Clean Energy Council recommendations (CEC 2009) the effective module temperature was assumed to be the ambient temperature plus 25°C. Therefore the effective module temperature at this ambient temperature could have been up to 56.7°C which would have signified a potential variation in the effects of the temperature coefficient of maximum power on system output of approximately 1.6% across the range of systems. These results would seem to be generally in agreement with Nishioka (et al. 2003, 670) which concludes that, in Japan, an improvement of

0.1%/°C in the temperature coefficient leads to an improvement in annual output of approximately 1%.

6.3 PV Array to Inverter Ratio

The absence of any clear link between the PV array size to inverter size ratio and the performance ratio is also in accordance with the literature. For high efficiency inverters, such as those employed in all these systems, Mondol et al. (2006, 1527, 1538) shows that sizing ratios, and particularly under sizing, are less of an issue as they tend to perform better under a partial load, concluding that a 42% variation in sizing ratio from the optimum ratio only affected system performance by 2%. In addition, any issues involving the under sizing of inverters and cut outs or power reductions due to high temperatures leading to overheating are more likely to occur in summer.

6.4 Inverter Efficiency

Although the results of the study showed no clear relationship between the efficiency of the inverter and the output of the system this is most probably due to the relatively small variation in inverter efficiencies in the study, ranging from 93.2% to 96%, a range of 2.8%. This issue is further complicated by the variation between the efficiencies of different inverters at part load. For assessment of the influence of inverter efficiency on system output the inverter manufacturers' stated efficiencies can be used as an indication of maximum performance and as an indication of inverter efficiency on system performance.

6.5 Panel Efficiency

The regression analysis showed now clear relationship between the efficiency of the panels and the output of the system. The power rating of a panel under standard test conditions is based on its size and efficiency and so this factor, to some extent, is factored in by the panel size. However, although no data has arisen out of this study it is important to keep in mind that more efficient panels may have other improved characteristics such as better performance in low light situations.

