

JAMES COOK UNIVERSITY

COLLEGE OF SCIENCE &  
ENGINEERING

EG4011/2

Electrical & Electronic Engineering

SOLAR PHOTOVOLTAIC AND  
STORAGE FOR DOMESTIC USE

Clinton Greg Elliott

12788727

Thesis submitted to the College of Science & Engineering  
in partial fulfilment of the requirements for the degree of

Bachelor of Engineering with Honours  
(Electrical & Electronic)

Submitted 6<sup>th</sup> October 2017



*When Alternative energy is no longer an alternative.*

*-Anonymous*

## STATEMENT OF ACCESS

I, the undersigned, author of this work, understand that James Cook University may make this thesis available for use within the University Library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and

I do not wish to place any further restriction on access to this work.

Or

I wish this work to be embargoed until:

Or

I wish the following restrictions to be placed on this work:

---

Signature

---

Date

## **ACKNOWLEDGEMENTS**

I would first like to thank my thesis supervisor Associate Professor Ahmad Zahedi of Electrical Engineering at James Cook University. The door to Prof. Zahedi's office was always open whenever I ran into issues or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it. His efforts and replies to late night emails was always prompt and contributed greatly to this paper.

Thanks to Kevin Smith from Kevin Smith Electrical, for showing me the current solar technology on the market and giving me the opportunity to install a system.

With a special mention to my family for their emotional support and especially Susan Elliott and Jessica Zhuang for editing the draft.

## ABSTRACT

Currently, the largest quantities of carbon emissions produced by any sector worldwide are from the generation of electrical energy. The call for clean, environmentally friendly and sustainable energy has never been greater. This demand is steadily increasing, which brings the world to the hope and age of green renewable technologies. This is the massive driving force behind the solar industry and the cause of the improvements over the last 50 years, which have been remarkable. The efficiencies and improvements of solar cells, inverters, electronics and batteries have been tremendous. This wave of developments has pushed the cost of electricity production down to parity with respect to gas and coal and even lower in at least 19 countries. We are in an era which the electrical industry has never seen before; we are in the era of renewable technologies.

The increasing costs of electricity combined with a greater awareness and exposure to the effects of carbon dioxide emissions, have moved people towards a sustainable energy future. Solar energy is agreeable as it has no security issues or military risk such as nuclear energy. A spill of solar radiation is generally considered an agreeable day. Solar power has the advantage of a long system life-time, generally 25 years with minimal maintenance. A solar system is modular, silent, has an infinite fuel source, and zero emissions. The fuel for solar systems does not need to be transported, thus providing additional economic advantages.

This project outlines the need, design, development, and verification of a MATLAB program, capable of receiving inputs for a solar system's requirements and appropriately sizing and optimising three selectable options for the user. This has a benefit at a household domestic level with electricity savings and the complimentary grid stabilisation consequences for Ergon Energy and other electricity suppliers. This is a suitable proposition for the Government, as a margin from the budget each year is directed towards renewable technologies. This thesis is the original framework to create a suitable program and calculate the feasibility of solar technology around Australia. The city of Townsville will be the focus of this project, and it is a very suitable place for solar production as it is situated with a low latitude and large levels of solar insolation. There are currently large-scale production solar farms being built around Australia, and there is potential for the export of this power to other countries.

The need for current up-to-date estimates and appropriate calculations for the cost and feasibility of solar installations has never been greater. This proposed program brings to light the availability and the indeed obvious decision to become a clean energy investor and promoter. Recently there have been developments in the solar industry with improved battery energy storage systems coming onto the

market. The figures need to be revised and new calculations and modelling are required for the potential use of solar energy in Australia, and particularly, northern parts of Australia and Townsville.

Word Count: 20,105

## CONTENTS

<b>ACKNOWLEDGEMENTS .....</b>	<b>I</b>
<b>ABSTRACT .....</b>	<b>II</b>
<b>CONTENTS .....</b>	<b>IV</b>
<b>LIST OF TABLES .....</b>	<b>VII</b>
<b>LIST OF FIGURES .....</b>	<b>VIII</b>
<b>LIST OF ABBREVIATIONS &amp; SYMBOLS .....</b>	<b>X</b>
<b>LIST OF APPENDICES .....</b>	<b>XII</b>
<b>CHAPTER 1: INTRODUCTION .....</b>	<b>1</b>
1.1 OVERVIEW .....	1
1.2 RESEARCH AIMS.....	3
1.3 SCOPE .....	3
<b>CHAPTER 2: LITERATURE REVIEW.....</b>	<b>5</b>
2.1 BACKGROUND.....	5
2.2 SOLAR SYSTEM SYNOPSIS .....	6
2.3 PHOTOVOLTAIC SYSTEMS.....	7
2.3.1 <i>Review of PV</i> .....	7
2.3.2 <i>Types of PV</i> .....	9
2.3.3 <i>Growth of PV</i> .....	10
2.3.4 <i>Efficiency of PV</i> .....	14
2.3.5 <i>Modelling of PV</i> .....	16
2.3.6 <i>Effects of Shadows on PV</i> .....	19
2.3.7 <i>Effects of Dust</i> .....	23
2.3.8 <i>Costs of PV</i> .....	23
2.3.9 <i>Payback of PV</i> .....	25
2.4 INVERTER SYSTEM TECHNOLOGIES .....	26
2.5 BATTERY ENERGY STORAGE (BES) SYSTEMS.....	28
2.5.1 <i>BES Utility &amp; Capital</i> .....	28
2.5.2 <i>Modelling of BES</i> .....	29
2.6 NORTH QLD SOLAR RADIATION.....	32
2.6.1 <i>PSH Conversion</i> .....	33
2.7 OPTIMAL ROOF TILT ANGLE & ORIENTATION .....	34
2.8 THE ELECTRICITY NETWORK (GRID) .....	37
2.9 LOAD PROFILE .....	39
2.10 NETWORK DEMAND CHALLENGES.....	41
2.11 TARIFFS & REBATE CHANGE .....	42

2.12 ECONOMICS OF PV & BES SYSTEM .....	44
2.13 MARKET SOFTWARE COMPETITORS.....	45
2.13.1 <i>Solar Power Calculator</i> .....	45
2.13.2 <i>Solar Choice Solar Battery Storage Sizing &amp; Payback Calculator</i> .....	46
2.13.3 <i>Solar Savings Calculator</i> .....	47
2.13.4 <i>Hybrid Optimisation Model for Multiple Energy Resources</i> .....	47
2.14 SUMMARY OF FINDINGS .....	48
<b>CHAPTER 3: METHODOLOGY .....</b>	<b>51</b>
3.1 MATRIX LABORATORY (MATLAB) .....	52
3.2 GRAPHICAL USER INTERFACE.....	53
3.3 DESCRIPTION OF FUNCTIONALITY .....	53
3.4 DATA SOURCING .....	54
3.5 USER PARAMETERS .....	55
3.5.1 <i>Input Parameters</i> .....	55
3.5.2 <i>Output Parameters</i> .....	55
3.6 PRODUCTION CALCULATIONS.....	56
3.6.1 <i>Linear Tilt Approximation</i> .....	56
3.6.2 <i>kWhr Production</i> .....	56
3.7 RISK ASSESSMENT.....	56
3.8 PROJECT FUNDING.....	56
3.9 GANTT CHART .....	57
3.10 ECONOMIC CALCULATIONS .....	58
3.10.1 <i>Life Cycle Costing</i> .....	59
3.10.2 <i>Annualised Life Cycle Cost</i> .....	60
3.10.3 <i>Annual Payment</i> .....	61
3.10.4 <i>Present Value</i> .....	61
3.10.5 <i>Net Present Value</i> .....	62
3.10.6 <i>Internal Rate of Return</i> .....	62
3.10.7 <i>Return on Investment</i> .....	62
3.10.8 <i>Simple Payback Period</i> .....	63
<b>CHAPTER 4: MATLAB GUI PROGRAM.....</b>	<b>64</b>
4.1 DATA ACQUISITION.....	64
4.2 INPUT DATA .....	67
4.3 ESTIMATED PRODUCTION .....	68
4.4 FINANCE OPTIONS .....	69

