TECHNO- ECONOMIC ANALYSIS OF PV/T HYBRID SYSTEM IN AUSTRALIA'S DOMESTIC MARKET

Jason Wild

Bachelor of Engineering
Mechanical

Department of Mechanical Engineering
Macquarie University

November 7, 2016

Supervisor: Dr. Nazmul Huda

ACKNOWLEDGMENTS

I would like to acknowledge my supervisor Nazmul Huda for his support and guidance.

STATEMENT OF CANDIDATE

I, Jason Wild, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechanical Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

Student's Name: Jason Wild

Student's Signature: Jason Wild

Date: 7/11/2016

ABSTRACT

The techno-economic performance of a hybrid photovoltaic/ thermal system depends heavily on local climate conditions, specifically the rise in module temperature of the solar panels. This study aims to quantify the impact current solar radiation data has on the overall performance of a domestic PV system, and compare it to the performance of a PV/T system. By using current solar radiation data collected by the Bureau of Meteorology Australia (BOM) via several solar ground stations, an accurate prediction of electrical energy collected by both systems is calculated. In order to compare the economic viability, and the environmental impact of both systems, the energy calculations is used alongside previous LCA study research of PV and PV/T systems that estimates the carbon equivelant emissions of the two systems. The 200 W solar panel system is projected to have a payback period of 21.2 years, whilst for the 200 W solar panel and water based thermal hyrbid system, a projected payback period of 15.4 years. The GHG emissions saved by the PV system is expected to be 837.98 g CO2 e/ kWh, whilst for the PV/T system, a predicted 264.61 g CO2 e/ kWh. This study has also provided the inital steps towards a lifecycle assessment for the small scale PV/T system.

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Chapter 1

Introduction

1.1 Photovoltaic/ Thermal hybrid solar energy collector

Australia's energy demand is growing, and the demand for energy per individual increases rapidly as technology advances week by week. The need for sustainable energy is abundant, and the shift from fossil fuel based energy to environmentally friendly sources is the next step to solving Australia's, and the world's, energy demand and supply crisis.

With advances in photovoltaic solar panel systems technology leading to more efficient systems that can be produced at a reduced cost, domestic installation and use is becoming more viable for every household. Having this type of technology be economically viable on a domestic level is especially important in applications across some of Australia's remote households.

This project is focused on researching and understanding the techno-economic performance of a small scale domestic photovoltaic system (solar panels) fitted with a hybrid solar thermal collector system, built by Macquarie University. In evaluating the performance of this small scale solar collecting system, this project will discuss whether upgrading existing PV solar panels with a solar thermal system is economically viable, and or offers less of an environmental impact for the electrical energy being generated in the current Australian climate.

The small scale PV/T system constructed by Niko De Leon, at the time a Bachelor of Engineering majoring in mechatronics at Macquarie University, is a 200Wp solar panel system fitted with copper heat pipes. These are designed to help reduce the operating temperature of the solar panels as they are exposed to the high ambient temperatures and solar irradiation weather conditions of NSW, Australia [55].

The system has 2 main sub-systems; the solar panels with the mount, and the hot water system, detailed in Niko's project report. The solar panels, as mentioned, are rated at 200Wp, made of monocrystalline solar panels with a surface area of 1580 mm by 808 mm.

The hot water system (thermal collecting system) has 4 components:

- 50 litre hot water tank
- 12V hot water pump
- Heat exchanger unit
- Hosing to and from the hot water tank

The PV/T system has not been tested rigorously enough to ascertain the true output performances of the system. This project intends to conduct research into the expected performances of similar PV/T systems, and determine a calculation method to predict the performance of the system in Australian weather conditions. In order to determine the economic viability and environmental impact of the system, research is conducted into the cost and equivalent GHG carbon emissions that are required to construct and assembly the rig.

This project has also aims to lay the ground work towards conducting a lifecycle assessment of the PV/T set up at Macquarie University.

1.2 Thesis Overview

This project is focused on researching and understanding the economic viability of a small scale domestic PV system fitted with a hybrid solar thermal collector system. The project also assesses whether upgrading existing PV solar panels with a solar thermal system is economically viable, and/ or offers less of an environmental impact for the electrical energy being generated.

This requires:

- Research into the economic viability of existing PV residential systems on the Australian market, and the systems environmental impact per kWh generated.
- Research into existing PV/T small scale systems and their techno-economic performances.
- Research into the current conditions of the Australian solar collector market, including the associated economic and environmental cost of electrical energy and hot water in the household.
- Collection of weather climate data for 2016 for use in expected PV energy generation calculations
- Calculation of expected energy generation of PV and PV/T system, and further calculation into the economic viability and environmental impact of each system

Furthermore, this project will provide a detailed plan for a lifecycle assessment to be carried out on the PV/T system built by Macquarie University, including an LCA of the basic materials used by the system, rudimental assembly of components of the system, and associated transport requirements for each component and sub-system.

Chapter 2

Background and Related Work

2.1 Number of solar power systems in Australia

According to Sioshansi et al. [72], since the start of 2010, Australia has seen a massive boom in domestically installed roof top photovoltaic systems. Over $9 billion has been spent by households to install photovoltaic systems, and $8 billion in subsidies will be received by these households along with the savings made from the electricity generated by the photovoltaic systems. This increased rate of installations in domestically installed PV systems has been reducing in recent years, as shown by Figure A.1, found by [8].

2.2 Small scale PV vs PV/T

In the energy statistics report of 2016, The Department of Industry, Innovation and Science published that the energy consumption per year used by all of Australia is in a slight downward trend since 2008- 2009 [47].

Although total energy consumption is reducing per year, the amount of total renewable energy being consumed is estimated to be less than 6%, whilst of the total amount of energy being produced, renewable only accounts for 2%, seeing a rise in 2013-2014 due to continuing growth in wind and solar photovoltaics.

In contrast, the Clean Energy Council reported that renewable electricity generation accounts for over 14% in 2015, which is an increase in 20% of wind and solar power generation [25].

The Department Of The Environment And Energy gave a quarterly update in December 2015 showing per capita a decline in greenhouse gas emissions, currently stating that an average of just over 22 tons of carbon emissions per person [31].

This decline in energy consumption, per capita emissions, and increase in renewable energy generation is promising for the overall future of Australia's impact on the environment. Further, to ramp up the process of reducing environmental impact the Australian Government aims to meet a renewable energy target of 33,000 GWh by 2020.

The renewable energy target has increased the amount of investment into small-scale renewable energy generation, meaning the number of installations per year of rooftop solar power systems are expected to remain constant until the end of 2017. As the Clean Energy Council reports, the largest domestic renewable energy generation comes from PV panels, and competition in the market for domestic PV systems has driven installation companies to build cheaper, more energy efficient products, ranging from standard standalone PV panels, and a hybrid of solar panels and solar thermal systems.

Seeing the potential of hybrid photovoltaic and thermal solar power generating systems in increasing solar power gain efficiency, this study aims to determine the financial viability and environmental impact difference between the standalone PV panels and the PV/T hybrid system within the current Australian climate.

2.2.1 Electricity cost and feed-in tariff within NSW, Australia 2016

The current state in Australia's household electricity supply cost as reported by the Australian energy market commission [3] in a financial year final report, is 28- 32 c/ kWh for market to standing offer. The Australian Renewable Energy Agency (ARENA) [19], agrees with these figures, producing 21 38 cents/ kWh (flat tariff).

The ARENA also reported on the feed-in tariff rates for 2016, being 5-10 c/kWh for unsubsidised systems. This feed-in tariff is significantly lower than the electricity tariff, which has inspired a substantial amount of research into electricity storage units to optimize payback by supplying feeding-in during peak feed-in tariff times during the day, or holding the charge for household peak time use.

The Australian Independent Pricing and Regulatory Tribunal [48] had given a media release at the end of the 2015/2016 financial year on solar feed-in tariffs, and Australia's benchmark range for solar feed-in tariffs, being 5.5 to 7.2 c/kWh. This was an improvement from 2014/2015's recommendation of 4.7 to 6.1 c/kWh. Although the feed-in tariff plays a large role in the economic viability of small scale domestic solar panel systems, the usage rate of the system and the amount of solar panel energy produced and used by the consumer is also significantly important in determining the economic viability.

The NSW Solar Bonus Scheme [54] is another avenue small scale domestic PV systems can become economically viable, and generate a larger incentive for domestic households to invest in solar technology. The scheme originally offered 60 c/kWh since the first of January 2010, but due to the popularity and unforeseen large numbers of investors capitalizing off the scheme, an amendment had to be made in October of the same year, reducing the subsidised feed-in tariff to 20c/kWh.

The scheme has been a large success for boosting the quantity of solar power produced in NSW, and Australia, with over 146,000 households and small businesses installing small scale energy generators under the scheme. The scheme is now closed to new applicants, and ends on the 31st of December 2016.

Although a new system cannot benefit from this scheme, any system that was connected before the first of July 2011 can still claim 20c/kWh in subsidized feed-in tariff until the end of the year, which will significantly change the economic comparison between this system and any new system installed in 2016 NSW, Australia.

2.2.2 Household electricity usage within NSW, Australia 2016

The Australian Bureau of Statistics Census of Population and Housing [1] has determined the average household size in NSW as 2.59 people. In determining an average household daily electricity expenditure in NSW, the Australian government have set up a website Energy Made Easy [28] maintained by the Australian Energy Regulator (AER) which has the specific purpose is to provide an energy price comparison tool that aids residential and small business owners understand which energy offer is suitable for them. This tool gives an accurate typical household usage for 3 person, reporting:

Season	Daily energy usage (kWh)	Total usage in season (kWh)
Summer	13.6	1228
Autumn	13.0	1197
Winter	15.1	1389
Spring	13.4	1215
Total	13.8	5028

Table 2.1: Energy usage of an average size household within NSW, Australia, 2016

It's important to understand household expenditure per day to;

- Determine the amount of electrical energy utilized by the household and;
- The amount being feed into the grid

In order to calculate what amount of energy the solar panel is supplying the household and what quantity is being feed into the grid. A report conducted by Deloitte Access Economics [27] commissioned by the Energy Supply Association of Australia details the typical network daily demand profile for all households across Australia.

It is obvious that the majority of electrical usage happens in the daytime, with a peak between 5pm and 9pm. Comparing the electrical energy profile of NSW against a sample solar intensity and peak sun hours profile [2].

Even from an early estimation, it is clear for a small 1m^2 solar panel operation at 15% efficiency (200Wp system), that all of the energy from the system will be used by the household and none will be feed into the grid. For such a small system (under 200 Watt system) 100% of power is reducing the grid electricity usage of the house, ie. All power generated is worth the market value of the grid electricity supply (30 c/kWh) rather than the value of the feed-in tariff (6.45 c/kWh).

For a 1 kW system, an early estimation shows that the energy generated exceeds the household usage, and so some of the electricity generated by the system will be feed into the grid. This amount of energy has a lower economic value, as grid electricity price / kWh is larger than the feed-in tariff / kWh. For a larger PV system, the household could

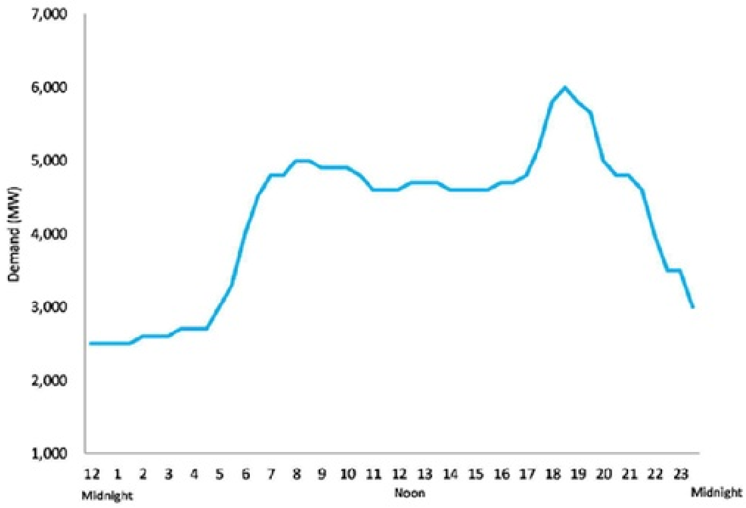


Figure 2.1: Average australian household energy usage profile

be powered without grid usage between the hours of 7am and 6pm. This means that just over 50% of the household energy demand can be directly supplied by the solar panel, and any excess will be fed back into the grid.

The calculation of 50% of household demand being directly supplied by the solar panels will be utilized in this study as a factor to determine the percentage of power used by a larger scale domestic PV system, and the amount being feed into the grid for any conditions in NSW, Australia.

2.2.3 Environmental Impact

As reported by the Australian government', Department of the Environment and Energy the net environmental impact of energy production for NSW, Australia [4] has been declining since 2007, showing an escalating decrease in overall GHG emissions per kWh produced. Even as NSW's energy consumption grows, due to the industry becoming increasingly environmental impact concerned. See Figure A.2.

In a quarterly update by the department of environment and energy, August 2016, an emissions factor for NSW was reported to be 0.84 kg CO2/ kWh indirect GHG emissions per kWh used residentially [31].

2.2.4 Impact climate has on solar panels systems

Solar panel systems are heavily reliant on day to day weather and environmental climate to determine the performance of the system. Many factors determine the true efficiency

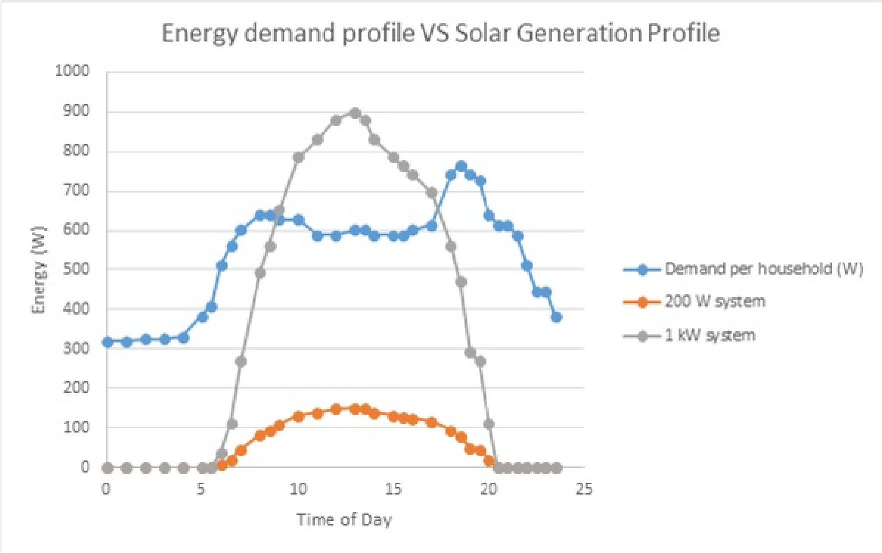


Figure 2.2: Energy demand VS estimated solar generation profile

and output of solar panels including: the amount of direct solar irradiation the solar panels have access to across the day; the ambient temperature surrounding the solar panels causing the temperature of the panels to rise; the humidity of the air around the panels; and the wind speed across the plane of the panels [76].

Although the level of solar irradiation, humidity of the air, and wind speeds across the day play a significant part in solar panel performance, the major difference between PV and PV/T systems is the temperature of the solar panel itself.

Solar panels are most efficient at lower temperatures, and lose efficiency at a linear rate as modules' temperature rises. Module temperature rise is a direct result from being exposed to solar irradiation, and being surrounded by dry, hot air for extended periods of time. Higher wind speeds across the panel will offer convective heat transfer reducing the modules temperature, and is another important factor to take into account.

Almost all solar panels report a Temperature coefficient as part of the technical specifications, which specifies the efficiency (%) drop per degrees Celsius rise for the specific solar panel. There are three main categories of solar panels;

1. Polycrystalline solar cells
2. Monocrystalline solar cells
3. Thin-film solar cells

Polycrystalline solar cells will typically have a higher temperature coefficient when compared to monocrystalline and thin-film solar panel materials. Polycrystalline solar cells are also the cheapest solar cells and produce lower waste silicon than mono-Si and thin film solar panels simply due to utilizing lower grade silicon, not requiring pure silicon during production.

Monocrystalline solar panels are made of pure silicon, which offers a lower temperature coefficient comparatively to multi-Si, allowing the solar panels to operate at a higher efficiency in higher module temperatures.

Of these three categories of solar panels, thin film solar panels offer the lowest temperature coefficient, but are also highly space inefficient, requiring a much larger surface area of panel to harvest the same amount of electrical energy than mono Si or multi Si.

2.2.5 Analysis and results of PV systems

Nicholls et al. [62], Orioli and Di Gangi [67], Keoleian and Lewis [52], Kaldellis et al. [50], and Ren et al. [69] have shown that globally the installation of roof top PV systems are economically viable for the household mainly due to the local feed in tariff, electricity price and purchase price [62]. Not only being economically viable, PV systems mitigate substantial quantity of greenhouse gas emissions during their lifetimes, which coupled with the fact this is a renewable energy source, is the leading reason PV technology is growing so rapidly Bazilian et al. [20] and Fthenakis et al. [42].

Merei et al. [57] presented a techno economic analysis for the suitability of a photovoltaic system in a supermarket within Aachen, Germany, where the electrical costs of the supermarket can be reduced by 20% in 2016, showing that current photovoltaic technology has the potential for a large increase in energy sustainability, and so further highlighting the need to assess an economical study of a domestic system here, within Australia.

Darras et al. [26] presented a techno- economic case study of a PV/H2 hybrid system operating in France. It was found that a reduction in /kWh from 1.55/1.60 to 0.65/0.66 is possible with this system in place, and that the PV/H2 system could supply 48-50 days of off-grid activity.

Hosseinalizadeh et al. [38] and Guinot et al. [6] have proven that investing in PV roof top systems can provide economic benefits in the domestic market in Germany and Iran.

Research has also been conducted on the environmental and political impact of implementing a PV system domestically in Australia by C. Good [44], Hua, Oliphant and Hu [15], Oliva H. et al. [45], and Ma et al. [13], with general findings of a lower payback time of both energy and greenhouse gas emissions than the lifetime of the PV/T system researched.

These case studies show that with current technology hybrid solar energy technology can be economically viable; commercially and domestically.

2.2.6 Analysis and results of PV/T systems

In order to understand the viability and comparison between a PV system and a hybrid PV and solar thermal system, research into the technical performances presented by previously done research on PV/T systems is required.

As there are various different design types of PV/T systems utilizing different thermal transfer fluids, different rig set ups, operating under different priorities (prioritizing usable thermal energy gain or electrical energy), the research needs to be categorized by;

- The heat transfer fluid used by the system
- The solar panel size of the system (Commercial or residential)
- The electrical efficiency proposed by the system

A PV/T hybrid system consists of a PV system coupled with a solar thermal system. There has been some research conducted on the performance and efficiency of similar Photovoltaic/ thermal hybrid systems by Zhang et al. [14], Moradi et al. [61], T.T. Chow [24] and Mishra and Tiwari [58].