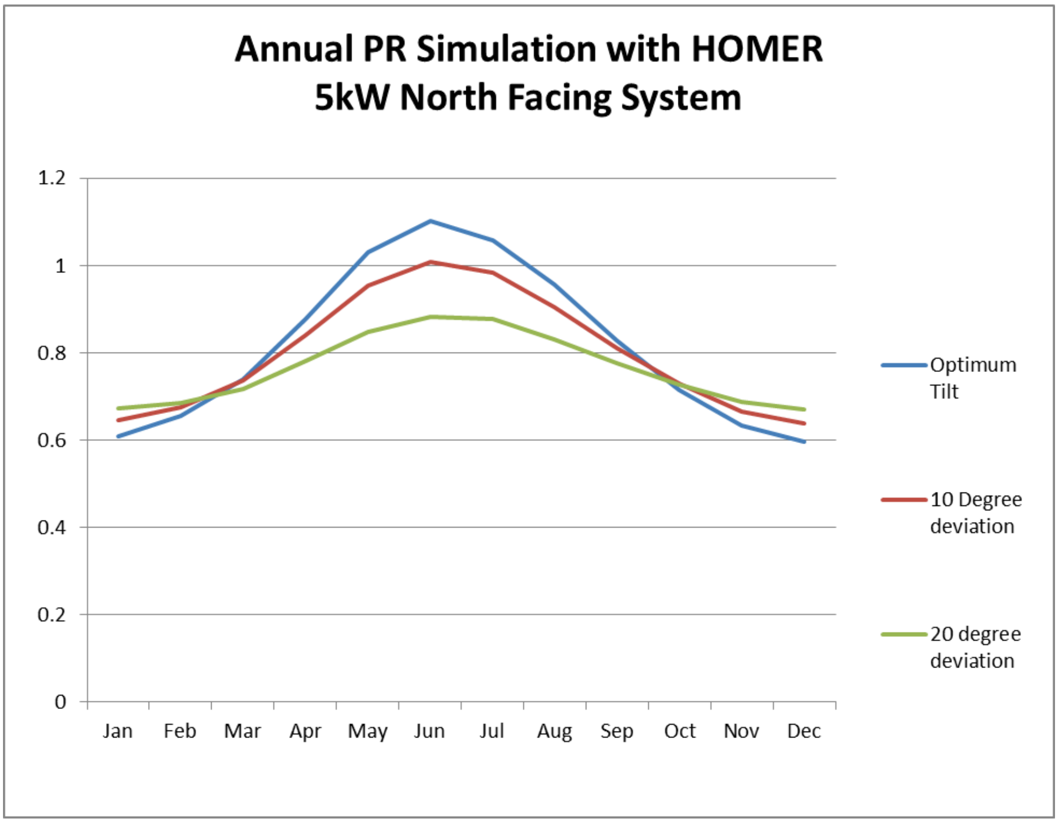
6.6 Shading

The results of the comparison of System G and System H highlight another potential cause of poor system performance. The effects of shading can have a great influence on system performance, even when the shading appears to be minor.

7. Period of Results

The total data collection period for this project was just over three months. It is therefore important to give some consideration to how the significance of these results would vary over the year. In order to assess this, a number of simulations were performed using HOMER, a renewable energy system performance simulation program. The simulations were done to determine how the performance ratio of a 5kW system would vary over the year and how this would be affected by variations in tilt, for a north facing system, and by variations in orientation, for a system with its array at the optimum tilt. The HOMER simulations produced monthly energy output values which were used with the available solar data to determine performance ratios. Whilst these performance ratios differed from the actual ratios observed during the study, it is reasonable to assume that the variation in the performance ratio over the year, and for different tilts and orientations, would give an indication of the variation that would be experienced by the systems under observation. Details of how the HOMER simulation was set up are contained in appendix 1.

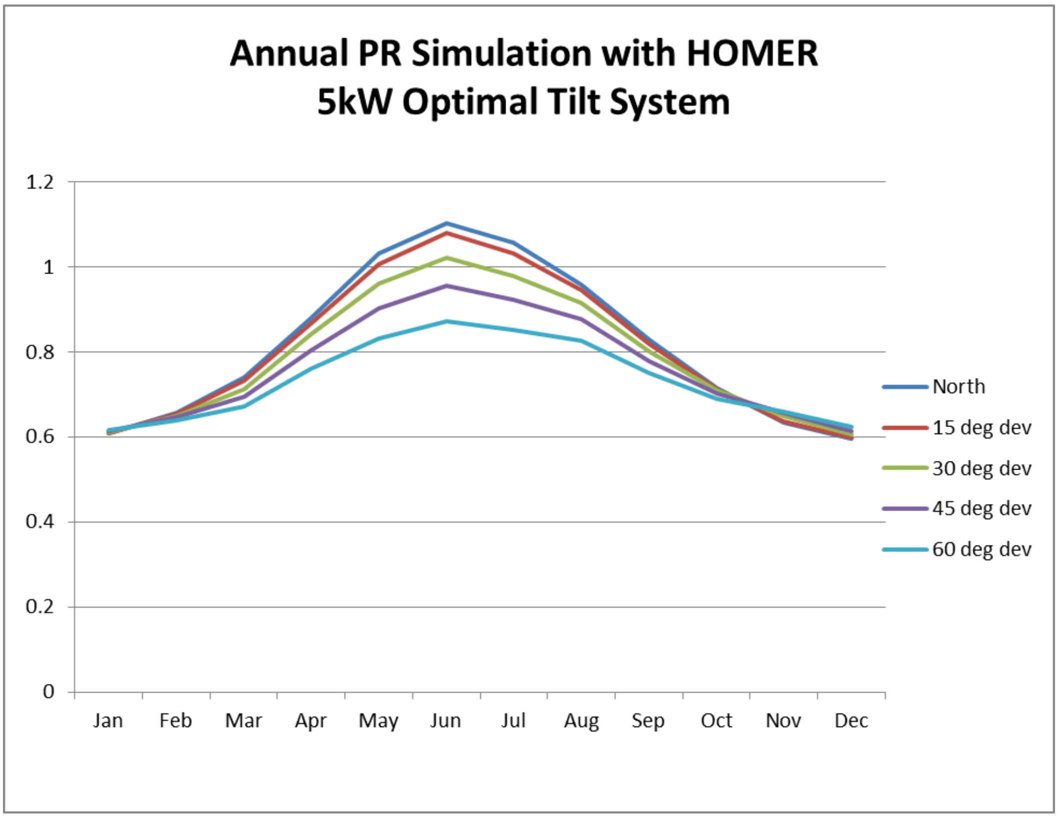
Graph 3 below shows the simulated variation in performance ratio over the year and shows how these results would vary with changes in the tilt of the array, for a system facing directly north.