4.5 DISPLAY .....	70
4.6 ADDITIONAL FEATURES.....	70
<b>CHAPTER 5: RESULTS.....</b>	<b>72</b>
5.1 CONSTANT PARAMETERS .....	73
5.2 OUTPUT PRODUCTION FIGURES .....	74
5.3 OUTPUT FINANCE FIGURES.....	75
5.4 MONTHLY POWER PRODUCTION GRAPHS .....	76
5.5 YEARLY SAVING PLOTS.....	77
5.6 DAILY ENERGY SOURCES CHARTS.....	78
<b>CHAPTER 6: DISCUSSION.....</b>	<b>79</b>
6.1 EFFECTS OF LOCATION & PARAMETERS .....	79
6.2 ENERGY PRODUCTION FEASIBILITY CALCULATIONS.....	80
6.3 ECONOMIC PAYBACK POTENTIAL.....	83
6.4 ASSUMPTIONS .....	86
6.5 LIMITATIONS IN MATLAB MODELLING .....	87
6.6 SOLAR SOLUTION COMPARISON TABLE .....	89
<b>CHAPTER 7: CONCLUSIONS &amp; RECOMMENDATIONS .....</b>	<b>90</b>
6.7 CONCLUSIONS .....	90
6.8 RECOMMENDATIONS FOR FURTHER RESEARCH .....	91
<b>REFERENCES.....</b>	<b>93</b>
<b>APPENDICES.....</b>	<b>99</b>
APPENDIX A – PROGRESS GANTT CHART .....	100
APPENDIX B – RISK ASSESSMENT.....	101
APPENDIX C – RISK ASSESSMENT (APPROVAL).....	102
APPENDIX D – PROGRAM OVERVIEW .....	103
APPENDIX E – TYPICAL INSTALLATION WIRING OF INVERTER .....	104
APPENDIX F – PROJECT CODE & TITLE.....	106
APPENDIX G – NASA PEAK SUN HOUR DATA .....	107
APPENDIX H – ENERGY CONSUMPTION DATA.....	110
APPENDIX I – MATLAB SOURCE CODE.....	114

## LIST OF TABLES

TABLE 2-1 - TEMPERATURE COEFFICIENTS OF POWER FOR VARIOUS TYPES OF PV MODULES [25].....	9
TABLE 2-2- ADVANTAGES AND DISADVANTAGES OF PV SYSTEMS [29].....	14
TABLE 2-3 - APPROXIMATE COST OF PV IN QLD [49].....	24
TABLE 2-4 - PASSIVE ANTI-ISLANDING SET-POINT VALUES [61] .....	28
TABLE 2-5 - ELECTRICITY PRICING INFORMATION [85].....	42
TABLE 3-1 - MERITS AND LIMITATIONS OF ECONOMIC TOOLS FOR CALCULATION OF LCC [108].....	58
TABLE 5-1 - LOCATIONS SELECTED .....	72
TABLE 5-2 - CONSTANT PARAMETERS .....	73
TABLE 5-3 - OUTPUT PRODUCTION FIGURES.....	74
TABLE 5-4 - OUTPUT FINANCE FIGURES .....	75
TABLE 6-1 - AVERAGE FINANCIAL FIGURES FOR EACH LOCATION.....	84
TABLE 6-2 - SOLAR SOLUTION COMPARISON .....	89

## LIST OF FIGURES

FIGURE 1-1 - WORLDS ENERGY CONSUMPTION BY SOURCE (MILLION TONNES ORE EQUIVALENT VS. YEAR) [7] .....	2
FIGURE 2-1 - OVERVIEW OF OPERATION OF SOLAR SYSTEM [17] .....	6
FIGURE 2-2 - BEHAVIOUR OF LIGHT SHINING ON A SOLAR CELL. 1/2/4/5.) REFLECTION 3/6.) ABSORPTION [21].....	8
FIGURE 2-3 - PHOTOVOLTAIC PANEL TYPES [21] .....	10
FIGURE 2-4 - CLASSIFICATION OF THE SILICON PV PANELS [21] .....	10
FIGURE 2-5 - SWANSON'S LAW: MODULE COSTS DECLINE AS SHIPMENTS INCREASE [26] ...	11
FIGURE 2-6 - CHANGES IN ELECTRICITY GENERATION BY FUEL TYPE [27].....	12
FIGURE 2-7 - SOLAR PV GLOBAL CAPACITY BY COUNTRY/REGION, 2005-2015 [28].....	12
FIGURE 2-8 - ANNUAL SOLAR PV INSTALLATIONS IN AUSTRALIA [27] .....	13
FIGURE 2-9 - STATE AVERAGE SOLAR PV SYSTEM SIZE [27] .....	13
FIGURE 2-10 - BEST RESEARCH-CELL EFFICIENCIES, 1976-2015 [31]......	15
FIGURE 2-11 - SOLAR CELL EFFICIENCY [19].....	16
FIGURE 2-12 - EQUIVALENT CIRCUIT OF A SOLAR CELL [31] .....	17
FIGURE 2-13 - I-V CHARACTERISTIC FOR SILICON 33 CELLS TESTED WITHOUT IRRADIANCE (A) REVERSE BIAS AND (B) FORWARD BIAS, AT 22 DEGREES CELSIUS [42].....	21
FIGURE 2-14 - ADDING NO-OVERLAPPED BYPASS DIODES [43] .....	21
FIGURE 2-15 - ADDING OVERLAPPED BYPASS DIODES [30].....	21
FIGURE 2-16 - SHADING SCENARIOS USED BY MAI [44] .....	22
FIGURE 2-17 - DIAGRAM OF BYPASS AND BLOCKING DIODE FUNCTIONS [45].....	23
FIGURE 2-18 - HISTORICAL TREND IN TIMES OF ENERGY RETURN (EPBT) OF PHOTOVOLTAIC MODULES OF CRYSTALLINE SILICON [56] .....	26
FIGURE 2-19 - GRAPHICAL VIEW OF POTENTIAL OFFSET WITH BES [63] .....	29
FIGURE 2-20 - AUSTRALIAN SOLAR IRRADIANCE [72].....	32
FIGURE 2-21 - AVERAGE HOURLY TOTAL SOLAR RADIATION ON HORIZONTAL SURFACE (MEASURED) [73] .....	33
FIGURE 2-22 - 3D ANNUAL RADIATION MAP OF PITCHED ROOF FROM SOUTH-EASTERN VIEW (LEFT) AND NORTH-EASTERN VIEW (RIGHT) [75] .....	35
FIGURE 2-23 - SOLAR AZIMUTH (LEFT) AND SOLAR DECLINATION (RIGHT) [78] .....	36
FIGURE 2-24 - DISTRIBUTION OF ANNUAL TOTAL INSOLATION NORMALIZED WITH RESPECT TO THE ANNUAL TOTAL MAXIMUM INSOLATION [78] .....	37
FIGURE 2-25 - ERGON ENERGY SERVICE AREA [80].....	38
FIGURE 2-26 - ACTIVITY PROFILES FOR “COOKING”, FOR ONE OR TWO ACTIVE OCCUPANTS ON A WEEK DAY [81] .....	39