Chapter 3

Research Methodology

3.1 Solar Data collection

3.1.1 Weather Stations

The solar data required for the calculations of module temperature, system efficiency and therefore system power output are:

- Solar irradiation throughout the day (W)
- Ambient temperature surrounding the solar panels (degrees C)

The Bureau of Meteorology Australia [21] has many weather stations across NSW that report on the solar irradiation measured as a total over the day. A smaller percentage of these stations report the maximum and minimum ambient temperature measured. 5 cites surrounding the central business district of Sydney, NSW have been selected as they report both irradiation and ambient temperature, both required for theoretical system output calculation.

Figure 3.1: Weather stations around Sydney, Australia.

Sydney Harbour (wedding cake west)

The station height at Wedding Cake West is 6 metres elevation, located in the middle of Sydney harbour where the nearest headland or blockage to any equipment readings is 400 metres away. The weather station was opened in February of 1996, and records the ambient air temperature via a dry bulb temperature probe, and the solar irradiation as a total amount (kWh/m^2) that is recorded over a day.

As the temperature probe is 6 metres in the air, and the average residential building is 3 metres tall, there will be a temperature difference due to elevation. This rise in temperature is 3.94 degrees Celsius per 304.8 metres descended, 0.013 degrees C per metre descended [29].

Observatory Hill

The station height at Observatory Hill is 39 metres elevation, and the barometer is 40.2m. Although the weather station is surrounded by buildings, foliage and other constructions, the readings of solar irradiation and air temperature are unaffected due to the height of the equipment above potential interference.

Sydney Airport

The station height at Sydney airport is 6 metres elevation, surrounded by foliage 10metres away to the south west, with a maximum height of 4 metres. This indicates readings of solar irradiance and ambient air temperatures will not be impacted on by local mediums by a significant amount.

Riverview Observatory

The station height of Riverview Observatory is 40 meters tall and is surrounded by foliage, some 20-25metre tall trees north east of the station. Similar to Observatory hill weather station, these potential interference mediums won't play a significant effect on solar irradiance readings or ambient air temperature readings.

Unfortunately on the 9th of January 2015, Riverview Observatory gave it's last ambient air temperature measurement to the BoM. The last full year of data acquired from Riverview Observatory is 2014, where under 76% of the year has a daily ambient air temperature measurement. Although this will impact on total results obtained, the data can still be used in comparison to show datum trends between weather stations.

Canterbury Racecourse

The station height at Canterbury Racecourse is 3 metres elevation, surrounded by 2 metres tall wire fence, and under 40 metres away is foliage at a maximum height of 2 metres tall. These potential blockage won't impact on the solar irradiance readings and ambient air temperature readings by a significant amount.

Weather Station	Temperature Probe elevation (m)	Difference in ambient air temperature (degrees C)
1. Sydney Harbour (wedding cake west)	6.0	0.039
2. Observatory Hill	40.2	0.481
3. Sydney Airport	6.0	0.039
4. Riverview Observatory	40.0	0.478
5. Canterbury Racecourse	3.0	0.000

Table 3.1: Energy usage of an average size household within NSW, Australia, 2016

3.1.2 Graphing Solar Data

The solar irradiation data given by all sights, although at differing elevation, is a total solar irradiance reading across the whole day (kWh/m^2/day). To take these measurements, the BoM uses new CM-11 ground based pyranometers manufactured by Kipp and Zonen. This equipment is sensitive to wind, rain and thermal radiation losses to the environment, and so is shielded by 2 glass domes.

Although the solar beams transmission through the glass domes limit the reading of the detector, direct transmission through the transparent material is minuscule. Interference due to transmission issue are considered negligible up to 20 degrees from ground, where transmission through the glass plays a larger impact on overall solar irradiance readings [22].

Between the solar beam incident angles of 20 and 0 degrees from the ground an exponential drop in the level of solar beam energy is observed due to transmission through the atmosphere. This indicates that a small change in measurement accuracy is non-critical, and reflections of the sun beam off the dome due to the low angle of incidence compensate for loss of absorptance of the detector.

The ambient air temperature measurements are modified due to the temperature probes elevation difference for all weather stations, to an expected 3 metre height of rooftop solar panels.

Refer to Figure A.3, Figure A.4, Figure A.5, Figure A.6, Figure A.7 for the solar irradiation and ambient temperature data collected from the Bureau of Meterology at the 5 weather stations.

3.2 PV energy output

As solar panels absorb solar irradiation, they convert solar energy into usable electrical energy, and heat energy that is held in the solar panels. However, not only does the heat energy in the solar panel remain uncollected, but it also hinders the efficiency of the electrical energy produced by the solar panels. Simply put as the solar panel module temperature increases, the photovoltaic efficiency decreases, as shown in the work by K.

Nishioka et. al. [37].

The relationship between ambient temperature, solar irradiation and module temperature is expressed in the widely used equation:

$$Tmodule = Tambient + (NOCT - 20) * E/800 \tag{3.1}$$

This equation was derived by Florschuetz et al. [41], [40], and has been used by several articles such as Khelifa et al. [5], Jarimi et al. [35], Hocine et al. [8], and Garg, H.P. and Adhikari, R.S [43].

The equation uses the variables of ambient air temperature (degrees C) surrounding the solar panels, the solar irradiation (W/m^2), and the solar panels nominal operating cell temperature (NOCT) given by the cell manufacture's technical specifications. Using the ambient temperature and solar irradiation from the Bureau of Meteorology Australia, and the specifications of the solar panel, the Equation 3.1 can be used to determine accurate solar panel temperature as a daily average.

In order to convert the solar irradiance (kWh/m^2) to an average (W/m^2) over the day, the solar irradiance is divided by the expected length of day per season, reported by Bureau of Meteorology:

- January: 7 hours
- February: 7 hours
- March: 7 hours
- April: 6 hours
- May: 5 hours
- June: 5 hours
- July: 6 hours
- August: 7 hours
- September: 7 hours
- October: 7 hours
- November: 7 hours
- December: 7 hours

The solar panel efficiency is directly related to the panel's module temperature and the specifications of the panels themselves. The module'technical specifications gives a value of 0.34 loss in solar panel efficiency (%) per module temperature (degrees C) rise.

$$\eta_{PV} = \eta_{NOCT} - (0.34 * (T_{Module} - T_{NOCT}) \tag{3.2}$$

Parameter Required	Metric
Ambient Temperature	Variable (Degree C)
Solar Irradiance	Variable (W/m^2)
NOCT	45 (degrees C) [73], Figure A.8

Table 3.2: Parameters required for PV module temperature calculation

Weather Station	Maximum average output power for 2016 (W)	Total output power in 2016 (kW)	Estimated 2016 Yearly Total (kW)
Sydney Harbour (Wedding Cake West)	187.23	38.00	46.38
Observatory Hill	169.39	35.78	43.68
Sydney Airport	185.59	36.21	44.20
Riverview Observatory (2014)	165.04	41.64	N/A
Canterbury Racecourse	178.90	36.44	44.49

Table 3.3: Average and projected total power outputs

Therefore, average electrical energy generated per day by the solar panels is given by:

$$P_{Generated} = P_{SolarIrradiance} * \eta_{PV} \tag{3.3}$$

Using these formulas, and the area of the solar panel module studied within the report, collectable electrical energy generated per day can be found from the overall efficiency of the PV system.

Refer to Figure A.9, Figure A.10, Figure A.11, Figure A.12, Figure A.13 for the solar irradiation vs expected PV system output at the 5 weather stations.

Refer to Figure A.14, Figure A.15, Figure A.16, Figure A.17, Figure A.18 for the expected PV system output and polynomial trendline of order 5, at the 5 weather stations.

Refer to Figure A.19, Figure A.20, Figure A.21, Figure A.22, Figure A.23 for the module temperature VS module efficiency at the 5 weather stations.

The maximum average output power per day achieved by the solar panel system is less than the rated wattage of the system (200W) for all weather stations. This is expected as the system efficiency suffers due to the module temperature rise in the heat of an Australian day. In the cooler season of winter, the solar panel efficiency rises as the module temperature is significantly less than in summer, but there is also a significant reduction in solar irradiation. This reduction in solar energy means the system, although more efficient, still generates less electricity in winter than in summer.

The estimated yearly electricity generation of the system for 2016 is an averaged 44.68 kW across all weather stations. Although the average output power in a day of winter has the lowest value, the range of averages overlaps with the range of summer and autumn

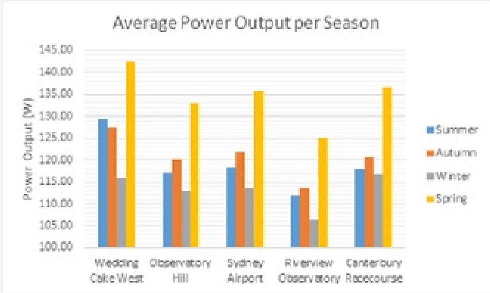


Figure 3.2: Average power output of each weather station per season

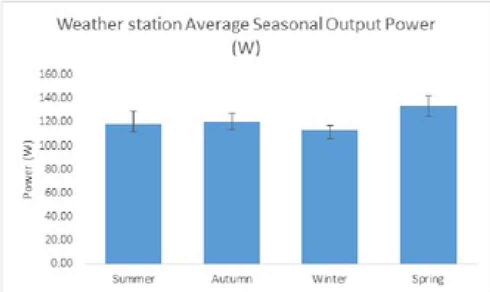


Figure 3.3: Average seasonal power output for all weather stations

values. It is expected that power output of the system will be greater in summer, but only by just over 5%, which isn't a significant difference.

The largest averaged values occur in spring, when daily ambient temperatures are lower than summer, and solar irradiation levels are higher than winter. All 5 weather stations share this trend, showing a 13.11% increase in averaged output power from summer, and a 19% increase from winter.

The systems estimated output graphs for each weather station also show this trend clearly. The 5th order polynomial trend lines, chosen for the 4 expected seasonal changes to irradiation levels and ambient temperatures, show a clear rise in the season of spring for all weather stations.

3.2.1 PV systems cost

The key costs associated with the life cycle of a photovoltaic energy collection system, as noted by the Australian solar institute are:

- Cost of equity, cost of debt, CPI
- Module costs, inverter costs

- Importer/ distributer system margins
- End system delivery margin/ installer margin
- Module efficiency

The base case system used by the APVA (Australian photovoltaic association) is reported as a polycrystalline solar panel of 1.5kW sizing, located in Sydney. Other base case input parameters used for calculation can be seen at Figure A.24.

A system breakdown of costings across the systems lifetime has been calculated and reported [18]. The report from late 2011 compares the average total cost of a standardised system against an individual design, showing that for a standardised 1.5kW polycrystalline system total costs would be approximately $7200, and for an individual design of the same parameters, total costs are approximately $8100. Refer to Figure A.25.

As the PV system at Macquarie University is an individually designed system, and only 200W, the expected pricing will be a smaller factor of the $8100 total cost of the 1.5kW residentially installed system.

The largest cost for the system reported by the APVA is the PV equipment cost, which for the smaller system will be approximately the same price per power. The distributer channel costs are assumed to cost the same for a smaller system. The structural and support cost should share a similar relationship to the PV equipment cost, being cheaper for a smaller system sizing at the same cost per kW.

The power balance of system (BOS) is the cost of all of the components of the system other than the panels themselves. This includes wiring, switches, mounting, and the inverter. It is assumed that even for a smaller system all these components will still be required, and the price for the smaller unit will the same. The system installation, end system channel costs will be assumed to have a cost to power size ratio equivalent to the PV equipment cost per kW.

This indicates that for a 200W system, the total capital cost will be $1526.67(incl. or ex. GST). The base case input parameters used reports a system lifetime of 25 years, meaning a costing of $61.07/ year, 16c/ day.

3.2.2 PV systems economic figures

As stated previously, The Australian Energy Market Commission has reported the grid electricity price as 30 c/kWh on average. As the small scale PV system won't produce more power than consumed by an average household in Australia, 100% of the electricity generated will be economically valued at grid-rates. For larger systems, it is expected that household electricity usage can only be covered 50% of the time, determining the fraction of power being utilized directly by the household at an electrical price of 30 c/kWh, and the excess being fed to the grid at the lower feed-in tariff of 6.45 c/kWh.

Weather Station	Total income for 2016 ($)	Total Profit for 2016($)	Payback period (years)
Sydney Harbour (Wedding Cake West)	73.11	23.08	20.9
Observatory Hill	68.67	18.64	22.2
Sydney Airport	69.55	19.53	22.0
Riverview Observatory (2014)	81.21	20.14	18.8
Canterbury Racecourse	69.93	19.90	21.8

Table 3.4: Economic figures for PV system costings and output in NSW, Australia, 2016

3.2.3 PV systems environmental impact

Sherwani et al. [71] collaborated many life cycle assessment studies of mono-crystalline PV systems, such as;

1. Schaefer et al. [70]
2. Prakash et al. [68]
3. Kato et al. [51]
4. Kannan et al. [11]
5. Mathur et al. [9]
6. Kreith et al. [7]
7. Muneer et al. [12]

Taking into account manufacturing, construction, installation and maintenance, the greenhouse gas emissions per kilowatt hour electricity produced by the solar panels are shown in Figure A.26.

These studies were conducted on older solar cell technology and show a trend of lowering GHG emissions per PV system each year. More modern studies further show this declining trend, such as;

Peng et al. [36] published there review in late 2012 showing that mono-Si PV systems, similar to the preposed small scale system, range from 29 to 45 grams of CO2 / KWh GHG emissions produced.

Published in 2012, the U.S department of energy (Hsu et al. [33]) screened 397 life cycle assessments, and of those that met the screen standard, reported for PV crystalline silicon, finding a median estimate of 45 g CO2e/ kWh, with module efficiency of 13.2% to 14.0%, expected lifetime of 30 years, using an average solar irradiation of 1700kWh/m^2/yr.

The national renewable energy laboratory in the U.S [64] reported similar finds of 55 g CO 2 e/ kWh.

A publication in february 2016 by Hou et al. [34], provided results of GHG emissions ranging from 60.1 to 87.3 g CO2 e/ kWh. These figures are generally higher than the expected results for 2016 solar technology, which may be due to several key factors:

- China's level of solar irradiation
- China's ambient temperature averages across the year
- Quality of PV technology used in the study

Similar to Sherwani et al., Wong et al. [77] conducted a review of previous LCA studies from 2004 to 2014, showing averages for both single silicon and multi silicon solar panel systems. The single silicon systems average for GHG emission is 171.2 g CO2/kWh. Refer to autoreffig:LCAofmono-crystallinesolarPVsystems2.

Amalgamating these previous LCA studies, taking the GHG emissions per kWh produced by the PV system, a plot of emission against year was established:

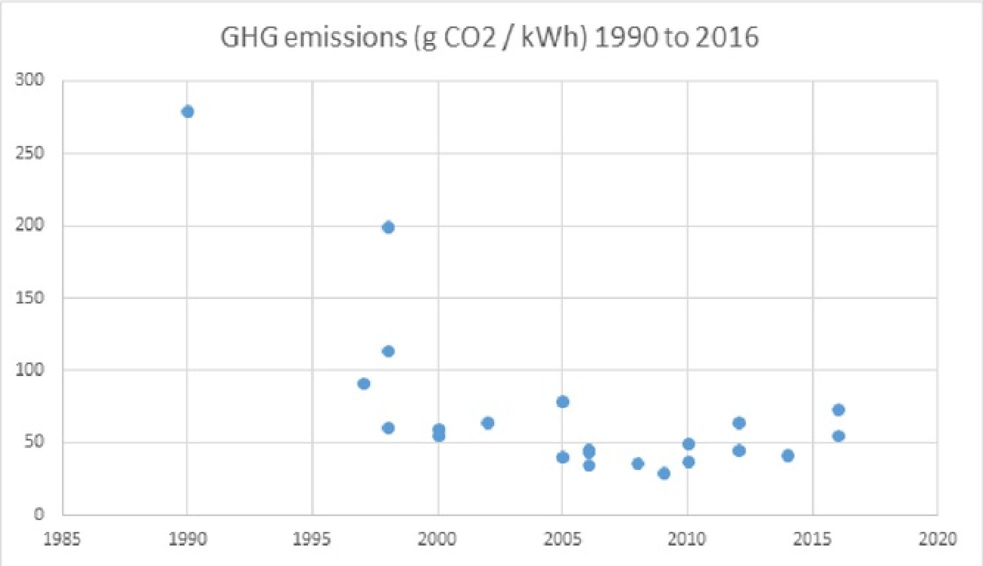


Figure 3.4: GHG emissions for PV systems from 1990 to 2016

As shown, the largest outliers in 2006 (Kannan et al.) show a clear difference to the declining trend of greenhouse gas emissions per kWh produced. These findings by Kannan et al. were updated by Fthenakis and Alsema with actual manufacturing production data, and were found to give a reading of 45 g CO2 / KWh.

Removing pre 2000 studies, and updating Kannan et al.'s work, a trend line is found for a greenhouse gas emission per kWh produced for a small scale solar panel system from the LCA studies included. The findings show a GHG emission rating of 50.51 g CO2/ kWh produced.

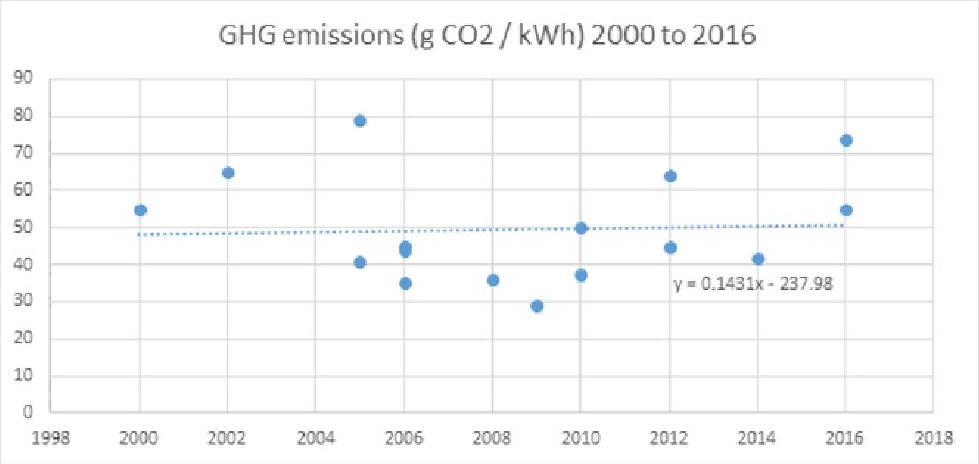


Figure 3.5: Updated GHG emissions for PV systems from 2000 to 2016

3.3 PV/T energy output

s There have been many studies into the performance of hybrid systems, and further study into the optimization of such systems using differing techniques such as different cooling fluid, flow rates, and cooling methods. Studies that are based on PV/T water based cooling systems shed light on the performances of devices very similar to the PV/T hybrid system being researched.