Graph 3: Annual PR variation and effects of variation in tilt on PR.

It can be seen from the graph that the effects of a variation in tilt are in fact greatest during the winter months, the time of year in which the study was conducted. The closer the tilt is to the optimum tilt the higher the performance ratio. As this is the time of year when there is the least solar radiation it is particularly important to maximize the efficiency of the system. The difference in performance between the different tilts would be much smaller during summer.

The pattern is similar for the optimal tilt systems, as is shown in Graph 4 which shows the effect of deviations from north on the performance ratios of systems at the optimum tilt.



Graph 4: Annual PR variation and effects of orientation on PR.

These simulations show agreement with the results of the present research and indicate that, although the effect of variations in tilt and orientation on system performance is noticeably less during summer, over the whole year, the effect is significant. The Homer simulations indicate that a 60 degree deviation in orientation from the optimum orientation would lead to an 8% reduction in annual output and a 20 degree deviation in tilt from the optimum tilt would result in a 3% fall in output.

8. Limitations of the Results

The results of this study are limited by a number of factors. The data collection period did not cover a whole year and therefore only gives a limited view of system performance and gives no overview of how the systems perform during summer, when operating temperatures and solar radiation are at a maximum. This will inevitably have significant implications on the value of the results, especially those relating to the temperature coefficient of maximum power. The HOMER simulations do however give some indication that these factors are important over the duration of the year.

The number of systems for which data was collected was relatively small. In addition, the range of values for some design characteristics, such as the temperature coefficient of maximum power, was quite small. Such limited sampling is unlikely to give an accurate view of system performance, especially for system characteristics outside the range of the systems tested, for example systems with an array tilt greater than the latitude angle. In spite of these limitations and potential variations the results give a clear indication that tilt and orientation are the primary design criteria in maximizing system output.

9. Success of the Investigation

The purpose of this report was to determine the primary factor in maximizing the output of a grid connect solar PV system and to determine the relative importance of other design factors. Subject to the limitations stated above, the study has succeeded in gathering a clear indication that the primary design considerations for grid connect solar PV systems are the tilt and then the orientation of the panels. The limited period of the data collection phase of this report means that conclusions drawn can only be applied with any degree of certainty to the time of year that the investigation was performed. However, consideration of the HOMER simulations and other papers in the field would indicate that, throughout the year, these two factors would remain the most significant design elements. Other factors, such as the temperature coefficient of maximum power, would obviously be more important during the constantly high operating temperatures experienced during summer. This would probably also be true for the PV array to inverter size ratio.

10. Conclusion

This investigation has analyzed system and performance data collected from 17 recently installed grid connected solar PV systems in the town of Geraldton, Western Australia with the intention of determining the relative effects on performance of key design criteria. The conclusion drawn from the data is that the most significant design elements are the tilt of the array and the orientation of the array. A variation of 1° in the tilt of the array from the optimum tilt, assumed to be the latitude angle, would have a greater effect on system performance than a similar deviation in orientation from true north. The results also indicate that shading can have a greater effect on system performance than any of the other design criteria, within the normal ranges.

The limitations of the data collected, especially the small number of systems and the limited period of data collection mean that no clear conclusions can be drawn about the relative importance of other design characteristics outside of the observations detailed in the Significance of Results above.

The key recommendation of this report is that any design methodology for grid connected solar PV systems must focus on the importance of tilt and orientation in maximizing system output along with stressing the importance of ensuring that PV arrays are completely shade free at all times during daylight hours.

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Appendix 1: Setup of Homer Simulation

The following settings were used for the base HOMER simulation:

Converter:

Size of 5kW

Efficiency of 97%.

PV:

Size of 5kW

Derating factor of 90%

Optimal slope of 28.75°

Azimuth of 180°

Ground reflectance of 20%

Consider the effects of temperature

Temperature coefficient -0.5%/°C

Nominal operating cell temp 47°C

Efficiency at standard test conditions 13%.

Annual solar and temperature data for Geraldton for the year to September, 2011 was used for the simulation.

The monthly output was taken from the Grid tab of the Simulations results and used with the solar radiation data to determine the performance ratio. The simulation was then repeated with different tilt angles and different orientations to produce the range of performance ratio results.