FIGURE 2-27 – 24-HOUR ENERGY PROFILE [82] .....	40
FIGURE 2-28 - STANDALONE HOUSEHOLD CONSUMPTION LOAD PROFILE [83] .....	41
FIGURE 2-29 - DUNDOWRAN FEEDER LOAD PROFILE [84].....	41
FIGURE 2-30 - TARIFF 11 kWhr/day - SUMMER Vs WINTER [89].....	43
FIGURE 2-31 - SYSTEM VARIABLES AND SAVING MECHANISMS [22].....	44
FIGURE 2-32 - SOLAR POWER CALCULATOR GUI [92] .....	46
FIGURE 2-33 - SOLAR CHOICE GUI [83].....	46
FIGURE 2-34 - SOLAR SAVINGS GUI [93] .....	47
FIGURE 2-35 - HOMER GUI [24] .....	48
FIGURE 3-1 - ILLUSTRATED SCOPE OF WORKS FOR PROGRAM DESIGN.....	52
FIGURE 3-2 - PROGRAM OVERVIEW .....	54
FIGURE 4-1 - ENTRY SCREEN TO GUI PROMPT .....	64
FIGURE 4-2 - DATA ACQUISITION PHASE OF GUI PROMPTING .....	65
FIGURE 4-3 - DATA ACQUISITION PHASE OF GUI PROMPTING (CONTINUED) .....	66
FIGURE 4-4 - INPUT DATA TAB .....	67
FIGURE 4-5 - ESTIMATED PRODUCTION TAB .....	68
FIGURE 4-6 - FINANCE OPTIONS TAB .....	69
FIGURE 4-7 - DISPLAY TAB .....	70
FIGURE 5-1 - LOCATIONS SELECTED FOR ANALYSIS [105] .....	72
FIGURE 5-2 - MONTHLY POWER PRODUCTION - TOWNSVILLE.....	76
FIGURE 5-3 - MONTHLY POWER PRODUCTION - DARWIN .....	76
FIGURE 5-4 - MONTHLY POWER PRODUCTION - HOBART .....	76
FIGURE 5-5 - YEARLY SAVINGS WITH SOLAR Vs. NORMAL RATE - TOWNSVILLE.....	77
FIGURE 5-6 - YEARLY SAVINGS WITH SOLAR Vs. NORMAL RATE - DARWIN .....	77
FIGURE 5-7 - YEARLY SAVINGS WITH SOLAR Vs. NORMAL RATE - HOBART .....	77
FIGURE 5-8 - HOUSEHOLD ENERGY SOURCES - TOWNSVILLE .....	78
FIGURE 5-9 - HOUSEHOLD ENERGY SOURCES - DARWIN .....	78
FIGURE 5-10 - HOUSEHOLD ENERGY SOURCES - HOBART .....	78

## LIST OF ABBREVIATIONS & SYMBOLS

AC	Alternating Current
AEMO	Australian Energy Market Operator
ALCC	Annualised Life Cycle Cost
ANN-PMT	Annualised Payment Plan
BES	Battery Energy Storage
CO <sub>2</sub>	Carbon Dioxide
DC	Direct Current
DER	Distributed Energy Resource
DOD	Depth of Discharge
DPB	Discounted Payback Period
EPBT	Energy Payback Time
EPS	Emergency Power Supply
F	Frequency
GHI	Global Horizontal Irradiance
GUI	Graphical User Interface
HEV	Hybrid Electric Vehicle
IC	Integrated Circuit
IRR	Internal Rate of Return
J	Joules
kWhr	Kilowatt Hour
LCC	Life Cycle Cost
LV	Low Voltage
M	Mega
MATLAB	Matrix Laboratory
NEM	National Electricity Market
NPV	Net Present Value
O	Outdoor
PDF	Probability Density Function
PSH	Peak Sun Hours
PV	Photovoltaic
ROI	Return on Investment
RTP	Real Time Pricing
SOC	State of Charge
SOH	State of Health
SPB	Simple Payback Period

STC	Standard Test Conditions
V	Volts
WAN	Wireless Area Network
$\gamma$	Temperature Coefficient
$P_{PV,STC}$	Standard Test Conditions for Photovoltaic Panels
$T_c$	Cell Temperature
$I_l$	Photocurrent source
$I_{SC}$	Short Circuit Current at 1,000W/m <sup>2</sup> and 25 Degrees Celsius
$T_s$	Surface Temperature of the Solar Cell
$S_l$	Irradiation Incident on the Solar Cell

## LIST OF APPENDICES

APPENDIX A – PROGRESS GANTT CHART .....	100
APPENDIX B – RISK ASSESSMENT.....	101
APPENDIX C – RISK ASSESSMENT (APPROVAL) .....	102
APPENDIX D – PROGRAM OVERVIEW .....	103
APPENDIX E – TYPICAL INSTALLATION WIRING OF INVERTER .....	104
APPENDIX F – PROJECT CODE & TITLE.....	106
APPENDIX G – NASA PEAK SUN HOUR DATA .....	107
APPENDIX H – ENERGY CONSUMPTION DATA .....	110
APPENDIX I – MATLAB SOURCE CODE .....	114



# CHAPTER 1: INTRODUCTION

Electrical energy has become a crucial element for human living and is essential for both social and economic development of a country states Vijayalashimi [1]. It is utilised directly or indirectly in every facet of human life. From study, occupation, education to entertainment, the ability to transform electrical energy into products and desired functions is a growing necessity. Shafiee and Topal have estimated the world's energy market to be approximately 1.5 trillion dollars, and explained that it is still dominated by fossil fuels [2]. The world's population doubled from 1927 to 1974, and this occurred again in the following 25 years (to 1999). Cohen emphasised that until this century, people had never lived through a population doubling, yet nowadays people are living through a tripling. Over 2 billion people have arrived in a single generation [3].

With the estimated population by the United Nations Population Division expected to reach 9.5-13 billion by 2100, the stakes have never been so high for the supply of clean, efficient and stable electrical energy [4]. The world's energy consumption is approximately 10 terawatts per year and is expected to rise to 30 terawatts by 2050 [5]. Kannan wrote that one of the greatest goals of the 21<sup>st</sup> century is simply being able to prevent a world energy crisis, due to the demand of a rising population [6].

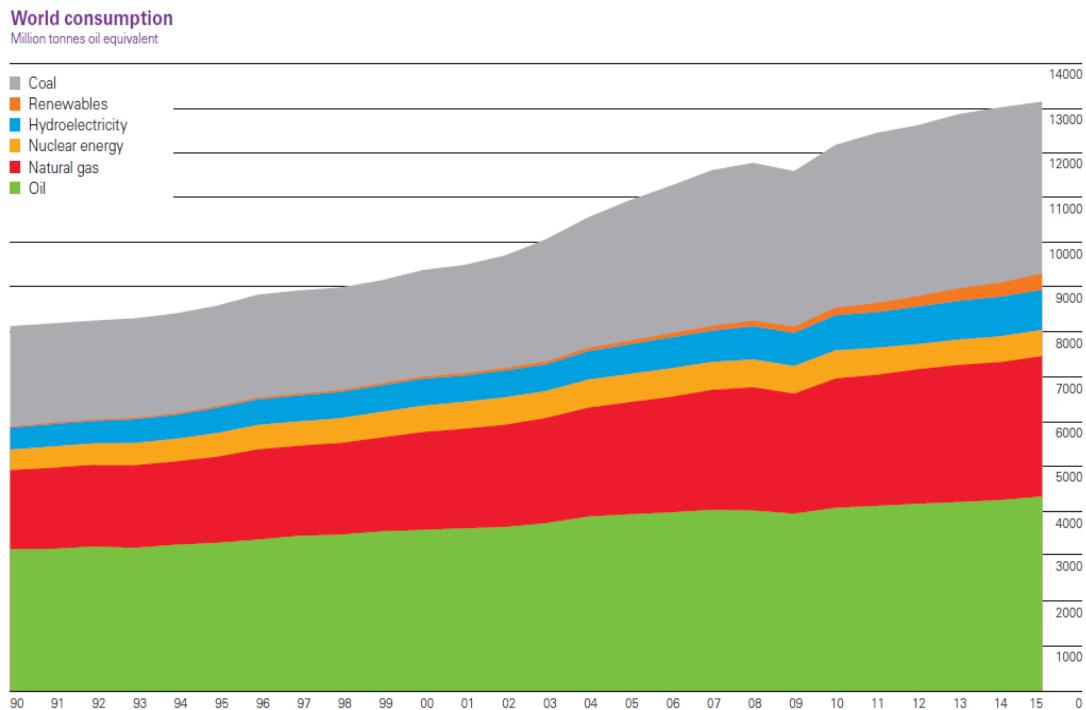
## 1.1 Overview

The sources of this grand supply of energy must be of high quality, dependable and above all ethical. Currently, 10 Giga-tonnes of carbon dioxide is produced each year as fossil fuel emissions (as a by-product of electricity production), and it remains the largest single sector emitter [7]. In the wake of global warming and carbon emissions figures, the demand for green renewable energies has grown exponentially.

The breakdown of energy from sources can be seen in Figure 1-1 - Worlds Energy Consumption by Source (Million Tonnes Ore Equivalent Vs. Year) [7]. The “green” energies wind, geothermal, wave, hydroelectricity and solar are now in their greatest demand, due to their ability to produce power and their minimal to non-existent carbon footprint. Valentine's studies show that the installed wind power alone since 2000, throughout the world, has doubled every three years [8].