3.3.1 Previous studies findings

H.G. Teo [74] shows that a PV/T air cooling based system will achieve a linear temperature reduction of 10 degrees Celsius at an irradiation of 600 W/m^2, that increases to a temperature reduction of 13 degrees Celsius at an irradiation of 1000 W/m^2.

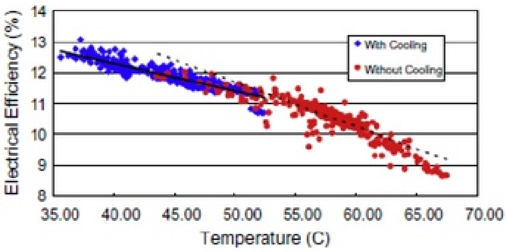


Figure 3.6: H.G. Teo [74] Electrical Efficiency as a function of PV temperature

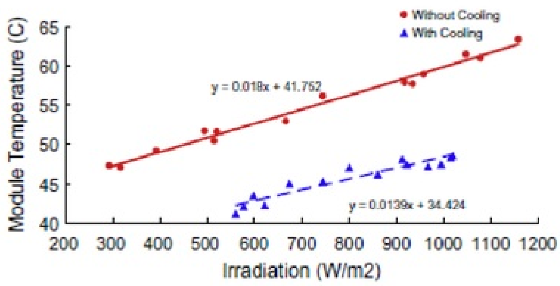


Figure 3.7: H.G. Teo [74] module temperature as a function of solar irradiation

Teo's experimental set up, being 1300mm long and 600mm wide, is of similar scale size to that of the PV/T system set up at Macquarie University.

In his research article, H. Hocine [8] shows that at 1000 W / m^2, and ambient temperature 298K, the solar cell temperature will be 355.29K using a PV/T water based cooling system of 1.290mm long and 330mm wide. Again, the size is appropriate to the scale of the PV/T system being studied.

K.E. Amori [17] shows that a PV/T air based system of domestic size (two sheets of 1200mm long,x 450mm wide) can achieve an electrical efficiency of between 9% and 10% for the solar panels on a summer day in Iran (ambient temperature average of 40 degrees C and solar irradiation between 800 and 1200).

At 12hours within this experiment, using Equation 3.2; ambient temperature 45 degrees C, solar irradiation 1200 W /m^2, gives a cell temperature of 82.5 degrees C. The experiment reads a cell temperature of 80 degrees C. This shows that the solar cell temperature reduction achieved by this air based coolant PV/T system is very minimal in solar conditions relative to an average day in Australia.

A. Khelifa [5] shows for a domestic scale (1300mm long and less than 400mm wide) PV/T system, a cell temperature reduction of 15-20% due to the flow of water through the manifold to the rear of the PV panel is observed. These results were obtained across a day with maximum solar irradiation readings of 1000 W/m^2, and average ambient temperatures of 30.6 degrees C.

A graph of outlet temperature of the water acting as coolant throughout the PV/T system against the time of day shows that predictable thermal energy extraction can be made in the heat exchanger. This experimental data is useful to extrapolate how the heat exchanger will act on an average sunny day in Australia, but further research into the more extreme temperature ranges a PV/T domestic system will be prone to needs to be conducted.

K.A. Moharram [59] conducts experiments on solar panels that have been water cooled to maintain working temperatures of under 45 degrees C. Results show that the efficiency of the solar panels can stay high if the reduction of the plate's temperature is kept rela-

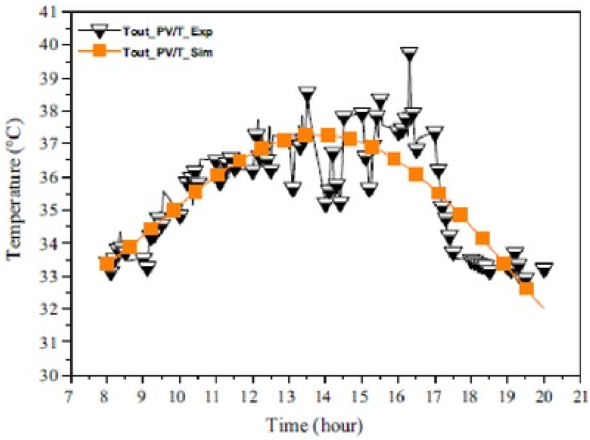


Figure 3.8: A. Khelifa [5] evolution of the outlet temperature of the PV/T system

tively constant at 45 degrees Celsius, as proposed by previously mentioned papers.

In summary; Teo shows a PV/T system optimization of the system by keeping the plates temperature below 50 degrees Celsius. Hocine's work shows poor efficiencies at high plate temperatures of over 80 degrees C. Amori shows PV/T technology that harvests thermal efficient energies even without solar panel temperatures being limited to under 45 degrees, C. Khelifa shows the panel temperature can be effectively reduced by 15-20%, and K.A. Moharram suggests keeping plates to maximum allowable temperature of 45 degrees.

These previous studies indicate using the assumption that the PV/T system is to operate under a constant module temperature of 45 degrees Celsius in hot weather, by changing the rate of heat extraction from the plates by the thermal sub-system of the PV/T system, and turning the thermal sub-system off if theoretical module temperature stays below 45 degrees C.

L. Marletta's [56] set up shows much detail into the mathematical modelling of conductive heat factors between the solar panels and the water based acting coolant. These models are important for the understanding of how the panel operates given solar irradiation, ambient temperature, and wind speed data. Marletta assumes the wind speed is a constant, and graphs the performance of the PV/T system:

This graph Figure 3.9 shows efficiency as a function of Plate temperature, Ambient Temperature and Irradiance level. Figure 3.9 also shows that the PV/T collector overall performs much better when the solar Irradiance is much higher, and the temperature difference between the solar panels and the ambient temperature is lower. These findings can be utilized to show the outcomes given Australian weather conditions found previously.

Using the formula found from L. Marletta's work:

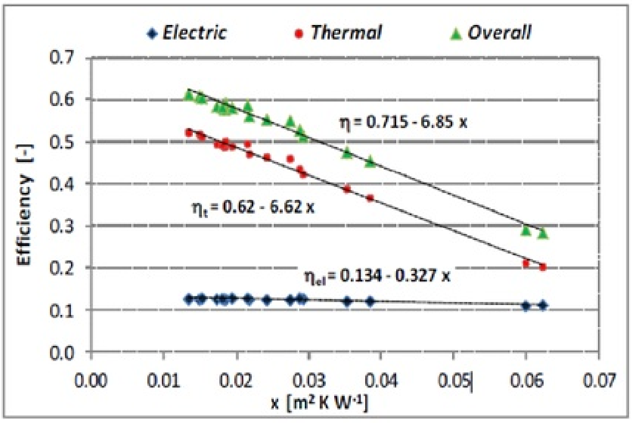


Figure 3.9: L. Marletta's efficiency curves for the prototype PV/T system

$$\eta_t = 0.62 - 6.62x \tag{3.4}$$

Where:

$$x = (T_{(PV/Tpanels)} - T_{ambients})/I_{Solar} \tag{3.5}$$

As per the assumptions, PV/T panel temperature will ramin at 45 degrees C:

$$\eta_t = 0.62 - 6.62((45degreesC) - T_{ambients})/I_{Solar} \tag{3.6}$$

$$\eta_{(overallPV/T)} = \eta_t + \eta_e \tag{3.7}$$

3.3.2 PV/T energy output

Wedding Cake West

Electrical Maximum power output (kWh)	1.75
Thermal Maximum Power output (kWh)	5.77
Total Electrical output (kWh)	268.05
Total Thermal Output (kWh)	619.61
Total combined (kWh)	887.65
Projected Yearly Average (kWh)	1083.59

Table 3.5: Theoretical output figures of PV/T system at weather station: Wedding cake West

Observatory Hill

Electrical Maximum power output (kWh)	1.77
Thermal Maximum Power output (kWh)	5.96
Total Electrical output (kWh)	263.12
Projected Yearly Average (kWh)	321.20
Total Thermal Output (kWh)	653.06
Total combined (kWh)	916.18
Projected Yearly Average (kWh)	1118.41

Table 3.6: Theoretical output figures of PV/T system at weather station: Observatory Hill

Sydney Airport

Electrical Maximum power output (kWh)	1.78
Thermal Maximum Power output (kWh)	6.15
Total Electrical output (kWh)	266.75
Projected Yearly Average (kWh)	325.63
Total Thermal Output (kWh)	663.06
Total combined (kWh)	929.81
Projected Yearly Average (kWh)	1135.05

Table 3.7: Theoretical output figures of PV/T system at weather station: Sydney Airport

Riverview Observatory

Electrical Maximum power output (kWh)	1.86
Thermal Maximum Power output (kWh)	6.57
Total Electrical output (kWh)	328.90
Total Thermal Output (kWh)	866.44
Total combined (kWh)	1195.34

Table 3.8: Theoretical output figures of PV/T system at weather station: Riverview Observatory

Canterbury Racecourse

Electrical Maximum power output (kWh)	1.78
Thermal Maximum Power output (kWh)	6.15
Total Electrical output (kWh)	265.95
Projected Yearly Average (kWh)	324.66
Total Thermal Output (kWh)	642.72
Total combined (kWh)	908.67
Projected Yearly Average (kWh)	1109.25

Table 3.9: Theoretical output figures of PV/T system at weather station: Canterbury Racecourse

Summary of PV results

Weather Station	Maximum average output electrical power for 2016 (kWh)	Maximum average output thermal power for 2016 (kWh)	Total output electrical power in 2016 (kWh)	Projected Yearly Electrical Total (kWh)	Total output Thermal power in 2016 (kWh)	Projected Yearly Combined Total (kW)
Sydney Harbour (Wedding Cake West)	1.75	5.77	268.05	327.21	619.61	1083.59
Observatory Hill	1.77	5.96	263.12	321.20	653.06	1118.41
Sydney Airport	1.78	6.15	266.75	325.63	663.06	1135.05
Riverview Observatory (2014)	1.86	6.57	N/A	328.90	866.44	1195.34
Canterbury Racecourse	1.78	6.15	265.95	324.66	642.72	1109.25

Table 3.10: Summary of theoretical output figures of PV/T system

Refer to Figure A.28, Figure A.29, Figure A.30, Figure A.31, Figure A.32 for the PV/T theoretical thermal and electrical generation for all weather stations.

Refer to Figure A.33, Figure A.34, Figure A.35, Figure A.36, Figure A.37 for the PV/T theoretical module tmperature against the thermal and electrical efficiency for all weather stations.

3.3.3 PV/T systems cost

The PV/T system designed and built by Niko de Leon, Macquarie University, has three main subsystems:

- Solar panel System
- Hot water System
- Data acquisition system

The difference between a PV domestic system and a PV/T domestic system will arise from the hot water sub-system, as the data acquisition sub-system will not be included in domestic scale production and installation.

The hot water sub-system is made of several components;

1. 50 litre hot water tank
2. 12V hot water pump
3. Heat exchanger unit
4. Hosing to and from the hot water tank

The components required to build the thermal sub-system of the small scale hybrid solar collector are:

50 litre hot water tank

The 50 litre hot water tank used was a dux proflo 50L electric storage water heater, which was chosen by Niko for its thermal storage characteristics, used only as a water storage unit. Niko reported the dux proflo hot water tank cost \$360. Its warranty life is 7 years, which suggests the hot water tank will need replacing within every 10 year period, meaning that three tanks will be required for a 25 year lifetime.

A total of \$1080 for the hot water storage tanks, at \$43.2 per year.

12V hot water pump

The 12V DC circulating pump is required to circulate water throughout the heat pipes, heat exchanger, and into/ out of the hot water storage tank. Niko reported the DC circulating pump to cost \$100. It is rated for 30,000 hours of pump life, meaning at an average 6.5 hours of operation life a day, the pump is expected to have a workable lifetime of 12.5 years. For a PV/T system lifetime of 25 years, 2 heat pumps will be required. A total of \$200 for the hot water pumps, at \$8 per year.

Heat exchanger unit

The heat exchanger unit is comprised of a header (808mm x 60mm x 60mm) made from sheet copper, 6 copper heat pipes (1620mm x 20mm diam.), 4 aluminium (808mm x 20mm x 20mm) strips for heat pipe mounting, 2 silver connectors either side of the heat header, and several silver solder joints. The aluminium strips used as support are considered to be a part of the PV system, as they are required to support not only the copper heat pipes, but the solar panels as well.

Niko reported the heat pipe header (heat exchanger) to cost $100, the copper heat pipes to cost $150. The 2 silver connectors cost $20 and the silver solder can be assumed to be costed under installation fees. Copper and silver are expected to last longer than the lifetime of the PV/T system (¿25 years).

Niko reportedly took 7 working days to complete the heat exchanger set up, and install all components onto the PV system to make up the hybrid collector. For the purpose of this report, an estimated 1 working day will be given for the assembly and installation of the heat exchanger at an average metal workers wage of $23.42 an hour, total $140.52 [60].

A total of $410.52 for the heat exchanger unit components, assembly and installation, at $16.42 per year.

Hosing to and from the hot water tank

The hosing used to connect the heat exchanger, the water pump, and hot water tank, was made of stainless steel braided water connectors commonly used in most household appliances, insulated in polyurethane foam rubber to reduce heat loss through the piping. 10 metres of stainless steel braided length insulated with polyurethane foam rubber is required, costing $6.74 per meter.

A total of $67.40 for the water hosing, at $2.3 per year.

Summary of PV/T costings

Component	Cost per year ($/ year)
Hot Water Storage Tank	43.2
Hot Water Pump	8
Heat exchanger	16.42
Water hosing	2.3
Total Hot Water Sub-system	69.92
Total PV/T System	130.99

Table 3.11: Summary of PV/T costings for all sub-systems

In total the thermal sub-system addition to the PV system will cost $69.92 per year, an additional 19c/ day for 25 years. This means in total the PV/T system costs $130.99 per year, at 36 c/ kWh.

3.3.4 PV/T systems economic figures

The electrical energy collected by the solar panel sub- system of the PV/T system, as determined before, will produce an income of 0.3c / kWh per day up to the production of 6.9 kWh. After this threshold the remaining power will be fed into the grid at a feed-in tariff rate of 6.45 c/kWh.

The thermal energy collected will be comparative to the cost to heat water in NSW. The cheapest system for hot water generation in NSW currently is instantaneous gas as reported by the Office of Environment and Heritage, NSW Government [32].

As reported by Industry Australia; gas price trends [46], Instantaneous gas price trends from 2006 to 2015 show a steady incline for NSW, recently spiking towards 4 cents per MJ, which is 14.4 c /kWh.

Wedding Cake West

Total Yearly Savings/ Loss ($)	62.33
Projected yearly savings ($)	76.09
Total % of profitable days (%)	0.72
Amount of Profit in Summer ($)	28.80
Amount of Profit in Autumn ($)	16.68
Amount of Profit in Winter ($)	-1.87
Amount of Profit in Spring ($)	18.00

Table 3.12: PVT Predicted economic figures for solar data from weather station: Wedding Cake West

Observatory Hill

Total Yearly Savings/ Loss ($)	65.67
Projected yearly savings ($)	80.17
Total % of profitable days (%)	0.74
Amount of Profit in Summer ($)	30.34
Amount of Profit in Autumn ($)	17.56
Amount of Profit in Winter ($)	-1.48
Amount of Profit in Spring ($)	18.50

Table 3.13: PVT Predicted economic figures for solar data from weather station: Observatory Hill

Sydney Airport

Total Yearly Savings/ Loss ($)	68.20
Projected yearly savings ($)	83.26
Total % of profitable days (%)	0.75
Amount of Profit in Summer ($)	31.46
Amount of Profit in Autumn ($)	17.93
Amount of Profit in Winter ($)	-1.12
Amount of Profit in Spring ($)	19.17

Table 3.14: PVT Predicted economic figures for solar data from weather station: Sydney Airport

Riverview Observatory

Total Yearly Savings/ Loss ($)	92.45
Total % of profitable days (%)	0.76
Amount of Profit in Summer ($)	45.94
Amount of Profit in Autumn ($)	11.22
Amount of Profit in Winter ($)	-2.07
Amount of Profit in Spring ($)	37.36

Table 3.15: PVT Predicted economic figures for solar data from weather station: Riverview Observatory

Canterbury Racecourse

Total Yearly Savings/ Loss ($)	65.03
Projected yearly savings ($)	79.39
Total % of profitable days (%)	0.75
Amount of Profit in Summer ($)	30.01
Amount of Profit in Autumn ($)	17.17
Amount of Profit in Winter ($)	-1.55
Amount of Profit in Spring ($)	18.65

Table 3.16: PVT Predicted economic figures for solar data from weather station: Canterbury Racecourse

Summary of PV/T economics figures

Weather Station	Projected Yearly Savings ($)	Payback period (years)	Profit in Summer ($)	Profit in Autumn ($)	Profit in Winter ($)	Profit in Spring ($)
Sydney Harbour (Wedding Cake West)	76.09	15.8	28.8	16.68	-1.87	18
Observatory Hill	80.17	15.5	30.34	17.56	-1.48	18.5
Sydney Airport	83.26	15.3	31.46	17.93	-1.12	19.17
Riverview Observatory (2014)	92.45	14.7	45.94	11.22	-2.07	37.36
Canterbury Racecourse	79.39	15.6	30.01	17.17	-1.55	18.65

Table 3.17: Summary of theoretical PV/T economics figures

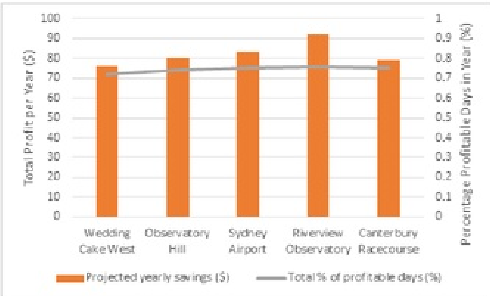


Figure 3.10: Average profit per day, Percentage of profitable days per weather stations for the PV/T system

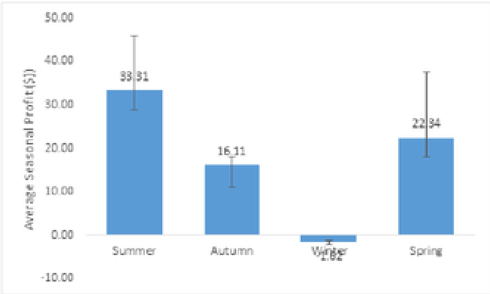


Figure 3.11: Average Seasonal Profit of all weather stations for PV/T system

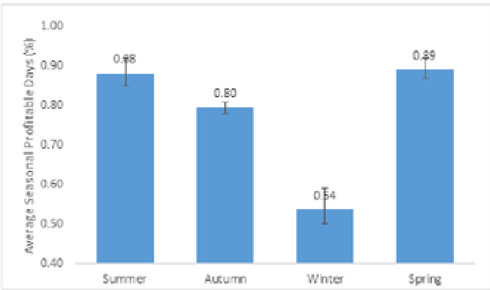


Figure 3.12: Average seasonal percentage of profitable days of all weather stations for PV/T system

3.3.5 PV/T systems environmental impact

For the purpose of environmental impact assessment of the PV/T system, the solar panel sub-system used will be assumed to produce the same GHG emissions as the stand alone PV system. The estimated GHG emissions produced by the hot water sub-system components are:

50 litre hot water tank

The hot water tank is made of a mild steel cylinder, which is reported to produce between 1.12 and 2.55 t CO2 e/ t steel. This range comes from a recycle based steel production, or primary production /cite67.

It is also important to note that steel is highly recyclable, being that The Australian Steel Institute claims the steel recycling rate in Australia is 80-90%. Therefore using 85% and interpolating between 1.12 and 2.55 t CO2/ t steel will be used, at 1.29 t CO2/ t steel. From the technical specifications sheet for the DUX proflo water tank, the dimensions of the cylinder are 694mm x 405mm diam. Assuming the steel is 5mm thick, the volume of steel used is 0.00497 m^3, therefore 39.04 kg of steel.

This equates to 50.36 kg of CO2 being emitted for the production and manufacturing of one hot water storage unit. The PV/T system will require three hot water tanks for a lifetime of 25 years, meaning 151.08 kg of total CO2 emissions.

12V hot water pump

The 12V hot water pump used is made of the following materials [55]:

- Hi-Temp Ryton Plastic- PPS (food grade)
- Brass Inlet/Outlet
- Viton "0" Ring
- Hi-Temp Ryton (PPS) Impeller
- Ceramic Ferrite Magnet

This component is assumed to have less than a 5% effect on the overall environmental impact to the PV/T system that GHG emissions are considered negligible from the 12V hot water pump.

Heat exchanger unit

For the purpose of this report the environmental impact of the silver connectors and silver solder joints, both materials and manufacturing/ assembly processes will be considered negligible.

Component	**Total GHG Emissions over 25 years (kg CO2 e)**
Hot Water Storage Tank	151.08
Heat exchanger	190.98
Water hosing	10.03
Total GHG emissions	352.09
Total GHG emissions per year	14.0836

Table 3.18: Summary of GHG emissions for PV/T system

The heat header and heat pipes make up 0.0059 m^3 of copper, meaning 53.30 kg of copper was used [30].

As reported by Northey et al. [63], who conducted a comprehensive collaboration of sustainable reports on the environmental footprint of copper mining, an average of 2.6 t CO2 / t Cu was found from copper production from various copper mines in Australia, Chile, Peru, Argentina, Laos, Papua New Guniea, South Africa, Turkey, Finland, the USA and Canada.

Memary et al. [39] presented a time-series LCA cradle-to-gate for the years 1940 to 2008 to review the environmental impact of copper mining and smelting in Australia. The carbon footprint was found to range from 2.5 to 8.5 kg CO2 / kg Cu, which largerly largely agrees with Northey et al.'s findings.

This indicates that the estimated carbon footprint of copper used for the proposed PV/T system is 138.59 kg of CO2 emissions.

Due to production of Aluminium requiring mining of bauxite, extraction of alumina, and refining into aluminium, the environmental impact of aluminium production is much larger than copper, as reported by the Australian Aluminium Council LTD [65] as 14.9 t CO2 / t aluminium produced.

This means for the use of 0.00129 m^3 of aluminium extrusion (3.516 kg), 52.39 kg of CO2 emissions where produced [75].

Therefor, the total GHG emissions to produce and assemble the heat exchanger is 190.98 kg CO2.

Hosing to and from the hot water tank

The production of stainless steel, as reported by the International Stainless Steel Forum (ISSF) [66] produces 2.9 t CO2 e/ t stainless steel. The stainless steel required for 10 metres of braided water connectors is 0.00044 m^3 of stainless steel, meaning 3.46 kg of stainless steel is used, and 10.03 kg of CO2 emissions produced.

Summary of GHG emissions of PV/T system

The estimated total GHG emissions for one year is 14.08 kg of CO2, which can be divided by the calculated total solar energy generated across the year to give emissions per kWh

Weather Station	Estimated emissions of Thermal system (g CO2 e / kWh/ Year)
Sydney Harbour (Wedding Cake West)	12.99
Observatory Hill	12.59
Sydney Airport	12.40
Riverview Observatory (2014)	11.78
hline Canterbury Racecourse	12.69
Average	12.49

Table 3.19: Summary of predicted GHG emissions per weather station annually for PV/T system

produced by the system. Shown here:

As the PV system was estimated to produce 2.0204 g CO2/ kWh/ Year from previous LCA studies and literature.not a sentence. This emission rating was for an energy generation total of 283.042 kWh for 2016, which is equivalent to 0.51 g CO2 / kWh/ Year for the PV part of the PV/T system.

Therefor the total emissions for the PV/T system is 13.00 g CO2/ kWh/ Year.

3.4 LCA of PV/T system

When conducting an LCA, there are standards created by the International Organization for Standardization (ISO) [49], one being the ISO 14040 standard describing the principles and frameworks for life cycle assessment. In conducting a LCA, there are four major steps:

- Goal and Scope definition
- Inventory Analysis
- Impact Assessment
- Interpretation of results

These major steps are iterative, meaning that advances in the inventory analysis may change the goal and scope of the LCA.

3.4.1 Goal and Scope of LCA

The intended application of this LCA study is to determine the economic and CO2 equivalent GHG emission cost of components and assembly of the small scale PV/T hybrid system components in order to assess the economic and environmental impact benefits of a hybrid solar system of a PV solar system.

In accordance with ISO 14040, the function of the product is to reduce the solar panel temperature via a heat mass system that also collects heat energy within a hot water tank in order to aid hot water systems within the household. This is done by 4 sub-sectional components:

1. 50 litre hot water tank
    - Mild steel cylinder of 695mm x 205mm diam.
    - Coated in vitreous enamel
2. 12V hot water pump
3. Heat exchanger unit;
    - 1 Copper extrusion header unit of 808mm x 60mm x 60mm, machined from sheet copper
    - 6 Copper heat pipes of 1620mm x 20mm diam.
    - 4 aluminium extrusion strips of 808mm x 20mm x 20mm
    - 2 silver connectors
    - Silver solder used in assembly
4. Hosing to and from the hot water tank

- Stainless steel braided water connecter of 20mm diam.
- Polyurethane foam rubber insulator

The system boundaries are defined by:

- The raw material Gathering processes for the mild steel, aluminium and copper
- The production; Manufacturing and assembly of the raw materials for the hot water tank, heat exchanger unit and hosing water connectors
- The system use process of using water and a small electrical input (water pump) to harvest solar energy
- The energy supply for these processes
- The transportation costs for these processes

As this LCA is conducted on a stand-alone system, no system allocation of inputs and outputs will be assigned to reduce sensitivity calibration of the LCA. As this is a research thesis, the data quality will be 100% secondary data, being that all sources of data of economic figures or greenhouse gas emissions are from GaBi's database, or from researched literature.

Throughout the building of the PV/T software model, reporting on the quality of data will be documented as to assess the relevance and accuracy of the data used for LCA:

- Time reference: how recent was the data obtained
- Location: what geographical location is the data relevant to
- Technology used to obtain data: how modern was the data recording technology
- Precision: How accurate is the data in reference to the system
- Completeness: How complete is the data set, what weighted percentage of data required for the system is missing

3.4.2 Life Cycle Inventory Analysis

The life cycle inventory (LCI) is the design of the PV/T hybrid system within the LCA program GaBi. The inventory analysis is important to be broken down into to stage as defined by ISO 14040 and ISO 14044. These stages include classifying data inputs and outputs, collecting data, relating data to the built functional unit, and refining the system boundary to the dataset acquired. Again, this is an iterative process that requires the system goals to be flexible to fit the LCI, and the LCI to address the system goals.

Data classification

Raw Material inputs: The raw material inputs being studied will include the mild steel for the hot water tank, the aluminium support extrusions for the copper heat pipes under the solar panels, the copper heat pipes and copper extrusion for the header unit.

Energy Inputs: The energy inputs include the energy required for the raw material gathering, and the energy required for the manufacturing and assembly of the components of the PV/T system.

Water Inputs/ Outputs: The water input into the thermal system comes from mains water supply, and is assumed to be utilized by the household after system use.

Aluminium

The production of aluminium requires several key steps, namely mining of bauxite, chemical processing to produce alumina, then electrolysis to produce pure aluminium. These steps usually involve:

- Strip Mining of top soil
- Alumina refining via the Bayer process
- Primary production via the Hall- Hroult electrolytic process

An important factor to consider is the recyclability of aluminium, as it can be reused and save more than 90% of the energy required to gather the same quantity of aluminium via mining and refining [16].

Steel

The production of steel is a lengthy process requiring iron ore, limestone and coal. The whole process can be broken into 6 steps:

- Ironmaking: Inputting iron ore, limestone and coke to produce pig iron
- Primary steelmaking: Oxygen is blown through the hot metal to reduce the carbon content or;
- Secondary Steelmaking: the treatment of hot metal mixed with scrap via stirring, ladle furnace, ladle injection, degassing or CAS-OB
- Continuous casting: casting of molten steel into cooled mould
- Primary forming: Cast steel is formed into desired shapes
- Manufacturing, Fabrication and Finishing: secondary forming techniques

This process does involve using scrap, but isn't as recyclable as aluminium as there is a heavy energy cost associated with refining scrap materials.

Copper

The production process of copper has 5 major steps; mining, concentrating, smelting, refining and casting. The waste products from copper production include arsenic, lead and other chemicals which have a large environmental impact.

3.4.3 Summary of LCA status

The lifecycle assessment is a time and resource consuming process requiring vast amounts of data to provide accurate accounting for the primary and secondary environmental impact of the system being researched. This project has highlighted the key components, and the key materials required to produce those components, and provided the ground work for a full LCA of the PV/T system.

The goal and scope of the LCA has been defined, and initial mapping of the full lifecycle process of the system has been established.

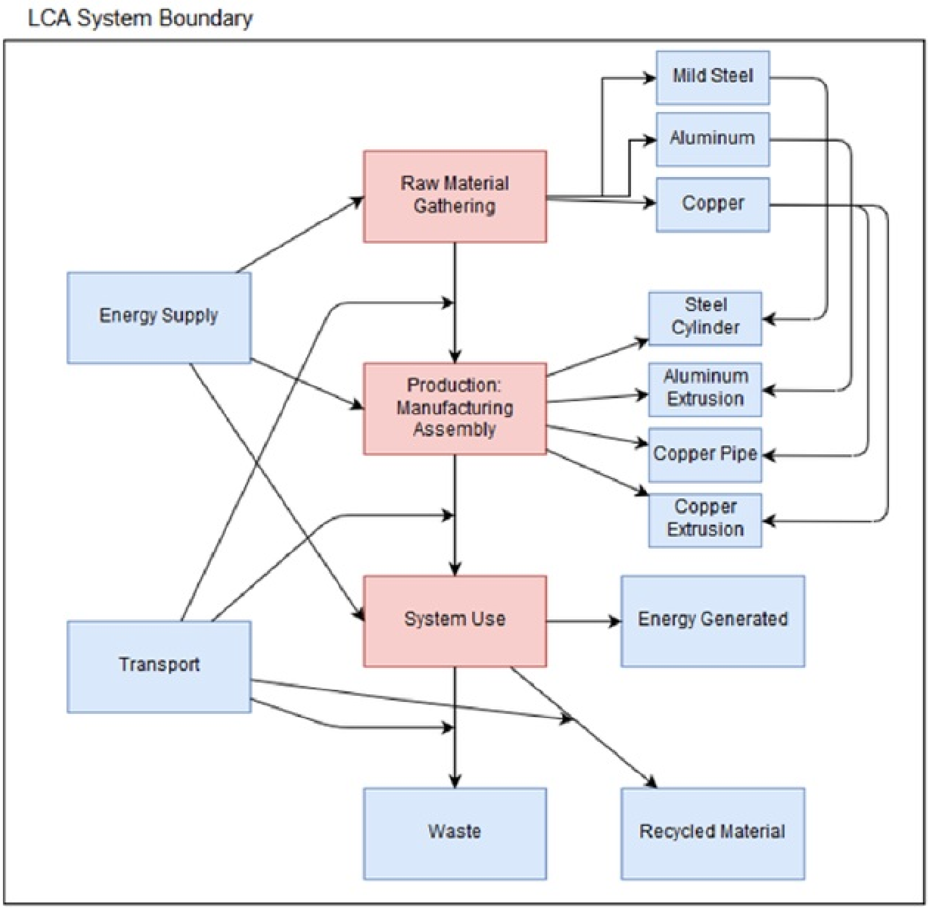


Figure 3.13: LCA system boundary

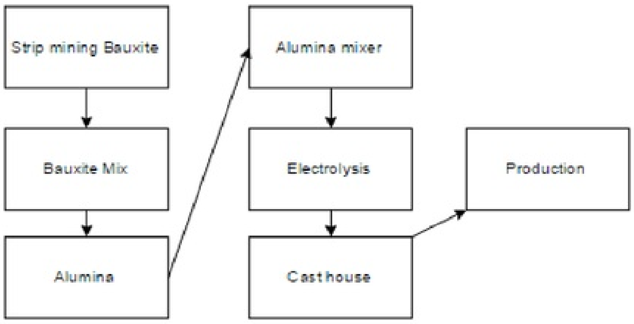


Figure 3.14: Production flow diagram of Aluminium LCA process

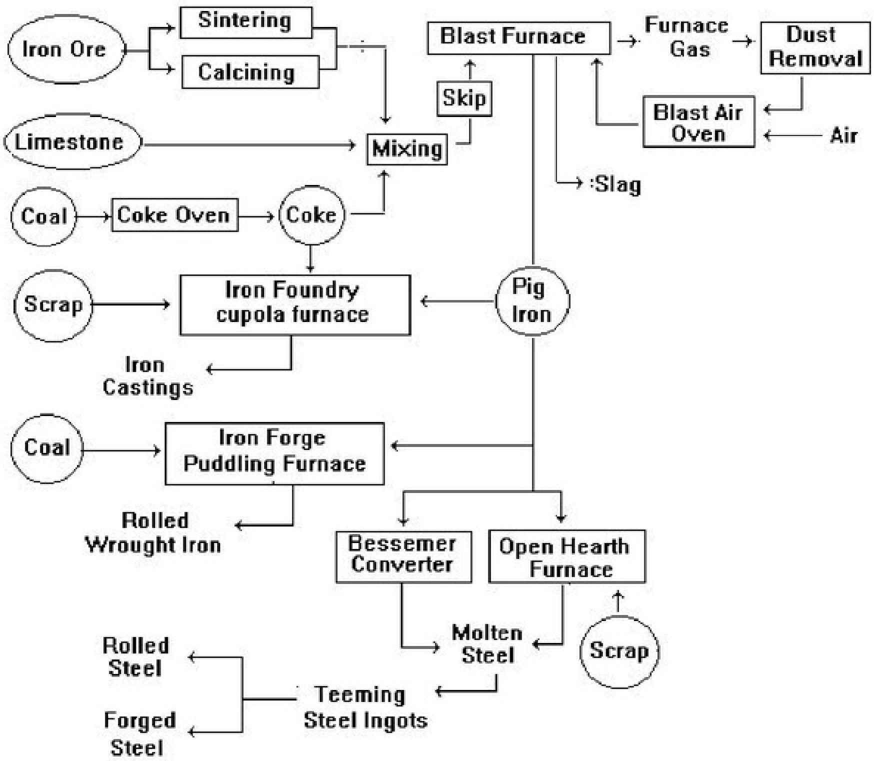


Figure 3.15: Production process of steel

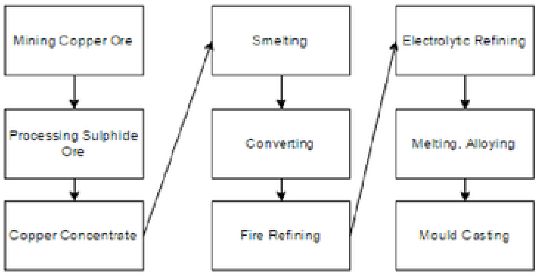


Figure 3.16: Production process of copper

Chapter 4

Discussion

This thesis intends to highlight the main differences between solar panel systems and hybrid PV and solar thermal systems, in terms of economic performances and the environmental impact. The PV/T system built at Macquarie University has a solar panel set up rated for 200Wp, which is substantially smaller than most domestically installed PV systems. The average size PV systems installed in Australian households in 2016 are between 3 and 5kW, arising from an average between 1kW and 2kW in 2010 [23].

Studying the performances produced by a lower rated system are important in understanding what results will be obtained without the larger financial investment overhead required for larger systems. But the theoretical data produced by a smaller system will show key differences to actual domestic scale installations which are discussed in further detail in this section.

Points of discussion focused on will include:

- The selection of the 5 weather stations as to simulating weather conditions expected for a household in NSW, and the daily solar and ambient temperature data received from the 5 selected weather stations
- The PV modules' techno-economic performance, and seasonal performance patterns across 2016
- The hybrid collectors' (PV/T) techno-economic performance, and seasonal performance patterns across 2016
- The Lifecycle assessment study conducted on the PV/T system built at Macquarie University.

4.1 Solar Irradiation Data

The weather stations selected are the 5 stations closest to the CBD of Sydney, NSW. These 5 stations record various different types of weather behaviours, but most importantly record the ambient temperature on the day and the total solar irradiation power across the day. These 5 stations don't adequately cover all of NSWs' geographically, but are focused on covering the most population dense area of NSW, therefore covering a larger percentage of households in NSW.

4.1.1 Solar Irradiation Profile

The solar irradiation data given by the BOM presents the solar power total across the day, rather than solar energy intensity measured at points across the day. Although a solar irradiation profile for the day can't be produced, the total of irradiation power that would be received by the panels is given.

This plays a large role in determining the true output of a PV system, where calculations are based off of a solar irradiation daily average, which negates the fact that the panels suffer severe efficiency lose at low solar intensity such as sub 400 W/m^2. Solar power recorded at dusk and dawn when intensities are below 400 W/m^2 should be discarded, which will produce a difference between total solar power and total usable solar power by the PV system. This difference means the calculated PV daily power output results will be higher than expected panel output.

As the data used is only a total, this change in true usable solar irradiation can be addressed in further research.

4.1.2 Maximum ambient Temperature

The ambient temperature figures used are the maximum ambient temperature recorded by the weather stations per day. The data offered by the BOM doesn't give daily profiles of ambient air temperatures across the day, but only minimums and maximums. The maximum air temperature across any day isn't sustained for very long, and varies significantly across the day.

This means for PV output results based off of the modules temperature in the day will be at a lower efficiency than what is actually experienced across the day. This indicates that the results of daily panel output are lower than expected panel output.