The solution to the energy crisis is renewable energies. In particular solar is ideal as it is clean, free, theoretically unlimited, long lifetime technology, accessible, and environmentally friendly [9]. Therefore, in several countries including Australia, feed-in tariffs for Photovoltaic (PV) have been significantly subsidised to augment and incentivise the installation, technological advancement, and use of such systems. From the start of the new millennium Australia's PV capacity rapidly increased, establishing itself as the 7<sup>th</sup> global market for PV and introduced one of the world's first renewable energy target schemes in 2001 [10].



*Figure 1-1 - Worlds Energy Consumption by Source (Million Tonnes Ore Equivalent Vs. Year) [7]*

In 2013 Australia, had over a million roofs with operating PV systems. This is due to Australia having the highest average solar radiation, sensitivity over sustainability, subsidised rebate schemes, increasing electricity prices and substantially decreasing install costs. Ma demonstrated the decreasing costs from \$9000/kW AUD in 2009 to \$2130/kW in 2013 [11]. These feed-in tariffs from consumer based production arising from increased distributed PV sources have caused disruption for the medium/low-voltage networks through induced voltage rises. These voltage rises are from reverse power flow along the feeders from the inverters. With the inverters there is also concern for harmonic pollution from PV [12].

This implication for production and effects on the network have caused changes to be made to Australia's National Electricity Market (NEM) and state schemes for use of solar PV energy



[13]. Due to the incompatibility between PV production and load-demand there is a minute potential for self-consumption. Appen and Braun show that to achieve a greater amount of self-consumption the battery energy storage (BES) systems can be utilised [14]. Hence, BES systems can be designed to reduce strain; adverse load profiles and voltage rises on the network while smoothing the grid integration and ultimately aiming towards off-grid standalone domestic systems.

An upshot of a standalone or hybrid system is that the user does not lose power when the grid does. Appen noted there was missing information and that the current requirements for sizing, performance and control need to be analysed and simulated both from technical and economical perspectives [15]. In response Ergon Energy (Queensland's Electricity Provider) is anticipating the effectiveness of the BES systems and planning revision of their tariff schemes.

## 1.2 Research Aims

The aim of this project is to develop a program in the MATLAB workspace to size and optimise PV/BES systems for different configurations of household demand to maximise savings and disruptive outputs to the LV grid network. The investigation into the estimated production capabilities of the lower latitudes receiving higher PSH to the kWh production per day for a given PV system will be analysed. The calculation of the cost of electricity for a domestic situation from a PV/BES system and up-front capital and lifetime payback will be modelled.

Households with combined installation of PV/BES in each location will be analysed for their reduced cost of electricity per kWh in respect to the Australian benchmark cost. The annual payment costs of a PV/BES system will be modelled for economic feasibility in the mortgage climate rates of optimistic, likely and pessimistic at different latitudes. All simple payback periods over the project lifetimes will be assessed for net savings compared to investment cost.

## 1.3 Scope

Photovoltaic systems have been around for just over 50 years and their daily use and efficiency is increasing. Farmer and Lafond proposed that PV is expected, with its rapid refinements to surpass its competition in the upcoming 10-20 years [16]. Now with the introduction of BES system technologies and their decreasing costs it is a logical path for domestic energy consumers who are conscious of pricing and environmental factors.



This project will only deal with domestic PV installations. It is beyond the scope to deal with anything larger than a general domestic sized PV installation usually with a maximum capacity of 10kW. Residential households will be assessed and modelled disregarding other commercial or industrial applications, although a working model extrapolating to other applications is possible. The different tariff schemes throughout the world and indeed Australia will not be analysed; although the models can be applied to other tariffs schemes. The tariff schemes currently in use by Townsville's energy supplier Ergon Energy will be used. The standard consumer type solar panels will be used and not advanced super solar panels, organic, off market or other configuration tracking panels.

When referring to solar power in this paper it will be meant solar photovoltaic energy power. This paper will not deal with other forms of renewable energy or other solar energies such as solar concentration energy. A solar system may have one or two arrays; any panel combined with an inverter is considered a solar system in this paper. The term solar system will refer to the entire system incorporating solar PV panels, the direct current (DC) to alternating current (AC) inverter and may contain a battery bank or BES system and no other configurations. For clarification, one cell is a P-N junction. Many cells make a module (generally 36 or 72) and usually 10 or 20 modules make an array. The inverter will be a grid-tie, battery backup inverter or stand-alone inverter system; all three applications will be dealt with. The battery systems described will not include lead acid batteries but instead focus on lithium ion batteries such as the Tesla Powerwall and LG Chem RESU and zinc bromide batteries such as ZBM 2 by Redflow. Only the solar irradiance for Australia and principally Townsville will only be analysed.



# CHAPTER 2: LITERATURE REVIEW

This Literature Review examines the current and relevant literature regarding PV systems, tariff schemes, solar-related economics, sizing, current technologies, modern programs for analysis and BES systems. It will give an insight into the operation and basic understanding of why these systems are starting to dominate the electrical industry. It will identify areas where the literature is unsubstantiated or incomprehensive. The key areas which do not have sufficient data or analysis will be examined. It is important to identify these gaps, as they have the potential to decrease carbon emissions, increase stability on the grid, and save the average domestic electricity consumer thousands of dollars.

## 2.1 Background

The recent doubling of the world's population has caused concern around the globe. The cry to slake increased energy demands has been met with unsubstantiated claims. The electrical energy sector is turning towards clean, ethical, dependable energy sources. The renewable energy industry has had massive growth in the past few decades. But with the dependability of renewable energy being called into question due to the power crisis in South Australia (SA) in February this year (2017), which left over 90,000 people without power. The move to justify and improve renewable energy technology has never been so evident.

In the fallout of the SA blackout, the necessity to make renewable technologies more reliable and less disruptive to the grid is being researched. This review gives a general background of PV systems, how they have developed and their various types. Consequences of PV systems are then explored in load profiles, PV rise, tariffs and the rebate schemes. It will explore how electricity is charged to the consumer and sold to the supplier. The solar irradiance is examined along with current market programs for the sizing and analysis of solar systems. The effects of shadowing and PV payback studies are all explored. The BES system is then explained, including its ramifications for the network and potential augmentation to the network discharge. New and emerging technologies will be noted and met with speculations of their effect on the electricity market and their benefits for consumers.

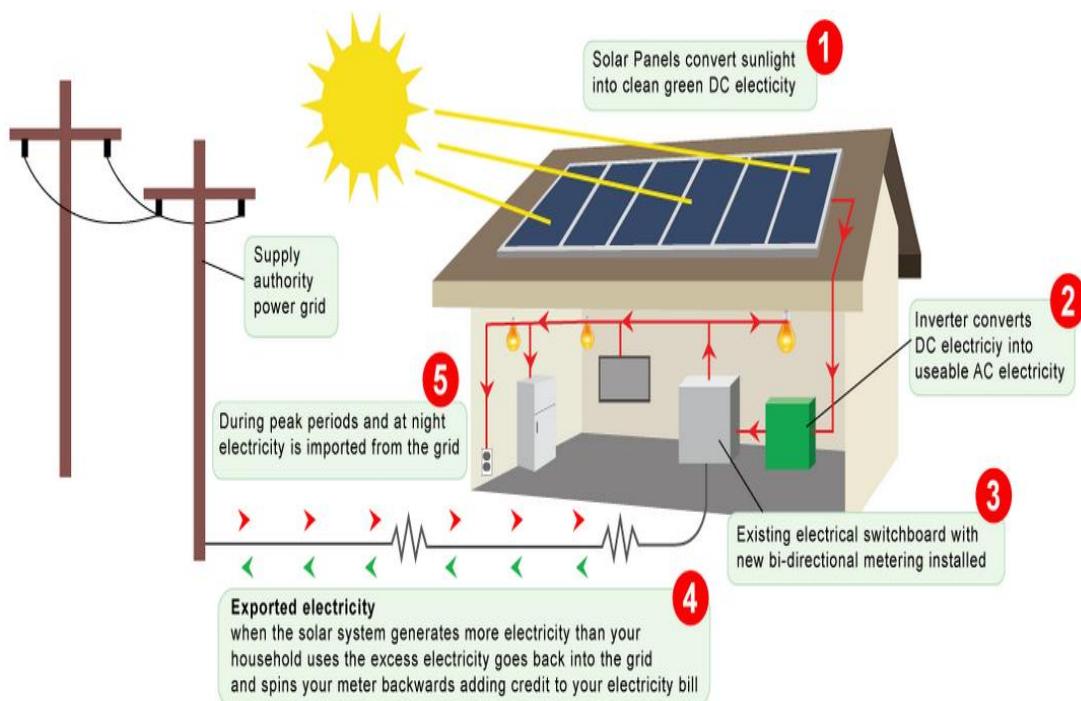
Finally, the economics of using the system and current developing technologies are reviewed. With this basis, the gaps in the literature will be identified, examined and evaluated. This



review was written principally from primary sources published in reputable peer-reviewed journals. Secondary sources were used for compilation of ideas, some graphics and themes but were endeavoured to be used as a guide and referenced against the primary sources. Grey literature for this Literature Review was not used in any of the references.