As solar irradiation data will produce an estimation of panel output higher than the expected, and maximum ambient temperature used for the day will produce an error lower than the expected output, the two errors should counter-act each. This is an error that can be further developed by more accurate data sets.

4.2 PV output calculation

In determining a calculated PV system output an efficiency formula utilizing solar irradiation and ambient air temperature was used to predict module temperature, and there for the true module efficiency given the weather conditions. Points for discussions of the formula used relate to the credibility and the accuracy of the formula.

Further discussion points around the PV system include:

- The size of the PV system compared to the average Australian PV system
- The module output seasonal changes

4.2.1 Mathematical formula for PV module temperature

The formula used to predict the solar panels temperature given solar irradiation levels, ambient temperatures, and the systems technical specifications is one the pillars of which this projects reporting's is based off of. This formula has been used by various published articles since its discovery, and is regarded as a sound theoretical prediction of the behaviour of solar panel module temperature.

4.2.2 PV system size

The PV system set up at Macquarie University has a rating of 200Wp. As discussed briefly earlier in this report, this is significantly below the average PV systems installed domestically across Australia. The economic difference between smaller and larger systems is not a linear relationship, as many features of the PV system don't require higher quantities or better quality when comparing 1kW to 3kW or higher+ systems.

This includes structural mounting, wiring, installation time and number of personnel required for installation, amongst other areas of cost required for PV assembly and installation. This generally means the economic performance of the 200Wp PV system won't show results equal to or better than the average installed PV system in Australia, but show comparatively worse results.

Although the results are expected to be worse for the economics and environmental impacts of the smaller system, they will be directly comparable to the results obtained from the performance of the PV/T system.

4.2.3 System output and seasonal changes

The data calculated agrees with Yixian, Lee and Andrew, A.O's work [53] being that at 25 degrees C, 15% efficiency of the PV panels is found; and at 66 degrees C, 12.2% efficiency is found, corresponding to data points at 25 degrees C module temperature, and 66 degree module temperature. This shows that the theoretical results are very similar to actual solar panel temperature and efficiency data calculated, adding credibility to the methods used within this research project.

4.3 PV/T output calculation

In assessing the techno-economic performance of a PV/T system within the Australian climate of 2016, one of the most important areas of discussion arises from the assumptions used to base the theoretical model off of. The key assumptions used in this report mainly effect the thermal power output, which directly impacts on economic and environmental impact results. Another large area of discussion is the seasonal change in solar irradiation and ambient air temperatures, and the effect these variables have on solar collection performances.

The theoretical performance discussion points addressed are:

- The assumptions used for calculations and their impact on the results obtained of energy collected by the system
- The effect seasonal changes of solar irradiation and ambient temperatures have on PV/T performance

4.3.1 PV/T performance assumptions

The assumptions used to define the output of the PV/T system shape the economic viability and environmental impact stated by this report. These assumptions are used either to replace variables that seemingly don't affect the outcomes this project is interested in, or values that aren't available by previous works.

The first major assumption used is that the thermal system will maintain the solar panels at a set module temperature of 45 degree C. This is the NOCT of the system, and maintaining a reduced operating temperature is the main goal of the PV/T system. As the true performance of the PV/T system built by Macquarie University hasn't been tested, using this assumption allows for an estimation of the expected performance of the system.

Another major assumption is that 100% of the thermal energy collected by the system is utilized by the household. This assumption arrives from an optimistic view of the true household energy usage throughout the day, in order to maximize the output efficiency of the PV/T system. Further debate into an outcome not based on this assumption is discussed further on in this report.

Some components of the PV/T set up have been disregarded due to assessed low impact on end outcomes. This assumption allows the focus of this project to remain on the majority of the PV/T system's components that affect the economic viability and environmental impact.

4.3.2 System output and seasonal changes

The PV/T system's electrical and thermal output graphs share a similar trend, maximizing in summer and spring, declining in autumn, and minimizing in winter. All 5 weather

System	Projected Yearly Output (kWh)	Projected Profit for 2016 ($)	Projected Payback period (years)
PV	283.04	20.26	21.2
PV/T (Electrical only)	325.52	N/A	N/A
PV/T (Thermal only)	688.98	N/A	N/A
PV/T (Total)	1128.33	82.27	15.4

Table 4.1: Comparison of PV and PV/T system electrical and thermal projected outputs

stations show that the efficiency of the thermal system from peak to trough drops over 25%, whilst the electrical generation efficiency from the solar panels increases in winter.

4.4 Comparison of PV and PV/T System

In comparing the solar panels against the upgraded solar panel and thermal hybrid system, there are 3 main points:

1. The energy generated throughout the year,
2. The costings and profit of the system throughout the year,
3. The greenhouse gas emissions produced by both system.

It is calculated that the hybrid PV/T system can generate more electricity, and produce more profit per year than the PV system. Not only does the system produce more profit across the year, but the PV/T system has a significantly reduced payback period to the PV system. Economically the PV/T system is a better investment, for a larger initial investment across the system's lifetime.

However, the environmental impact of the two systems has been determined, and the PV system is clearly more efficient in generating energy for the amount of emissions produced. The PV/T system produces over 80% more equivalent carbon emissions per kWh than the PV system. The PV system also saves over 67% more GHG emissions than the PV/T system per kWh generated.

4.4.1 Systems energy output

The total projected energy generation in 2016 by the PV only system is 283.04 kWh, averaged from the 5 weather stations. The PV/T system generates 15% more electricity, and generates over 3 times more total energy. The calculated increase in electrical generation from the solar panels arises from controlling the solar panel temperatures in the hotter seasons, and reducing the efficiency loss when weather climates aren't optimal for solar energy collection.

The projected profit for 2016 has been quadrupled from \$20.26 to \$82.27. The systems profit relies heavily on the energy market in which it is used. The assumptions for the energy market are that the electricity produced in the day can be equivalent to purchasing the same energy from the grid at \$0.30/kWh. If the system produced more than 6.9kWh in the day, the excess would have an economic value of \$0.06/kWh.

The market value per kWh thermal heat has been found at \$0.144/kWh, which is the market price for instantaneous gas water heating for residential NSW. In Australia instantaneous gas water heating is currently the most popular method of generating hot water in the residential sector. If a household used electricity for their hot water generation which is the second most popular choice, the cost per kWh of heat energy would be comparable to the cost per kWh of electrical energy (\$0.30/kWh).

There is a significant difference between the two market values which will impact heavily on the economic viability of the PV/T system when installed domestically. This depends on the individual consumer, and what hot water system the PV/T solar collector will aid, and needs to be assessed on a case by case basis.

Another large determining factor is the amount of thermal energy utilized by the consumer. The previous figures assumed that 100% of the thermal energy gathered is utilized by the consumer, which isn't the case in a real life scenario. As hot water is stored in the thermal storage tank for interval use throughout the day, the efficiency of the thermal storage plays a large roll into how much thermal energy is saved. Although the system may produce a peak of 6.12 kWh thermal energy in the day, this is spread across times that normal hot water usage isn't seen for a normal household hot water profile.

A study by Kaiser et al. [10] shows a nominal household hot water usage load profile peaking in between 6am and 8am in the morning, and again in the afternoon between 6pm and 8pm. The solar panel load profile ranges from 7am to 6pm, and for an expected PV/T system warm up period of 2 hours, where the solar generation drops to zero at 6pm, the thermal gain from the system will cover less than 15% of the total usage times.

This indicates that for a household that uses on average 6737 MJ/year (5.13 kWh/day), only 0.77 kWh of thermal energy will be utilized. This changes the economic figures of the PV/T system significantly, showing less than \$2 profit per year, a payback period equal to the PV/T system's lifetime of 25 years, and 32.84 GHG emissions per kWh produced by the system in the year.

The assumptions of the usage of the system effect the economic and environmental impact performances significantly, and the true performance of any system is dependant on the conditions of usage. The most significant of these conditions are the electrical usage times, and the hot water usage times of the household.

4.4.2 Economic Figures

The income per season generated by the PV system stays relatively constant, declining in winter and spiking in spring. The PV/T system is heavily seasonally dependant, and changes significantly for each season. Summer has the highest income stream, being that

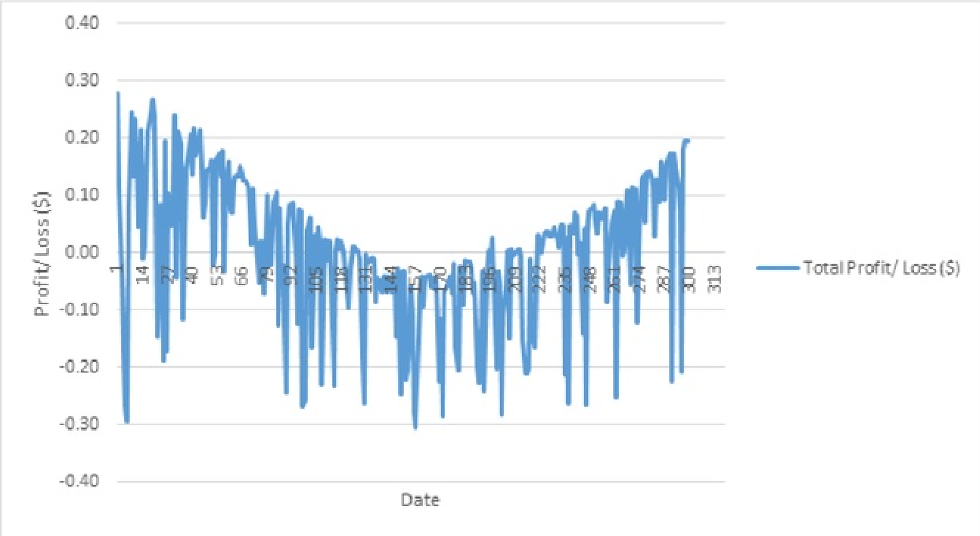


Figure 4.1: Total profit of the PV/T system when thermal usage is 15%

System	Total Initial Investment ($)	Payback Period (Years)
PV	1526.67	21.2
PV/T	3274.75	15.4

Table 4.2: Comparison of PV and PV/T projected economic figures

a significant amount of the energy being generated is the thermal energy from the higher irradiance levels and the higher ambient temperatures each day.

For the PV/T system, winter shows a net loss, where per day not enough energy is being generated to compensate for the projected costings per day for the system. Autumn and spring show midrange levels of income generation, due to the lower levels of irradiation than summer, whilst also having ambient temperatures hot enough to generate substantial thermal energy.

The initial investment to the PV system is less than half of the PV/T system, but takes 5 more years to pay off through the potential income earnt from solar collection. This is once again reflective of the higher energy collection rates of the PV/T system, and shows the economically positive effect of installing PV/T systems, or upgrading standalone PV systems to hybrid systems.

4.4.3 Environmental Impact

From research into previous LCA studies of PV systems that have been calibrated and compared, the PV system is expected to have the equivalent of producing 3.56 g CO2

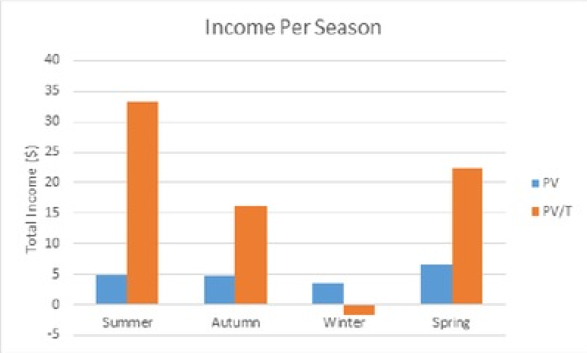


Figure 4.2: PV against PV/T seasonal Income

Generation Method	**GHG emissions / Solar Generation (g CO2/ kWh)**
Fossil Fuel electricity production	840.00
Natural Gas	3.56
PV	2.02
PV/T	13.00

Table 4.3: GHG emissions of energy generation by generation method

equivalent emission per kWh. This is directly compared to the emissions produced by average electricity generation via fossil fuels at 840 g CO2 e/ kWh. This indicates that the project PV system is saving the environment 837.98 g CO2 equivalent emissions per kWh generated, which is a significant advance in Australia's attempt to reduce the total carbon footprint.

The PV/T system is estimated to produce more than 13 g CO2 e/ kWh, which is 80% more than the PV system. Part of the energy generated by the system is electrical energy, saving the fossil fuel generation, and the other part is thermal energy generation, which is equivalent to the GHG emissions from producing and supplying natural gas to Australian residential homes.

The overall saving of GHG emissions for the PV/T system will be 264.608 g CO2 e/ kWh generated. The GHG emission savings are comparatively low due to the extremely low GHG emission production per kWh of natural gas being utilized by an average Australian household.

If the household used electrical heating in their hot water system, the GHG emission savings for the PV/T system would be 827 g CO2 e/ kWh, which has less than a 5% difference to the PV system. Regardless of hot water system used in the home, the projected figures based on initial assumptions for the system show a positive gain in emissions per kWh energy produced and used for the household.

Chapter 5

Future Work

Using actual system performance data

This research project had originally intended to utilize actual PV/T system performance data collected and analysed from the system set up at Macquarie University, but due to system test setbacks, the data was unavailable in time to be used within this study.

There is an opportunity for future work to provide an accurate, detailed techno-economic analysis of the PV/T system built with that data when testing of the system is completed.

Accurate residential energy consumption profile data

An assumption this research project used was the amount of electrical and thermal energy consumed throughout the day by the household. The profile of household energy consumption is vastly different to the energy generation profile, specifically the peak of generation being at midday, and the peak of electrical consumption being at dusk and dawn.

Utilizing accurate residential energy consumption profile data provides further detail and accuracy to the economic figures and environmental impact calculations produced by this report, and so is another area of which further study will be required.

Accurate solar intensity data day profiles

The data collected from the Bureau of Meteorology from the 5 weather stations, as discussed before, is simply solar irradiation power totals measured across the day, and the maximum ambient temperature of the day. Similar to the residential energy consumption profile, an accurate profile of solar irradiation data and ambient temperatures across the day will provide systems electrical and thermal outputs with smaller error variations.

The performance of any solar collector system relies on the solar activity for the day, meaning further research will be required to refine the expected energy output of the system in an average day of weather conditions in NSW, Australia.

Techno-economic analysis of larger size PV/T system

Australian households consume a lot more energy than a small 200Wp solar panel system can output, even in perfect weather conditions. The majority of Australian households install systems upwards of 1.5kWp, which is significantly larger than the system built by Macquarie University.

As was discussed previously, larger solar collector systems don't have a linearly larger economic cost and environmental impact, and in fact become more economically viable, and produce less GHG emissions per energy generation produced by the system.

Further analysis into larger PV/T hybrid system techno-economic performance will be required to better understand the true nature of hybrid PV and thermal solar collector systems in the Australian market.

Chapter 6

Conclusions

The main goal of this project was to conduct research into the economic viability of a small scale domestic PV system fitted with a hybrid solar thermal collector system. This project also assessed whether upgrading existing PV solar panels with a solar thermal system is economically viable, and/ or offers less of an environmental impact for the electrical energy being generated.

Throughout this research project there have been many assumptions made in order to provide meaningful techno-economic performance results. These assumptions were discussed in detail, and have led to the need for further research and refinement in the field of PV/T systems energy generation and consumption. Such assumptions include the performance of the PV/T system based off other PV/T technical performance findings. The unfinished testing of Macquarie University's PV/T system can further the accuracy of this report.

The comparison between PV and PV/T systems showed that for the environmental impact the GHG emissions saved by the PV system is expected to be 837.98 g CO2 e/ kWh generated, whilst for the PV/T system a predicted 264.61 g CO2 e/ kWh generated was found.

The economic viability of the PV system showed a large payback period of 20 years, whilst the PV/T system is projected to have a payback period of 15 years. Although these results indicate the PV/T has a better economic viability than the PV system, the assumptions of household thermal energy usage used for these calculations are heavily optimistic, and discussion into the validity of that assumption has been addressed.

The economic viability and environmental impact of a PV/T system can be improved by investing into a larger scale system, which due to the rising popularity of apartment style living in Sydney, is a viable avenue of further study.

The PV/T system has shown positive results for economic viability, and environmental impact, being that the built system can produce significantly greener energy than that of fossil fuel generation, and has the potential to boost the economic viability of simple PV systems installed on residential households, especially in Australia's hot summers.

Chapter 7

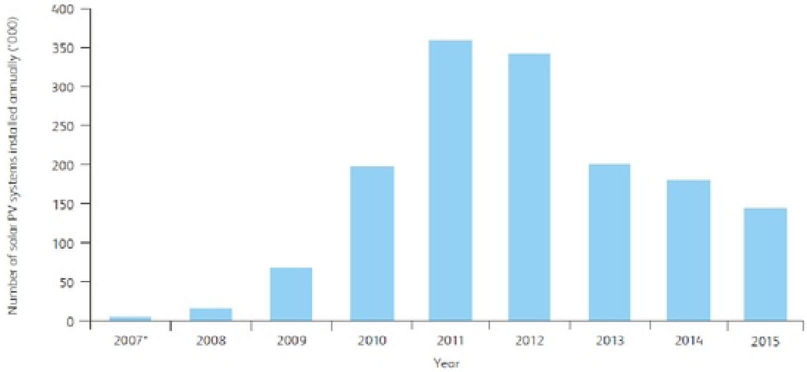
Abbreviations

BOM	Bureau of Meterology
ARENA	Australian Renewable Energy Agency
PV	Photovoltaic
PV/T	Photovoltaic / thermal
GHG	Greenhouse Gas
AER	Australian Energy Regulator

Appendix A

Figures

ANNUAL SOLAR PV INSTALLATIONS[19]



INSTALLATION YEAR	ACT	NSW	NT	QLD	SA	TAS	VIC	WA	NATIONAL
2007*	102	779	26	475	1037	26	828	262	3535
2008	278	2890	88	3087	3456	161	2036	2068	14,064
2009	803	14,008	215	18,283	8569	1452	11,847	11,157	66,334
2010	2323	69,988	637	48,697	16,705	1889	35,676	22,293	198,208
2011	6860	80,272	401	95,303	63,553	2475	60,214	51,667	360,745
2012	1522	53,961	513	130,252	41,851	6364	66,204	42,653	343,320
2013	2411	33,998	1024	71,197	29,187	7658	33,332	21,600	200,407
2014	1224	37,206	1026	57,745	15,163	4207	40,059	23,493	180,123
2015	975	33,931	1208	40,809	12,259	2020	30,950	20,803	142,956
TOTAL	16,528	328,085	5242	466,966	193,436	26,302	282,059	196,232	1,514,851

*Total includes pre-2007 installations

39

Figure A.1: Solar Panel Installations in Australia

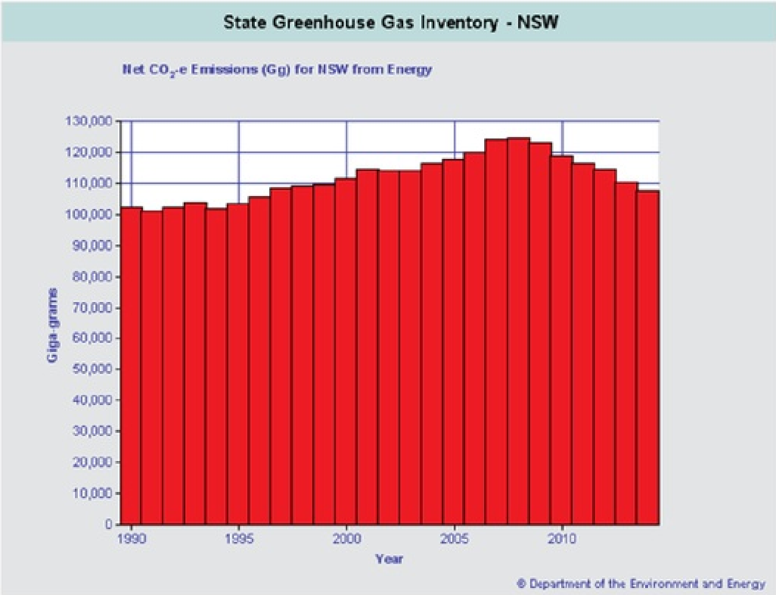


Figure A.2: Net CO2 Emissions for NSW from energy generated

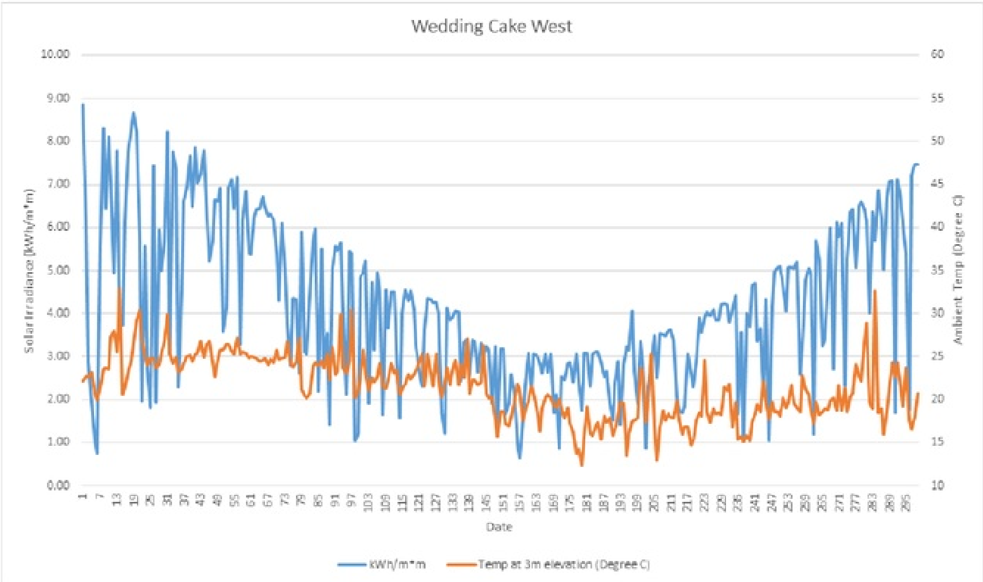


Figure A.3: Solar irradiation and ambient temperature at 3 metres elevation, at weather station Wedding Cake West

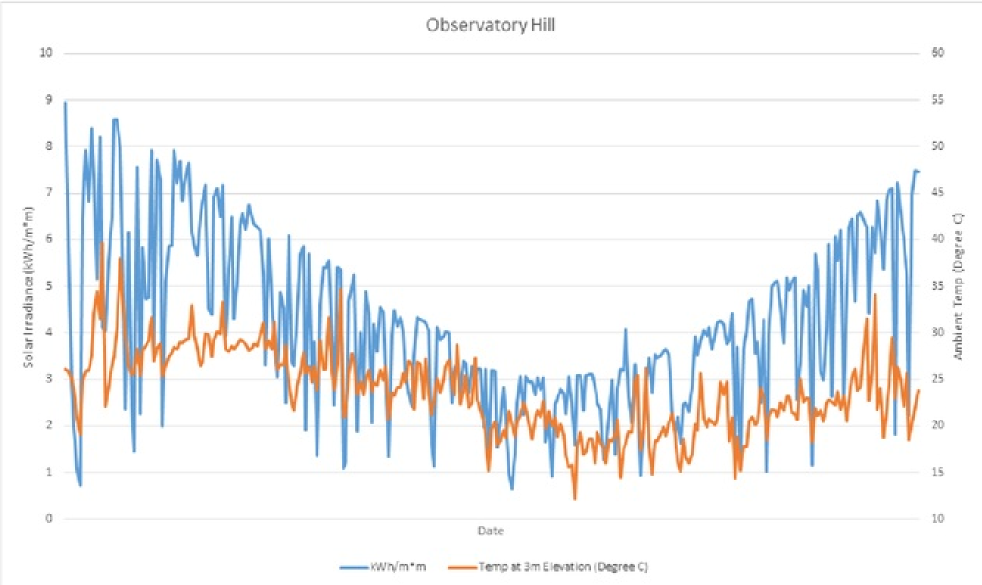


Figure A.4: Solar irradiation and ambient temperature at 3 metres elevation, at weather station Observatory Hill

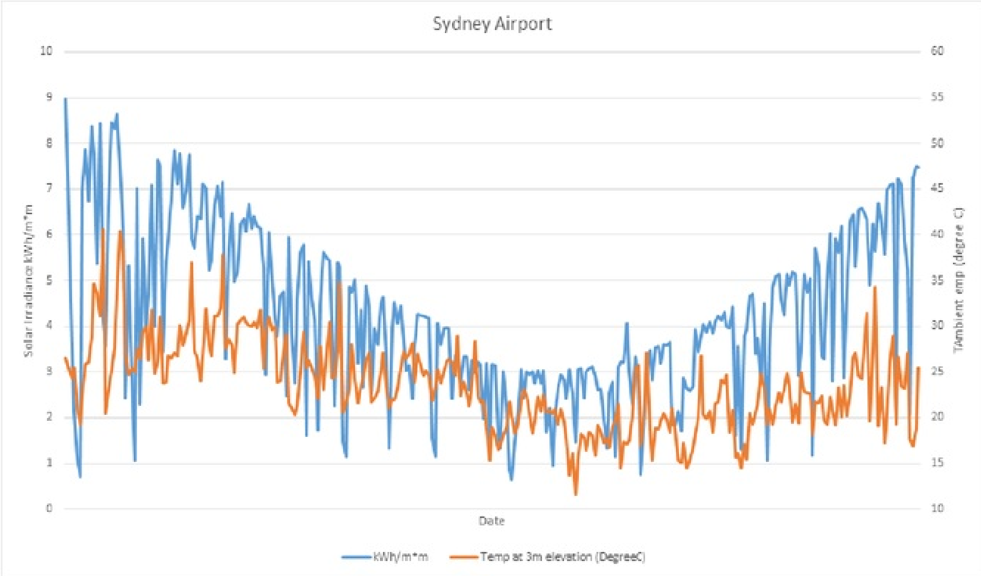


Figure A.5: Solar irradiation and ambient temperature at 3 metres elevation, at weather station Sydney Airport

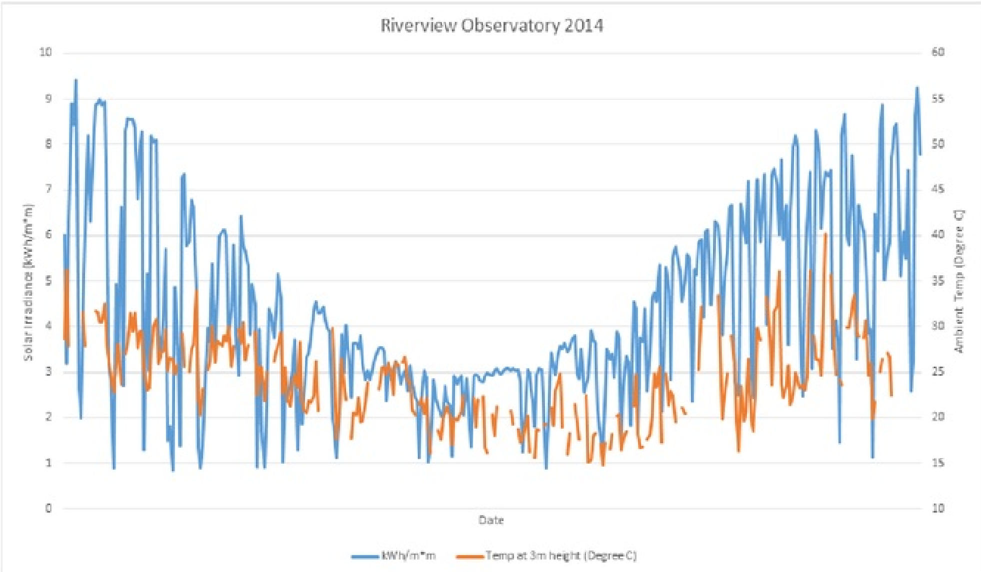


Figure A.6: Solar irradiation and ambient temperature at 3 metres elevation, at weather station Riverview Observatory

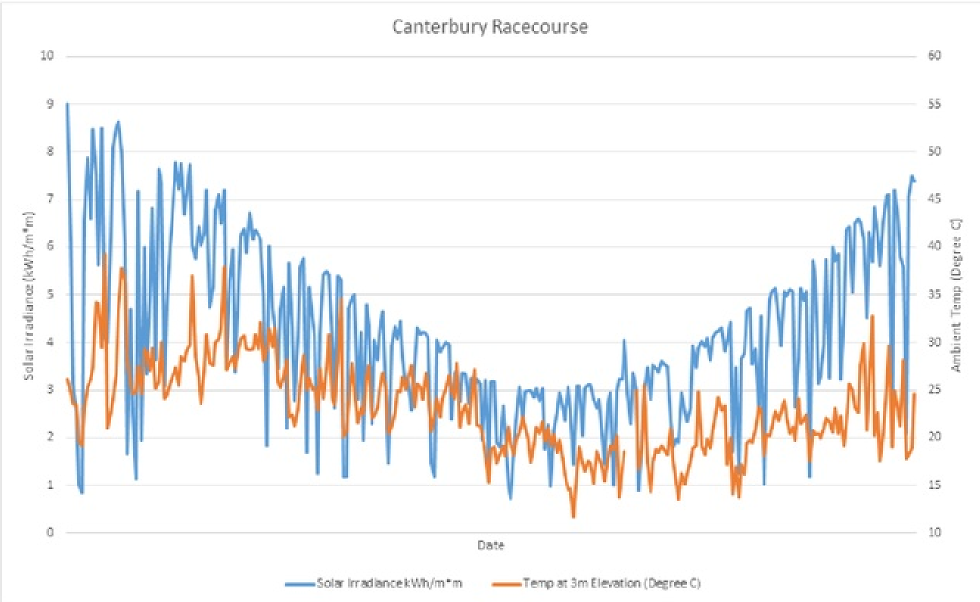


Figure A.7: Solar irradiation and ambient temperature at 3 metres elevation, at weather station Canterbury Racecourse

Specifications

Electrical Data (@ STC[1])

Peak Power (P_{max})	200W
Power Output tolerance	-0/+3%
Max Voltage (V_{mp})	36.95 V
Max Current (I_{mp})	5.42 A
Open Circuit Voltage (V_{oc})	44.95 V
Short Circuit Current (I_{sc})	5.65 A
Module Efficiency	15.5%

Mechanical Data

Cells	Monocrystalline 125mm x 125mm
Cell Orientation	72 Cells (6 x 12)
Dimension (L x W)	1580 x 808 x 40 mm
Weight	14.7 kg
Connector	MC-4 Compatible

Temperature Characteristics

NOCT[2]	45±2°C
Temperature Coefficient of Pmax	-0.340 / °C
Temperature Coefficient of Voc	-0.35% / °C
Temperature Coefficient of Isc	0.053% / °C

Figure A.8: Specification sheet of PV panels utilized by Macquarie University

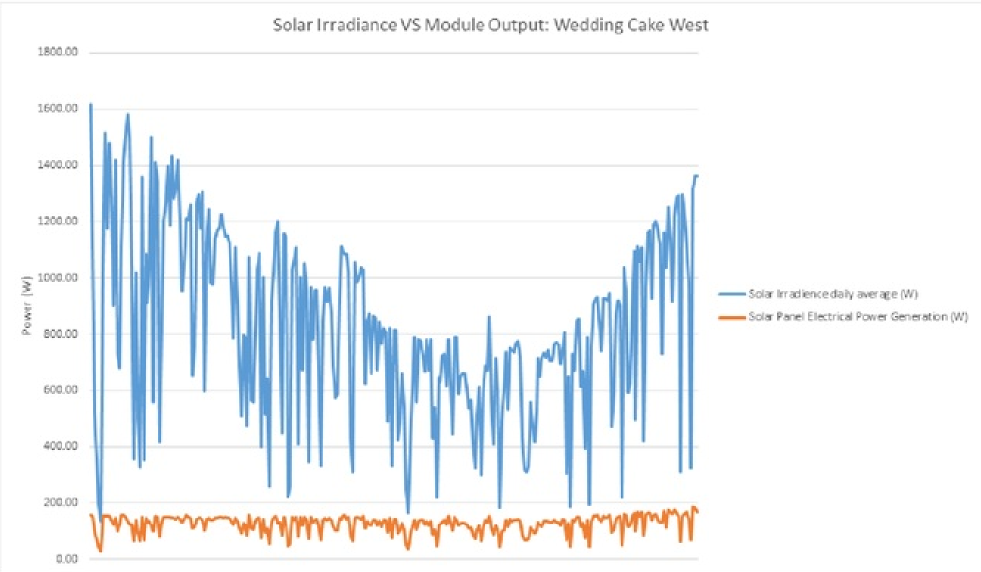


Figure A.9: Solar irradiation and expected PV system output at weather station: Wedding Cake West

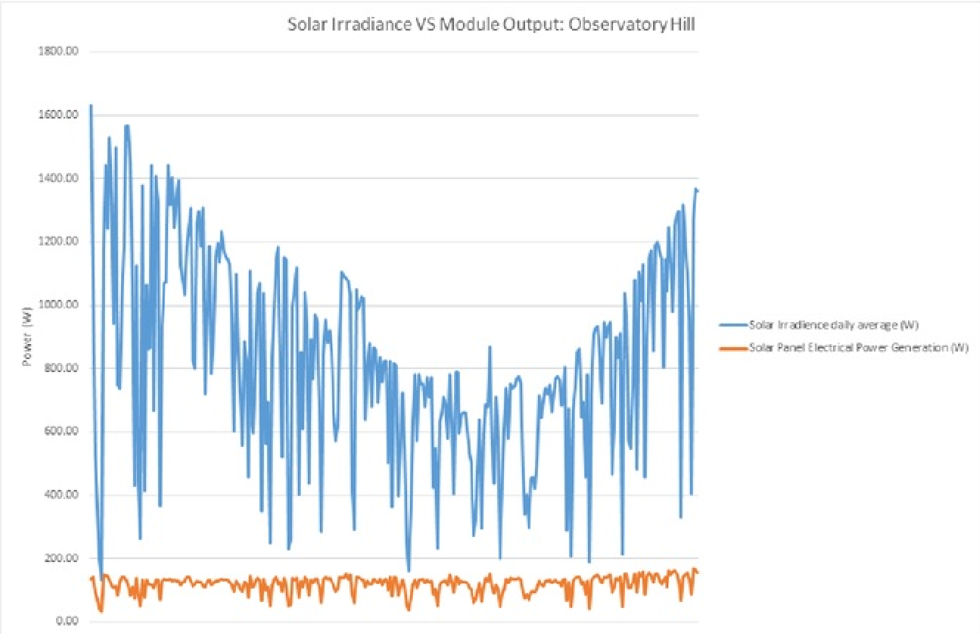


Figure A.10: Solar irradiation and expected PV system output at weather station: Observatory Hill

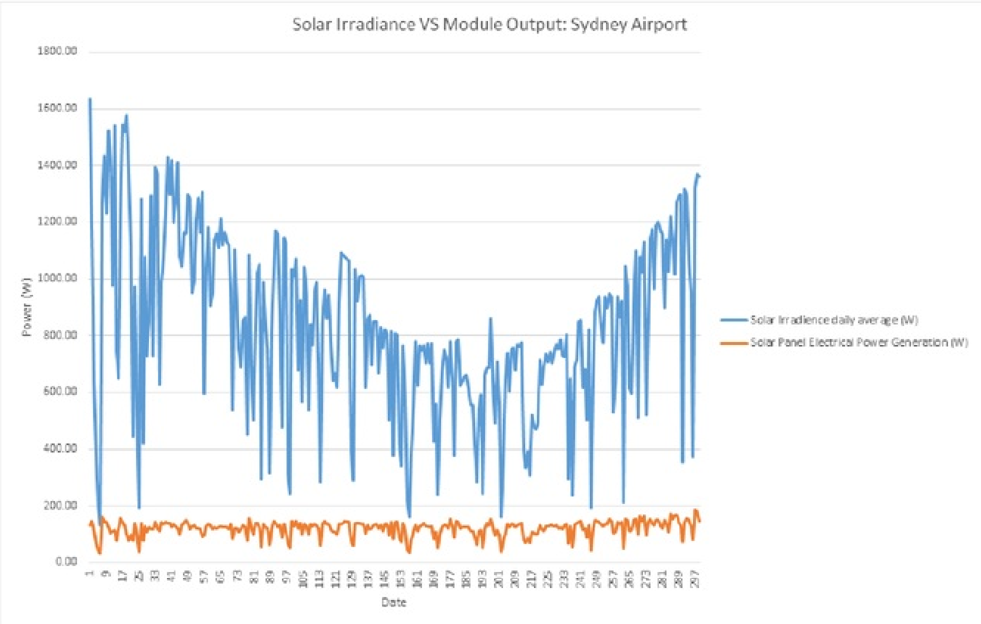


Figure A.11: Solar irradiation and expected PV system output at weather station: Sydney Airport