## 2.2 Solar System Synopsis

The main premise of this thesis will deal exclusively with solar PV systems which are comprised of three primary components: the solar panels, the DC to AC inverter system and the battery energy storage system. Figure 2-1 - Overview of Operation of Solar System [17] shows the operation of a solar system with the export and import of power to the grid and the conversion of DC to AC for coupling with the grid and household consumption [17].



*Figure 2-1 - Overview of Operation of Solar System [17]*

The solar panels convert solar radiation from the sun into DC electrical energy. This DC then flows into the inverter system. The inverter is designed to convert DC power into AC power. Usually, the inverter (in a hybrid system) is connected to the mains power for coupling with the feed frequency i.e. 50Hz. The power is then fed from the inverter system to the house for use. The excess power which is produced during the day is fed back into the grid through a bi-directional meter to measure the different tariff rates for import and export. Each component of the solar system will now be discussed in greater depth.



## 2.3 Photovoltaic Systems

### 2.3.1 Review of PV

Every day there is approximately 100 000 terawatts of energy provided by the sun. Currently, the Earth's energy demand is 10,000 terawatts; Grätzel emphasised that this is a 10 time surplus. [18] There is a way to tap into this vast energy source and that is with the humble solar panel. The solar panel or photovoltaic panel is a device which converts light energy into electrical energy. The word "photovoltaic" which originated in 1849 came from the Greek word "Phos" meaning "light" and from the English word "volt" (which is) a measure of electro-motive force. The photovoltaic effect was first observed in 1839 by French physicist A. E Becquerel [19].

A photovoltaic panel or PV panel or solar panel is any solid state electrical device which converts light energy to electrical energy by using the photovoltaic effect. Solar panels consist of a simple PN junction which is a P-doped layer and an N-doped layer. Both layers usually consist of Silicon with the P (positive) layer being doped usually with boron or gallium and the N (negative) layer is doped with usually phosphorus or lithium [20]. Light which arrives from the sun comes in the form of photons and can do one of three things once it reaches the PN junction.

Firstly, they can pass straight through; which lower energy photons usually do. Secondly, they can reflect off. Thirdly, they can hit the electrons in the silicon and move them out of their current orbital up to a higher energy band as seen in Figure 2-2 - Behaviour of Light Shining on a Solar Cell. 1/2/4/5.) Reflection 3/6.) Absorption [21] . These electrons either convert the energy to heat and return to their original orbital, or travel through the cell until they reach an electrode. This flow of electrons is photo current flow and is the electricity produced by a solar cell. If many solar cells are connected in series they form a solar panel or module [21].

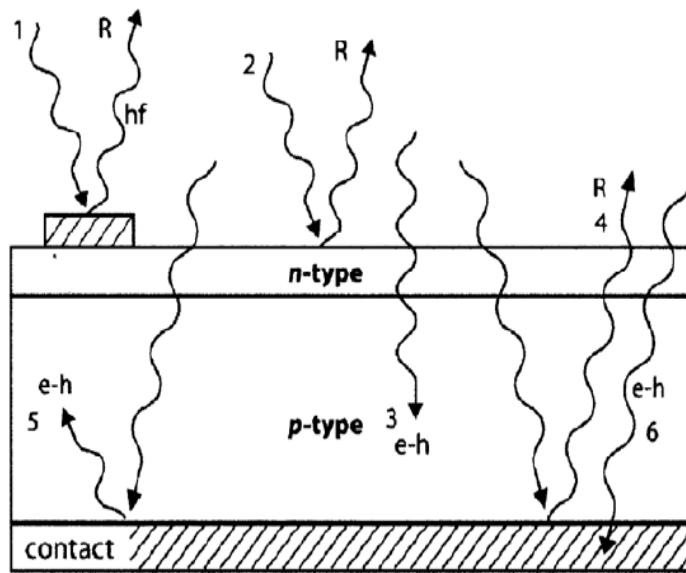


Figure 2-2 - Behaviour of Light Shining on a Solar Cell. 1/2/4/5.) Reflection 3/6.) Absorption [21]

The generation output for a solar cell is dependent upon many variables such as Global Horizontal Index (GHI), temperature data and the type of PV cell or module. The following equation is used to calculate PV generation [22]:

$$P_{PV} = \frac{P_{PV,STC} * GHI[1 - \gamma(T_C - 25)]}{1000} * N_{PV,S} * N_{PV,P} \quad (2-1)$$

Where:

- $P_{PV,STC}$  – solar output under STC (see below for definition)
- $GHI$  – Global Horizontal Irradiance
- $\gamma$  – temperature coefficient (generally  $-0.41\%/\text{°C}$ )
- $T_C$  - cell temperature
- $N_{PV,S}$  &  $N_{PV,P}$  - constants determined by the system design

Standard Test Conditions (STC) for the performance of PV modules is an industry-wide standard and specifies a cell temperature of  $25\text{°C}$  and an irradiance of  $1000 \text{ W/m}^2$  with an air mass 1.5 (AM 1.5) spectrum. These conditions correspond to the irradiance and spectrum of sunlight incident on a clear day upon a sun-facing  $37\text{°}$ -tilted surface with the sun at an angle



of  $41.81^\circ$  above the horizon at spring and autumn equinoxes in the United States of America (USA) [23].

The temperature coefficient is an indication of how the PV cell's power output is affected by the change in temperature. A study by King stated that generally the percentage change in power output per degree is  $-0.41$  [24]. This is important for at higher temperature climates the production will decrease. To illustrate this we can assume a maximum day temperature of  $50^\circ\text{C}$ . This means that for each degree an average (depending on the type of PV cell) drop of  $-0.41\%/\text{ }^\circ\text{C}$  can be expected. Therefore, we can calculate the loss in production by:

$$0.4\% \times (50^\circ\text{C} - 25^\circ\text{C}) = 0.4\% \times 25^\circ\text{C} = 10\%$$

This means that a 10% drop in productivity can be expected at this temperature. King went on to say that for a typical flat-plate module with solar irradiance varying from perhaps  $100 \text{ W/m}^2$  to  $1000 \text{ W/m}^2$ , there is typically less than a 5% change in the voltage coefficients. Homer Energy summarised the temperature coefficients for different types of PV modules in Table 2-1 [25].

*Table 2-1 - Temperature Coefficients of Power for Various Types of PV Modules [25]*

PV Module Type	# Modules	$\alpha_P$	[%/ $^\circ\text{C}$ ]
Polycrystalline silicon	10	7	-0.48
Monocrystalline silicon	8	4	-0.46
Monocrystalline/amorphous silicon hybrid	1	1	-0.30
Thin film amorphous silicon	4	4	-0.20
Thin film CIS	1	1	-0.60

### 2.3.2 Types of PV

There are many solar cells which make up solar panels or modules. The different types of cell material and configuration are what create the different types of solar panels. Below is a list of the most common types of cell arrangement:

- Amorphous silicon solar cell (a-Si)
- Concentrated PV cell (CVP and HCVP)
- Crystalline silicon solar cell (c-Si)
- Multi-junction solar cell (MJ)
- Nanocrystal solar cell



- Perovskite solar cell
- Photo-electrochemical cell (PEC)
- Plasmonic solar cell
- Polycrystalline solar cell (multi-Si)
- Thin-film solar cell (TFSC)
- Organic solar cell (OPV)

The main types of solar panels in use in the domestic sector are shown in Figure 2-3 - Photovoltaic Panel Types [21] and are monocrystalline, polycrystalline and thin film silicon. The classification of solar panels is shown in Figure 2-4 - Classification of the Silicon PV Panels [21].

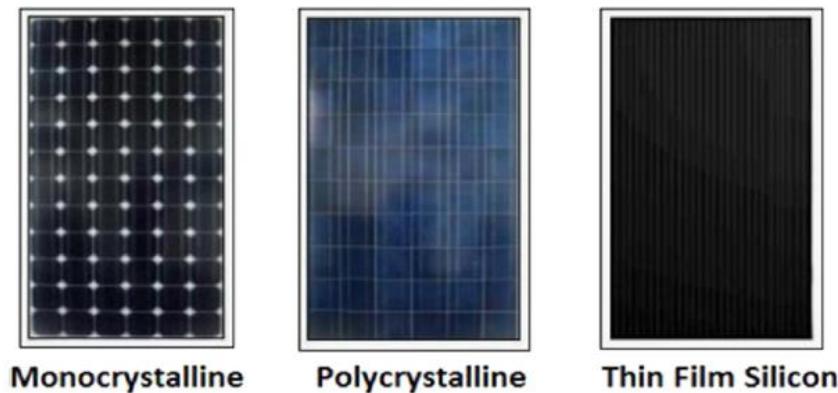


Figure 2-3 - Photovoltaic Panel Types [21]

The main difference between monocrystalline and polycrystalline is that for the same wattage polycrystalline is slightly larger than monocrystalline. Thin film panels are larger than both monocrystalline and polycrystalline.

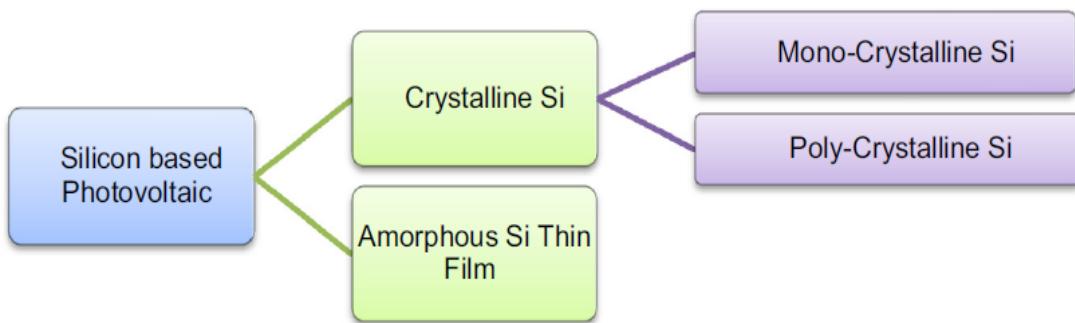


Figure 2-4 - Classification of the Silicon PV Panels [21]

### 2.3.3 Growth of PV

Moore's Law is a law well-known to the semiconductor industry. This law observes that approximately every two years the number of transistors on an integrated circuit (IC) will



double. What Moore is to the semiconductor industry, Swanson is to the PV industry. Richard Swanson in the 1970's observed that for every doubling of global shipments the price for solar photovoltaic modules drops by 20%. The decrease in cost is due to the scale of materials needed i.e. silicon prices dropped and decreased cost of labour due to automation of processes [26]. Figure 2-5 - Swanson's Law: Module Costs Decline as Shipments Increase [2] trends the decrease in PV module cost. From the Figure 2-5 - Swanson's Law: Module Costs Decline as Shipments Increase [2] it shows that the cost in 1976 was approximately 100.00\$/W and in 2014 it is approximately 0.80\$/W.

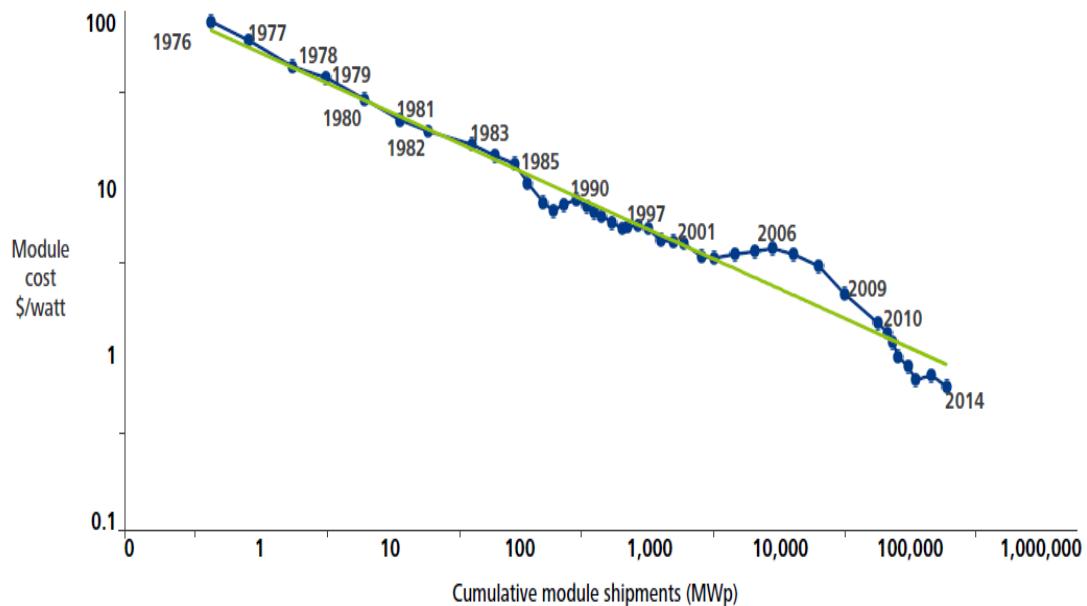


Figure 2-5 - Swanson's Law: Module Costs Decline as Shipments Increase [26]

The massive growth in renewables is borne from an economic shrewdness and increasing sensitivity to sustainability and greenhouse gas emissions. The increasing price of electricity and the non-existent cost of fuel for renewable technology contribute to the growth of renewables. The magnitude of the growth of renewables can be seen in Figure 2-6 - Changes in Electricity Generation by Fuel Type [27] which compares renewables to other sources of energy [27].

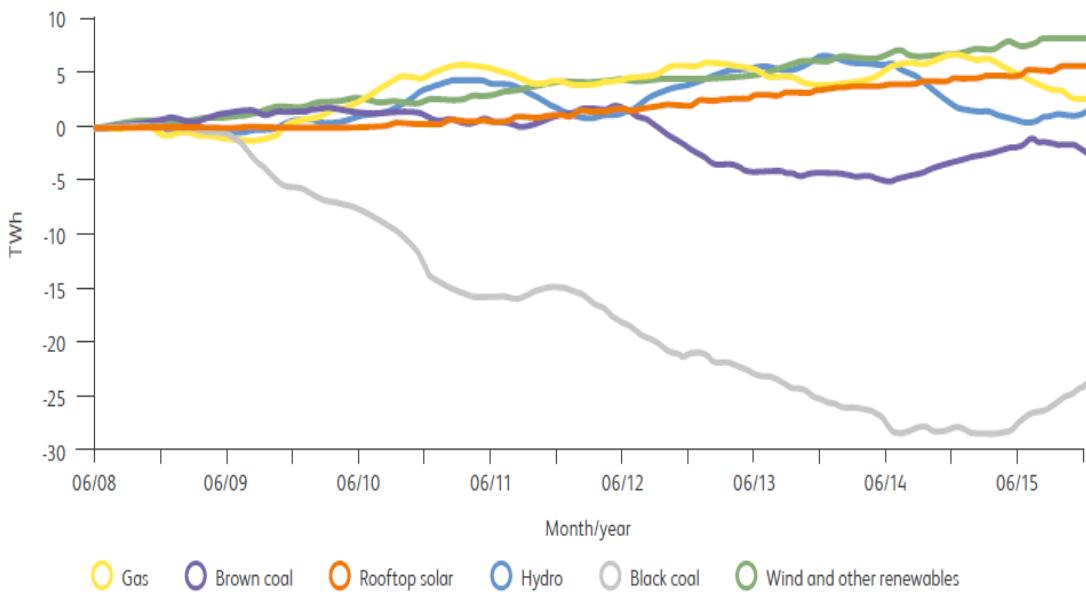


Figure 2-6 - Changes in Electricity Generation by Fuel Type [27]

The renewable energy industry is growing substantially each year and is comprised of wind, solar PV and solar concentration, wave, geothermal, bio and hydroelectricity. This paper will principally comment on solar photovoltaic technologies. Figure 2-7 - Solar PV Global Capacity by Country/Region, 2005-2015 [28] trends the last decade of growth for PV production from 5.1 GW in 2005 to 227 GW in 2015. This clearly demonstrates the growth of PV technologies all over the world [28].