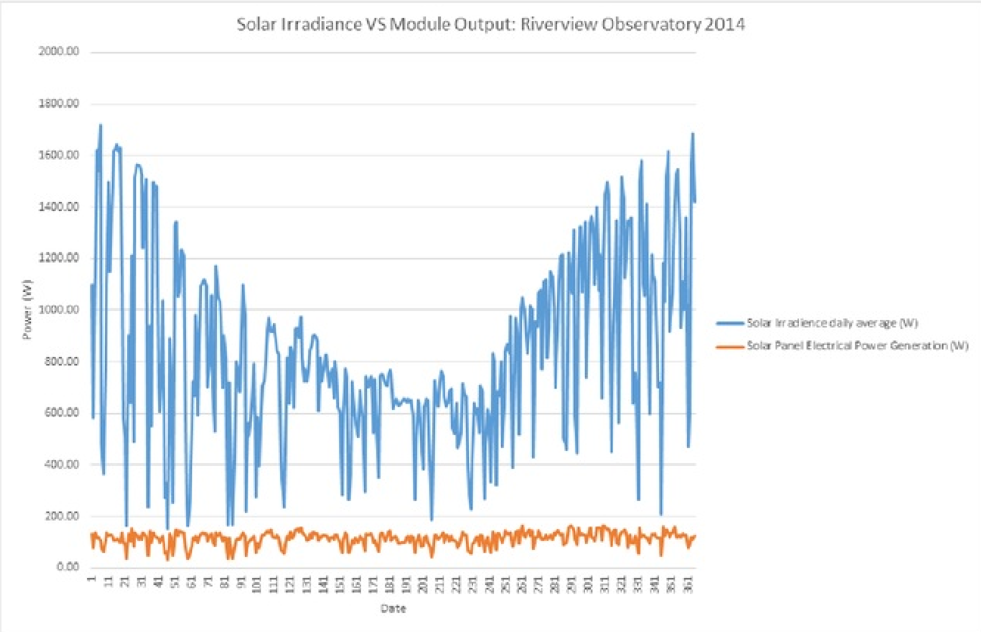


Figure A.12: Solar irradiation and expected PV system output at weather station: Riverview Observatory

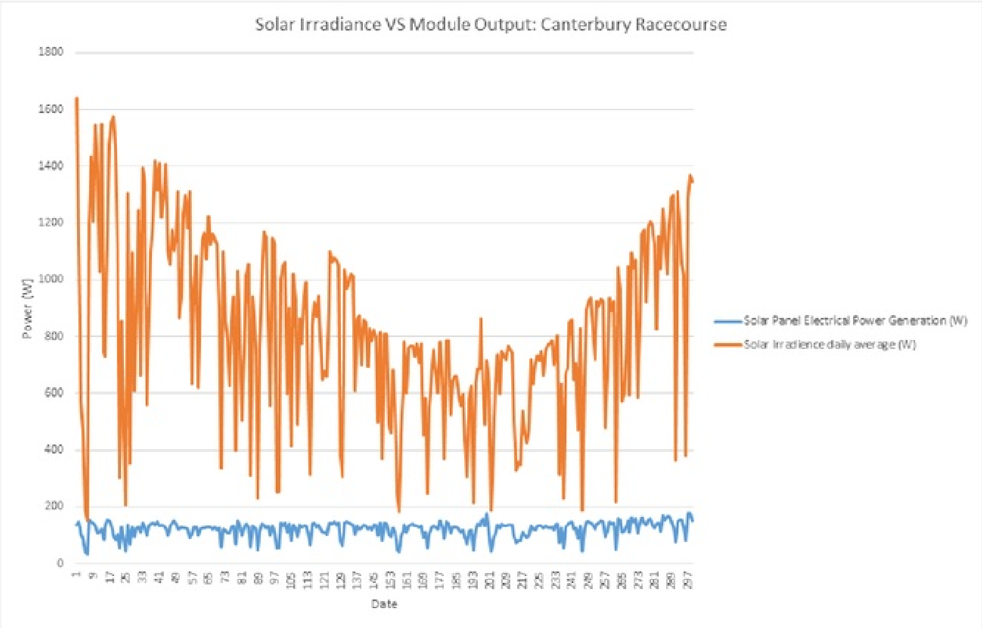


Figure A.13: Solar irradiation and expected PV system output at weather station: Canterbury Racecourse

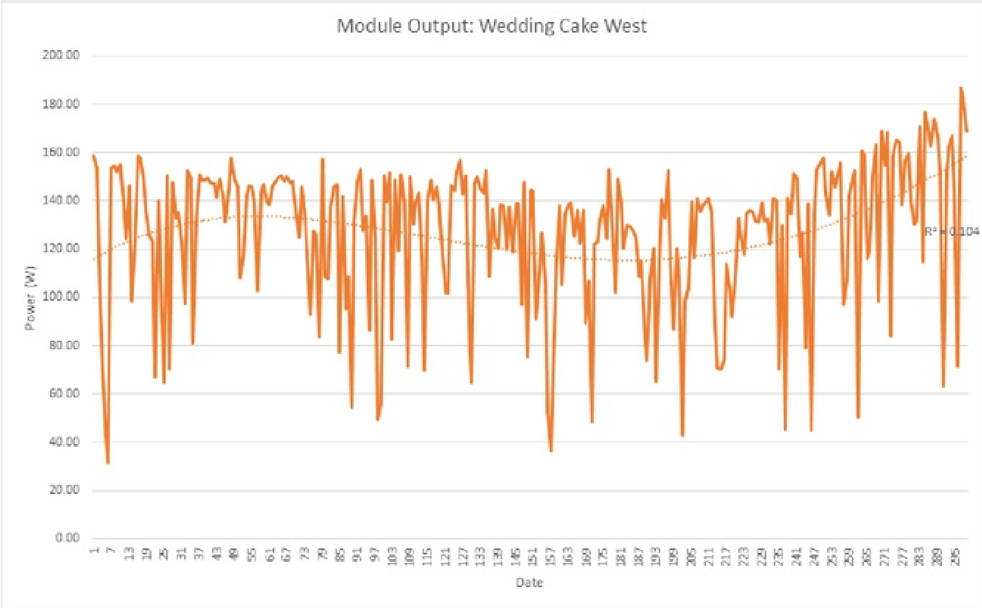


Figure A.14: Expected PV system output at weather station: Wedding Cake West

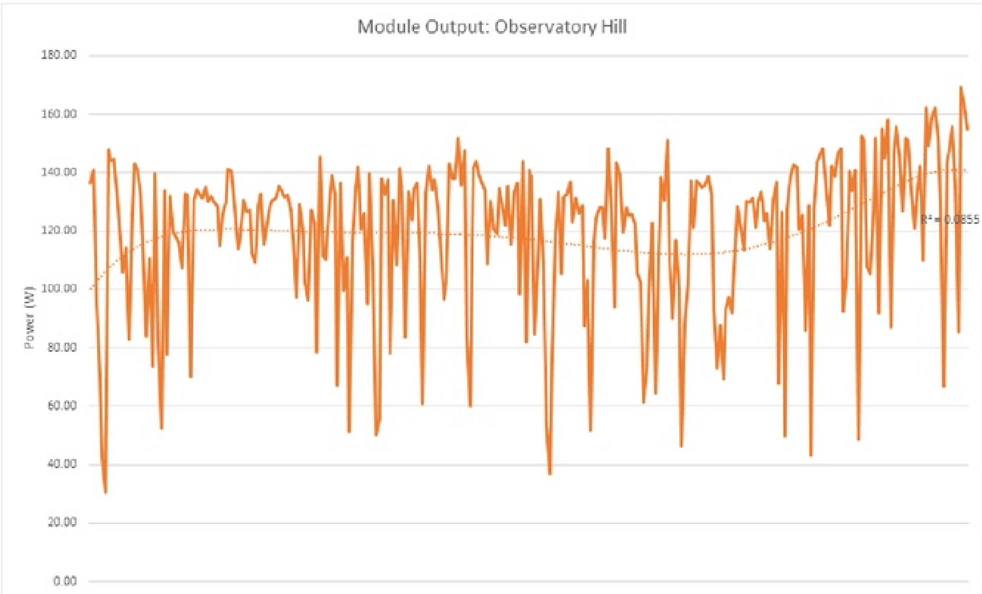


Figure A.15: Expected PV system output at weather station: Observatory Hill

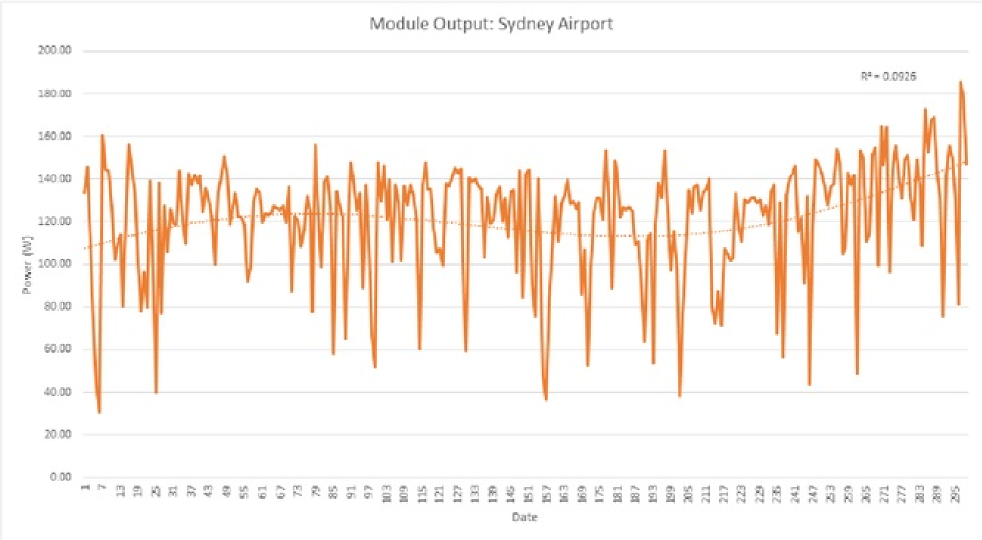


Figure A.16: Expected PV system output at weather station: Sydney Airport

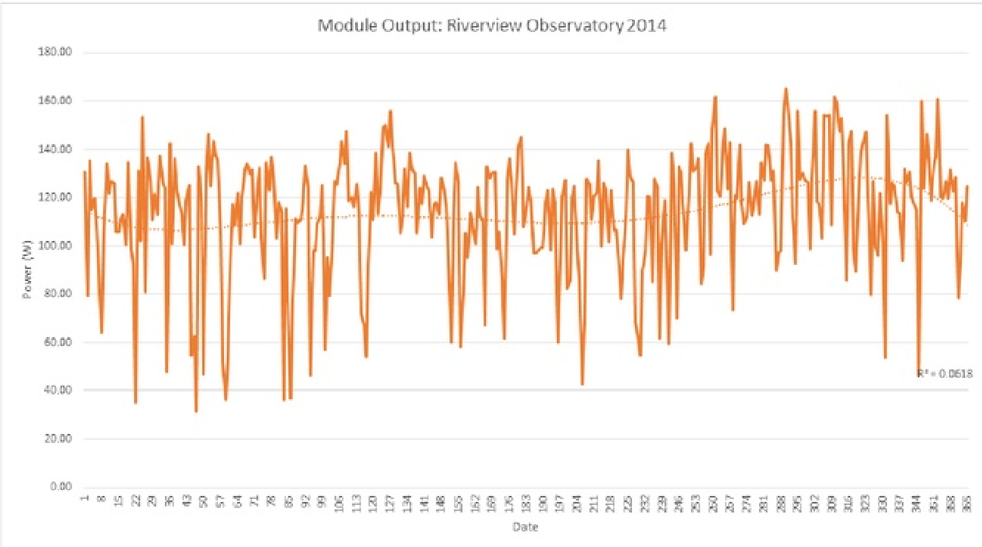


Figure A.17: Expected PV system output at weather station: Riverview Observatory

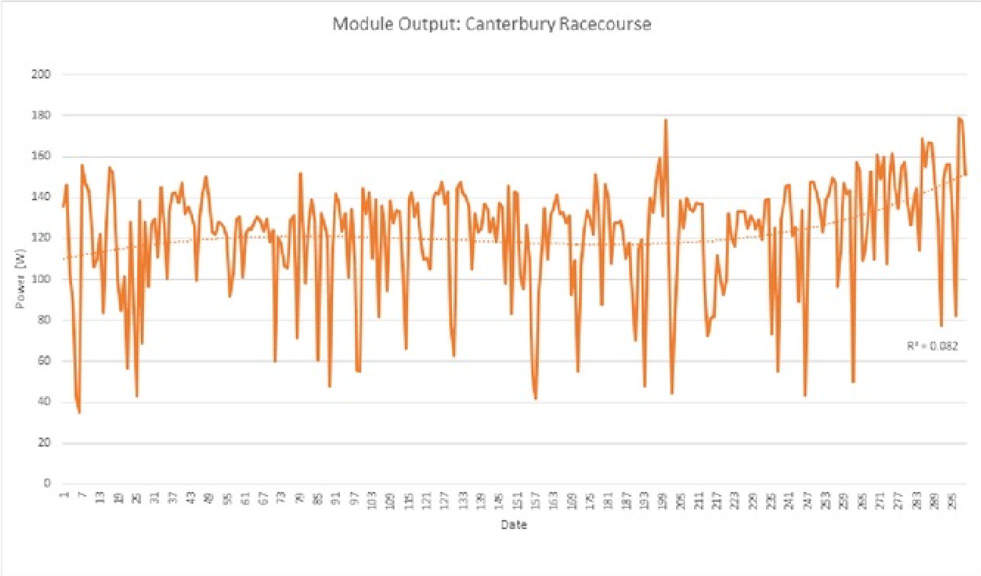


Figure A.18: Expected PV system output at weather station: Canterbury Racecourse

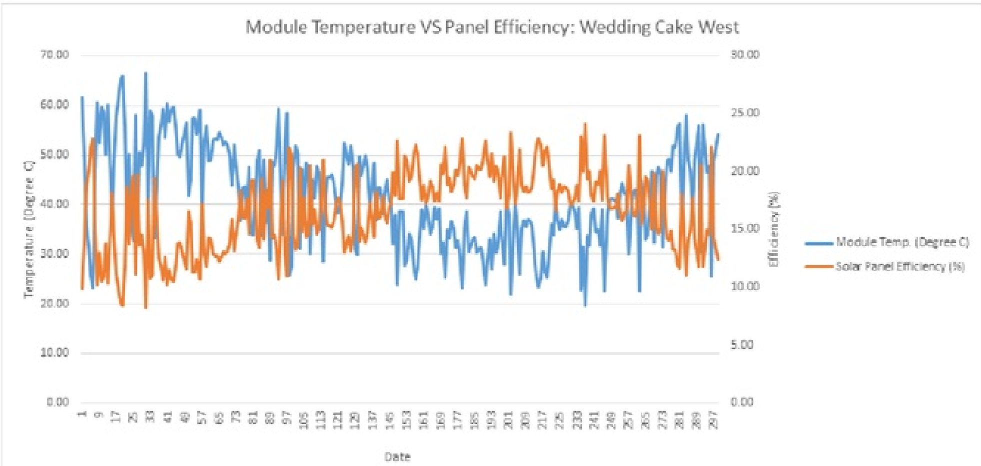


Figure A.19: PV system temperature against system efficiency at weather station: Wedding Cake West

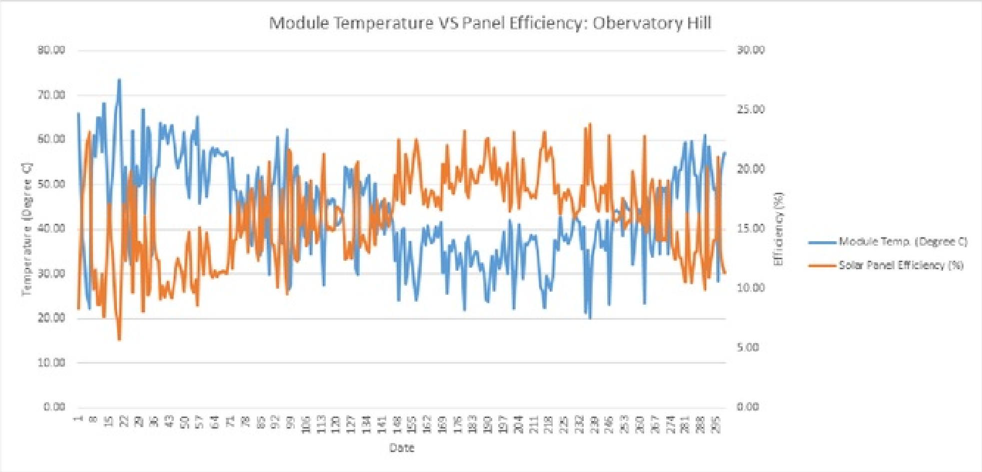


Figure A.20: PV system temperature against system efficiency at weather station: Observatory Hill

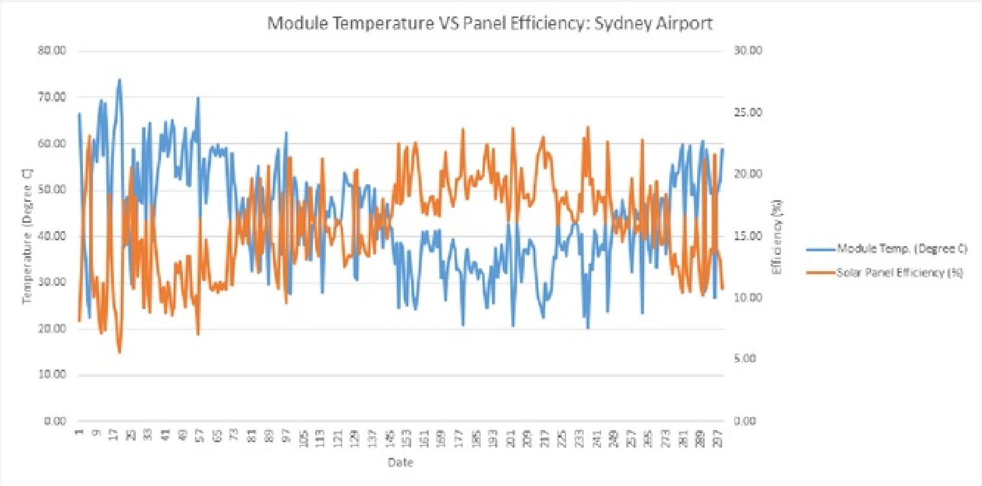


Figure A.21: PV system temperature against system efficiency at weather station: Sydney Airport

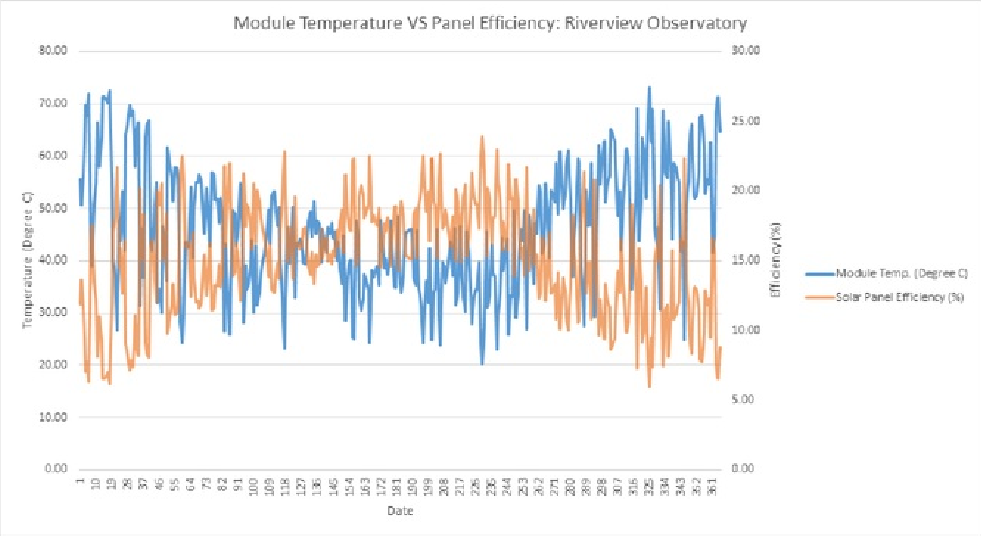


Figure A.22: PV system temperature against system efficiency at weather station: Riverview Observatory