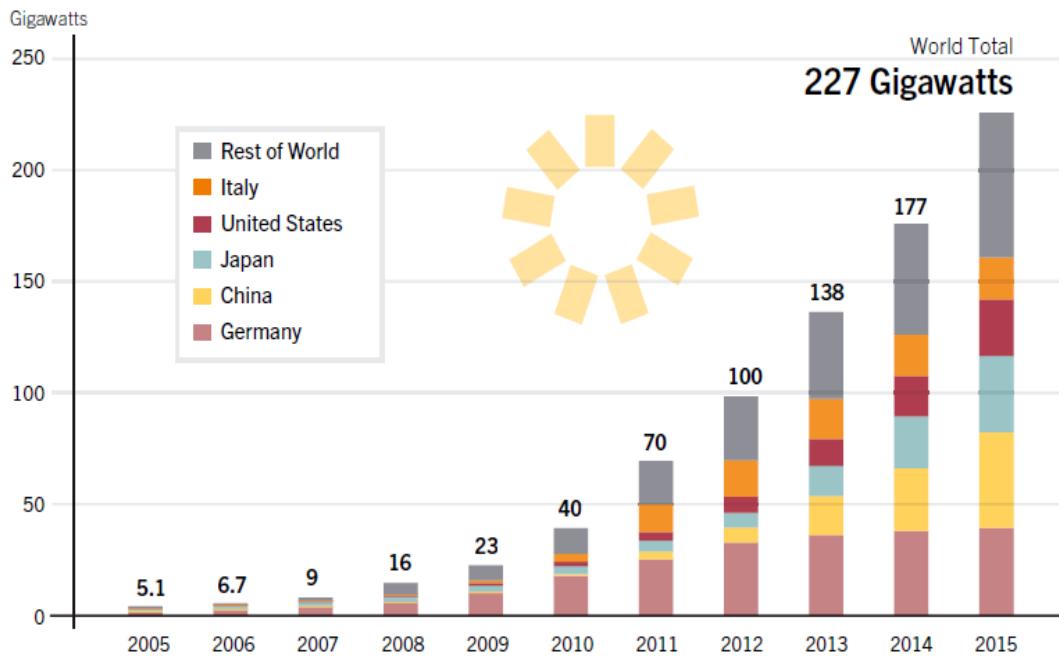


Figure 2-7 - Solar PV Global Capacity by Country/Region, 2005-2015 [28]

The growth in solar PV is occurring all over the world and Australia has seen huge increases in the amount of solar installations. Figure 2-8 - Annual Solar PV Installations in Australia [27] shows the amount of installations per year in Australia. The peaks noted in the years 2011 and 2012 were due to the rebate programs [27].

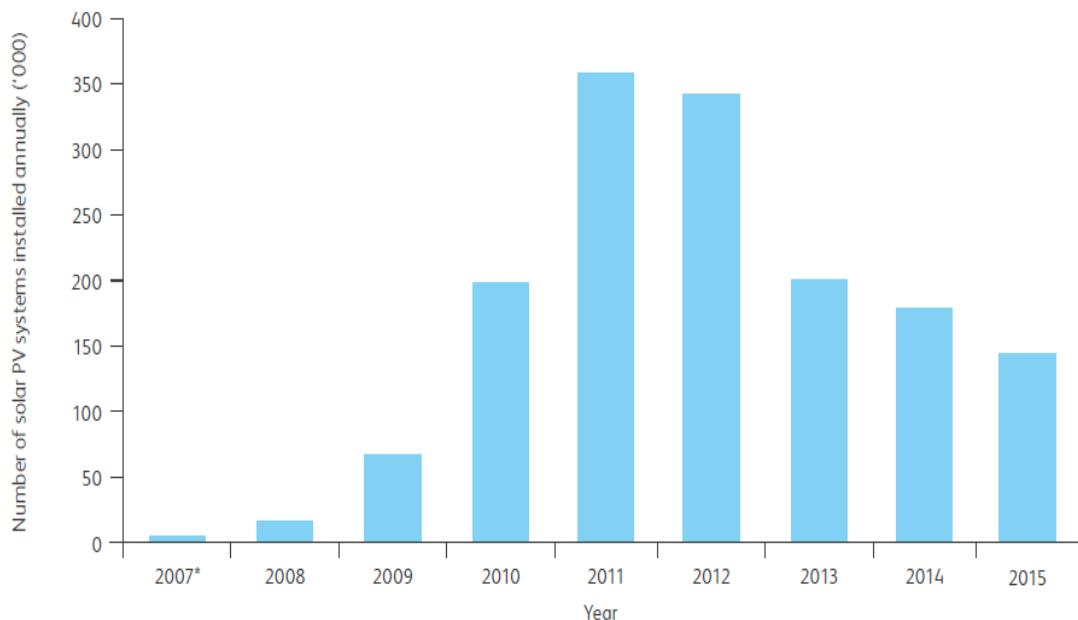


Figure 2-8 - Annual Solar PV Installations in Australia [27]



While the amount of installations has started to decrease, the size of the installation has increased. Figure 2-9 - State Average Solar PV System Size [27] shows that the average kW capacity of the systems installed has increased and is due to price decreases and better technology [27].

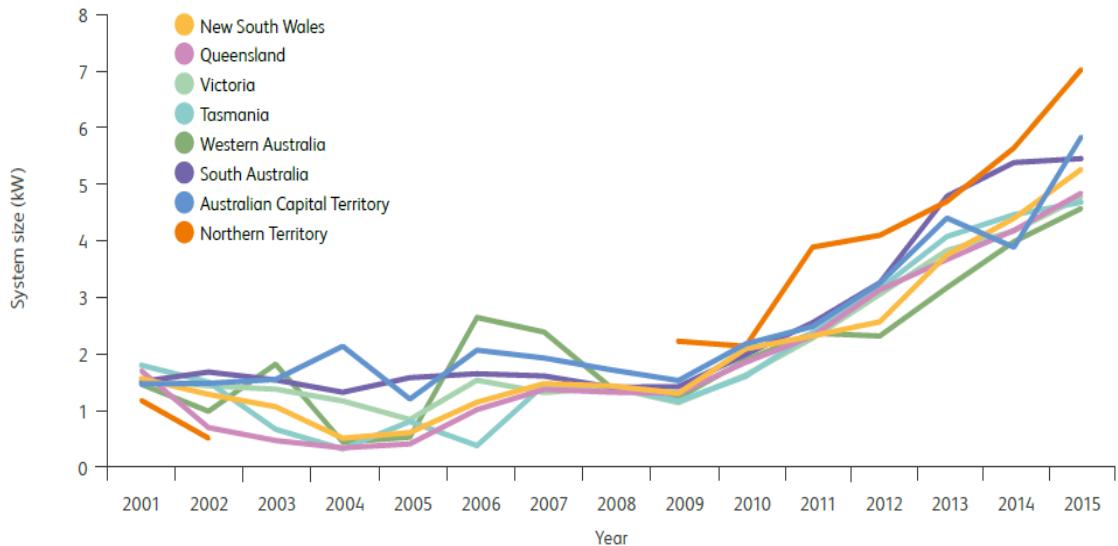


Figure 2-9 - State Average Solar PV System Size [27]

The renewable energy trend has allowed Queensland (QLD) to generate 4% of its electricity from renewables, with two wind farms and 466,966 domestic solar systems [27]. Onat has highlighted in Table 2-1 the advantages and disadvantages of PV systems [29].