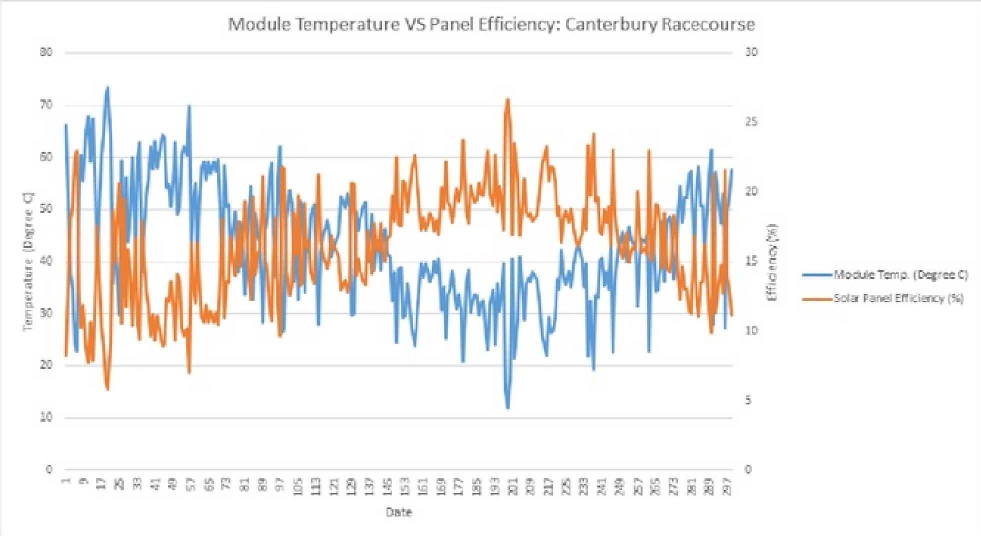


Figure A.23: PV system temperature against system efficiency at weather station: Canterbury Racecourse

Input Parameter	2011 Value	Base Case – Annual % Change
System lifetime	25 years	
Sydney generation	1,522 kWh/kW	
Brisbane generation	1,606 kWh/kW	
Melbourne generation	1,401 kWh/kW	
Cost of equity/debt (discount rate)	8.5%	
Inflation	2.5%	
Annual performance degradation	0.8% p.a.	
Module Efficiency	13.5%	2% p.a.
Module Cost (factory gate / landed)	1.30 ($/Wp)[11]	-4% p.a.
Inverter Cost (factory gate / landed)	0.90 ($/Wp)[12]	-2% p.a.
Importer / distributor margin	10%[13]	-2% p.a.
End System installation margin(s)	20%	-2% p.a.

Figure A.24: Base case input paramaters used by APVA

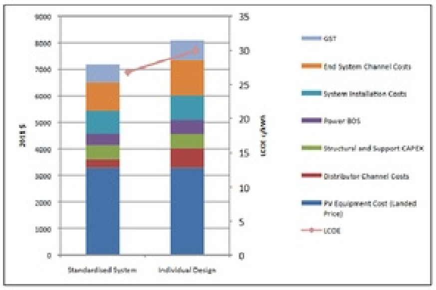


Figure A.25: Base case system capital cost breakdown (Standardised system vs Individual design)

S. no.	Year	Location	Efficiency (%)	Power rating	Life time (years)	EPBT (years)	GHG emissions (g-CO_2/kWh$_e$)
1.	1990 [24]	US	8.5	300 kW	30	na	280
2.	1997 [21]	Japan	na	3 kW	20	15.5	91
3.	2000 [13]	Netherlands	14.0	na	30	3.2	60.0
4.	2002 [23]	India	13.0	35 W	20	na	64.8
5.	2006 [25]	UK	11.5	14.4 kW	30	8	44.0
6.	2006 [22]	Singapore	7.3–8.9	2.7 kW	25	5.87	217
7.	2006 [22]	Singapore	10.6	2.7 kW	25	4.47	165

Figure A.26: Collaboration of LCAs of monocrystalline PV systems

LCA results review of single crystalline silicon PV systems.

Authors	Year	Location	Mounting type	Irradiation (kWh/m^2/yr)	PR	Module efficiency (%)	Lifecycle (Year)	EPBT (Year)	GHG emission (g CO_2-eq./kWh)
Kim et al. [28]	2014	South Korea	Ground Mounted	1301.35	0.80	15.96	30	4.65	41.8
Fthenakis et al. [27]	2012	United States	Ground Mounted	1800	0.80	20.1	30	1.4	64.2
Ito et al. [51]	2010	China	Ground Mounted	1702	0.78	N/A	30	2.5	50
Lu and Yang [33]	2010	Hong Kong	Roof Mounted	1600	N/A	13.3	20-30	7.3	671
De Wild-Scholten [32]	2009	Europe	Roof Mounted	1700	0.75	14	30	1.75	29
Fthenakis et al. [12]	2008	Europe	Ground Mounted	1700	0.80	14	30	2.7	36
Jungbluth et al. [50]	2007	Switzerland	Roof Mounted	1117	0.75	14	30	3.3	N/A
Kannan et al. [7]	2006	Singapore	Roof Mounted	1635	N/A	11.86	25	5.87	217
Muneer et al. [49]	2006	United Kingdom	N/A	800	N/A	11.5	30	8	44
Alsema et al. [15]	2006	Europe	Roof Mounted	1700	0.75	14	30	2.1	35
Alsema and de Wild-Scholten [37]	2005	Europe	Roof Mounted	1700	0.75	13.7	30	2.6	41
Jungbluth [9]	2005	Switzerland	Roof Mounted	1117	N/A	16.5	30	3.0–6.0	79
Mathur et al. [48]	2002	India	N/A	1800	N/A	13	20	3.2	60
Knapp and Jester [31]	2001	United States	N/A	1700	0.80	N/A	30	4.1	N/A
Alsema [30]	2000	Europe	Roof Mounted	1700	0.75	14	30	2.5–3	50–60
Kato et al. [24]	1998	Japan	Roof Mounted	1427	0.81	12.2	20	8.9	61
Dones and Frischknecht [8]	1998	Switzerland	Roof Mounted	1117	N/A	16.5	30	N/A	114
Frankl et al. [47]	1998	Italy	Ground Mounted	1700	0.85	11.2	25	9	200
Kato et al. [46]	1997	Japan	Roof Mounted	1427	0.81	N/A	20	15.5	91
Wilson and Young [21]	1996	United Kingdom	Roof Mounted	573–1253	0.80	12	20	7.4–12.1	N/A
Brown [19]	1990	United States	Ground Mounted	N/A	N/A	8.5	30	N/A	280

Figure A.27: Collaboration of LCAs of PV systems between 2004 and 2014

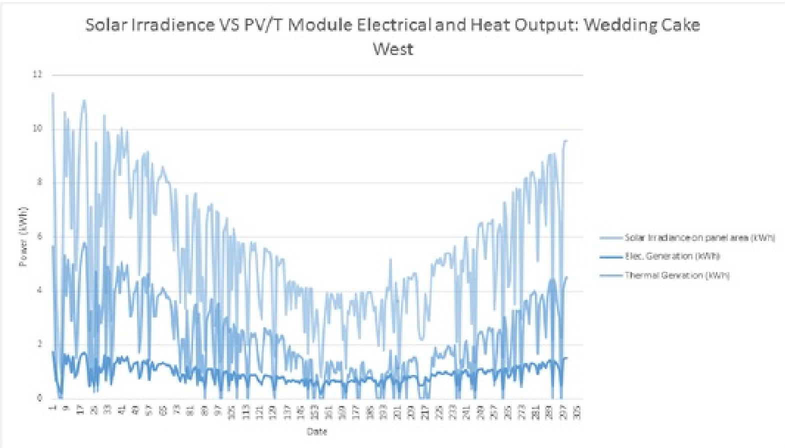


Figure A.28: PVT theoretical thermal and electrical generation for weather station: Wedding Cake West

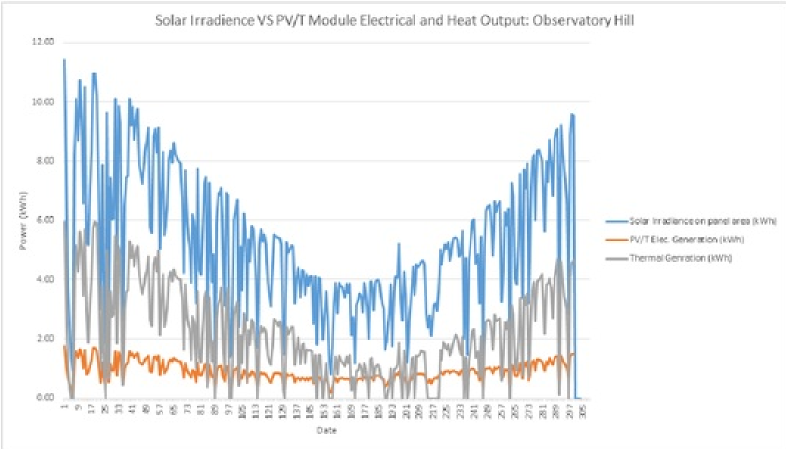


Figure A.29: PVT theoretical thermal and electrical generation for weather station: Observatory Hill

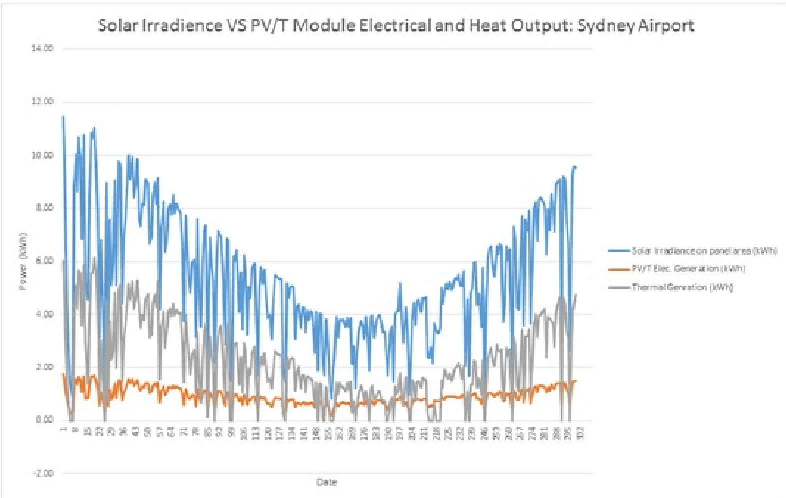


Figure A.30: PVT theoretical thermal and electrical generation for weather station: Sydney Airport

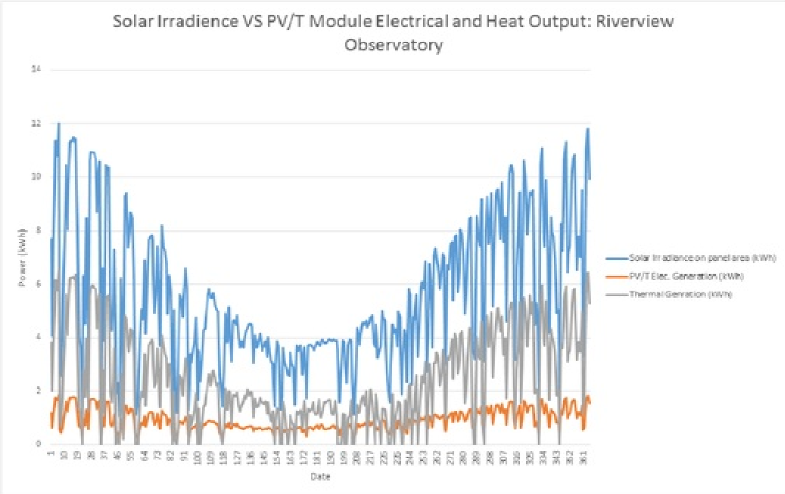


Figure A.31: PVT theoretical thermal and electrical generation for weather station: Riverview Observatory

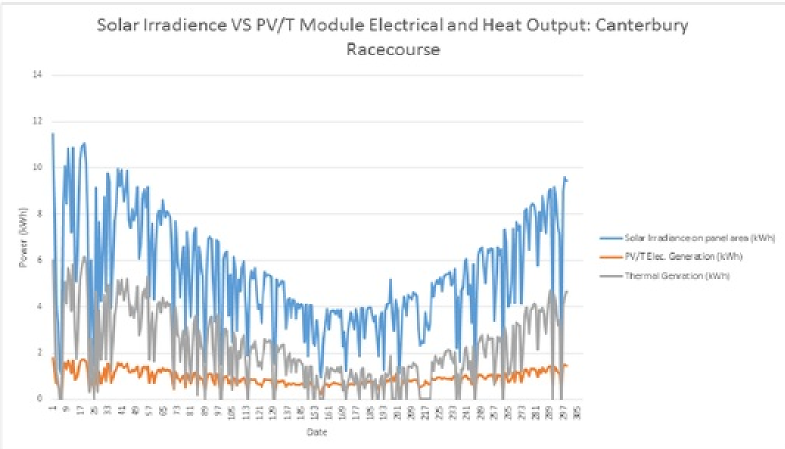


Figure A.32: PVT theoretical thermal and electrical generation for weather station: Canterbury Racecourse

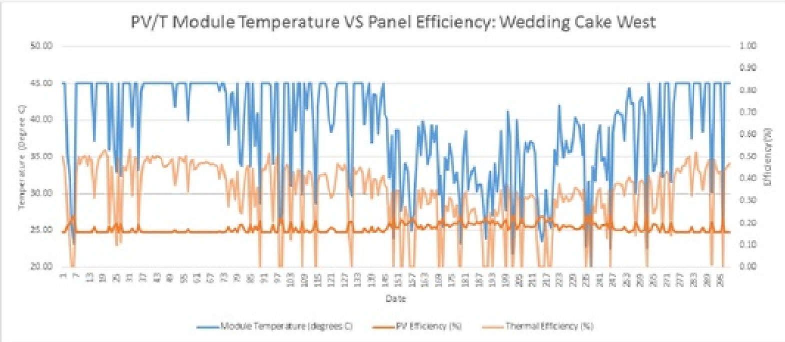


Figure A.33: PVT theoretical module tmperature against the thermal and electrical efficiency for weather station: Wedding Cake West

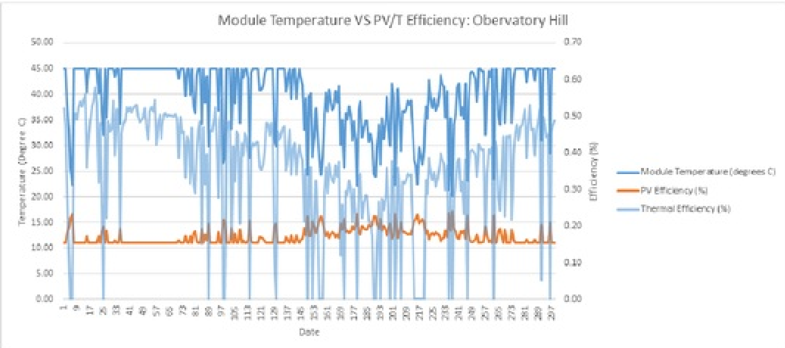


Figure A.34: PVT theoretical module tmperature against the thermal and electrical efficiency for weather station: Observatory Hill

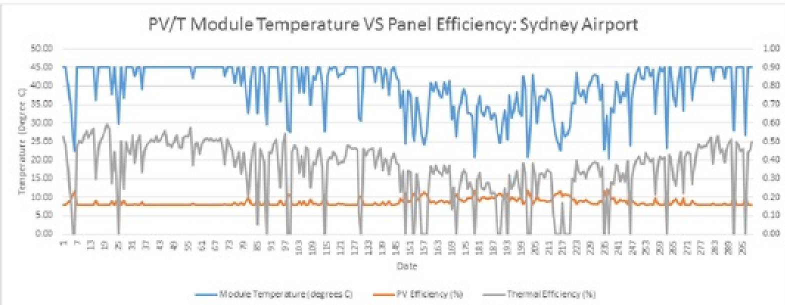


Figure A.35: PVT theoretical module tmperature against the thermal and electrical efficiency for weather station: Sydney Airport

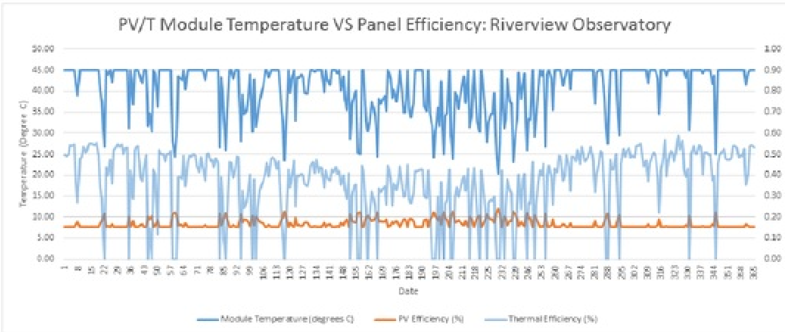


Figure A.36: PVT theoretical module tmperature against the thermal and electrical efficiency for weather station: Riverview Observatory

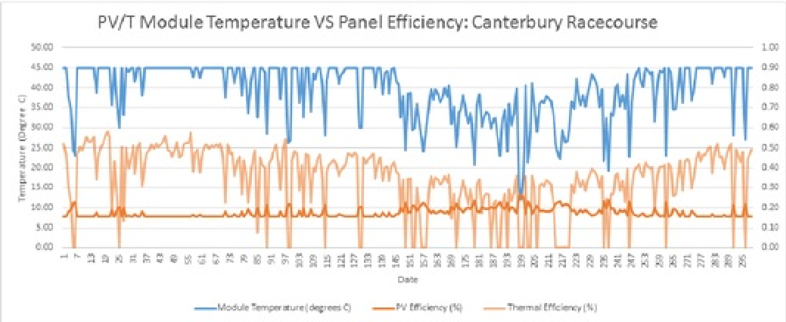


Figure A.37: PVT theoretical module tmperature against the thermal and electrical efficiency for weather station: Canterbury Racecourse

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