Table 2-2- Advantages and Disadvantages of PV Systems [29]

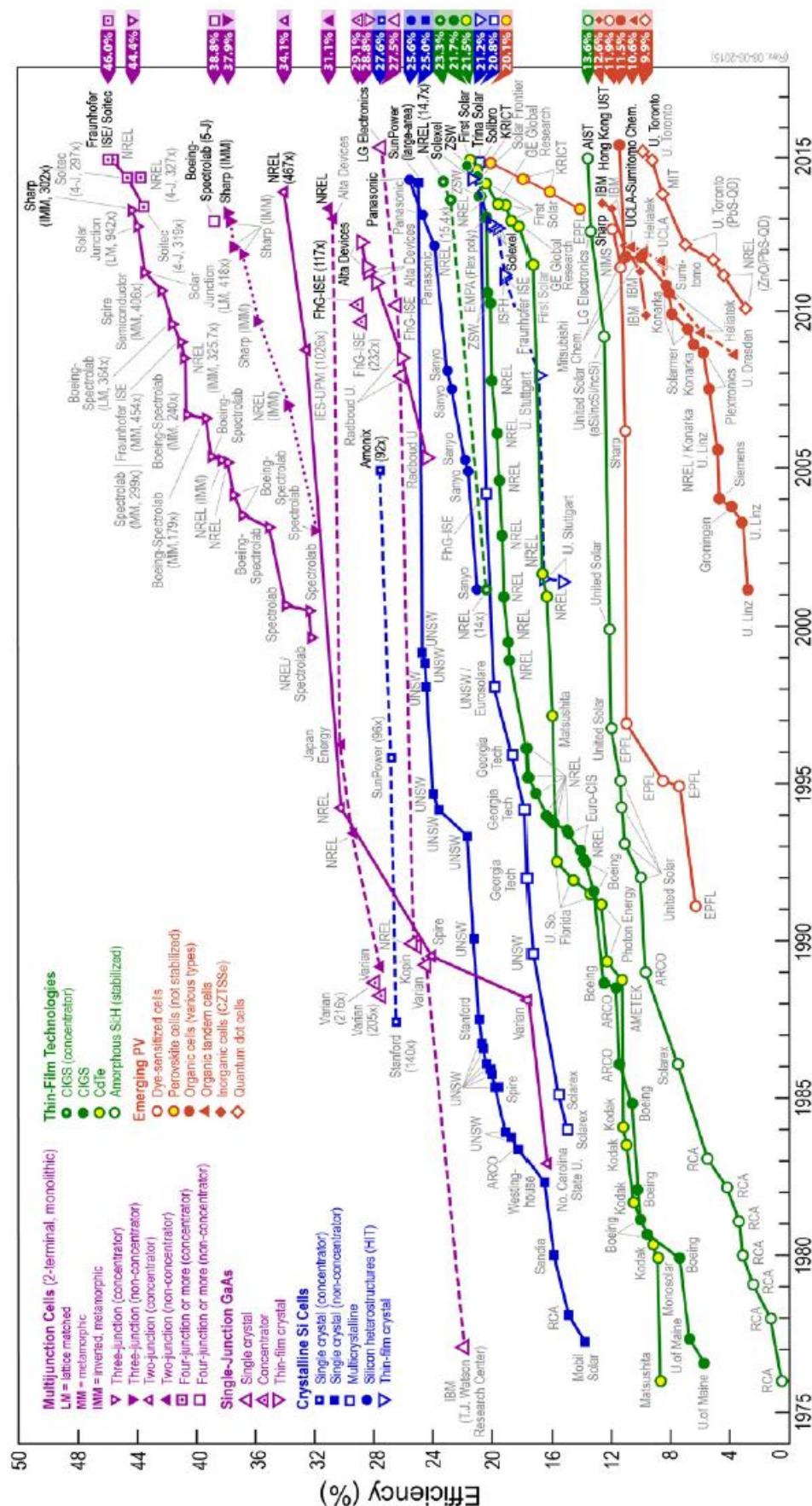
Advantages of PV	Disadvantages of PV
Fuel source is vast and essentially infinite	
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	Fuel source is diffuse (sunlight is relatively low-density energy)
Low operating costs (no fuel)	
No moving parts	Low conversion efficiency <40% for commercial applications
Ambient temperature operation	
High reliability in modules (>20 years)	
Modular (small or large increments)	Poorer reliability of auxiliary (BOS) elements including storage
Quick installation	
Can be integrated into new or existing building structures	
Can be installed at nearly any point of use	Initial investment sum



Daily output peak may match local demand	Lack of economical efficient energy storage
High public acceptance	
Excellent safety record	

### 2.3.4 Efficiency of PV

The PV cell is a technology which is rapidly improving. The first solar cells had less than 1% efficiency and in the 1950's the Si cells had around 6% efficiency [30]. Currently Si crystalline has 25.6% efficiency while the best solar cell is InGaP/GaAs/InGaAs with 37.9% efficiency [31]. Figure 2-10 - Best Research-Cell Efficiencies, 1976-2015 [31] shows the trending increase in efficiency for solar panels.





While the efficiencies of PV are undoubtedly increasing it is important to mention the declining performance of PV over its lifetime. Shamra wrote that PV experiences a continuous degradation due to aging [32]. A study by Meyer and Dyk reported that after an initial exposure of 130 sun hours, the performance of the CIS module degraded by more than 20%. That a-Si module degraded by about 60%, and the a-SiGe module degraded by approximately 13%. They mentioned that crystalline EFG-Si and mono-Si modules showed no degradation [33].

These percentages are quite ranging, while a study by Jordan and Kurtz in 2013 after an extensive study on relatively newer solar panels contested the findings in 2004 by Meyer and Dyk. Jordan and Kurtz stated the distribution is skewed toward high degradation rates with a mean of 0.8%/year and a median of 0.5%/year. They reported on the degradation rates of flat plate terrestrial modules recorded in literature from testing for the most recent four decades. The study spanned 2000 degradation rates and the data showed the median value of 0.5%/year [34].

In the most recent study for the trending increases of efficiency for PV technology conducted by Sampaio and Gonzalez in 2017 the Figure 2-11 - Solar Cell Efficiency [19] was produced [19].

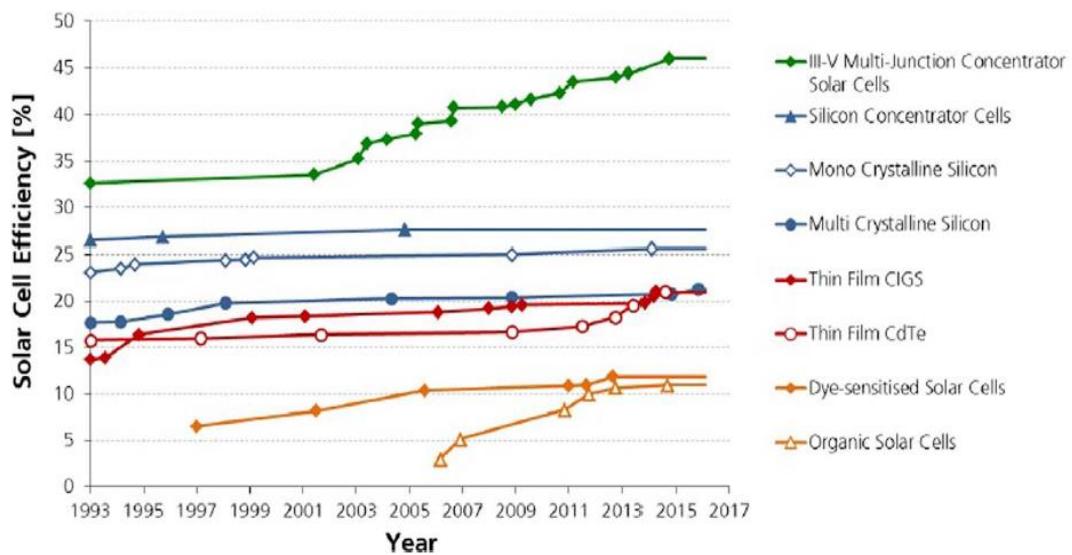


Figure 2-11 - Solar Cell Efficiency [19]



### 2.3.5 Modelling of PV

As mentioned previously solar cells are PN junctions which can be reduced to an electrically equivalent solar cell model of a single diode, dependant current source and resistors as shown in the Figure 2-12 - Equivalent Circuit of a Solar Cell [31]. The voltage drop over the diode depends on the type of material which is used to construct the solar cell. Silicon crystalline cells have 0.74 V, thin film (GaAs) have 1.122 V and silicon amorphous have 0.896 V forward biasing drop [31].

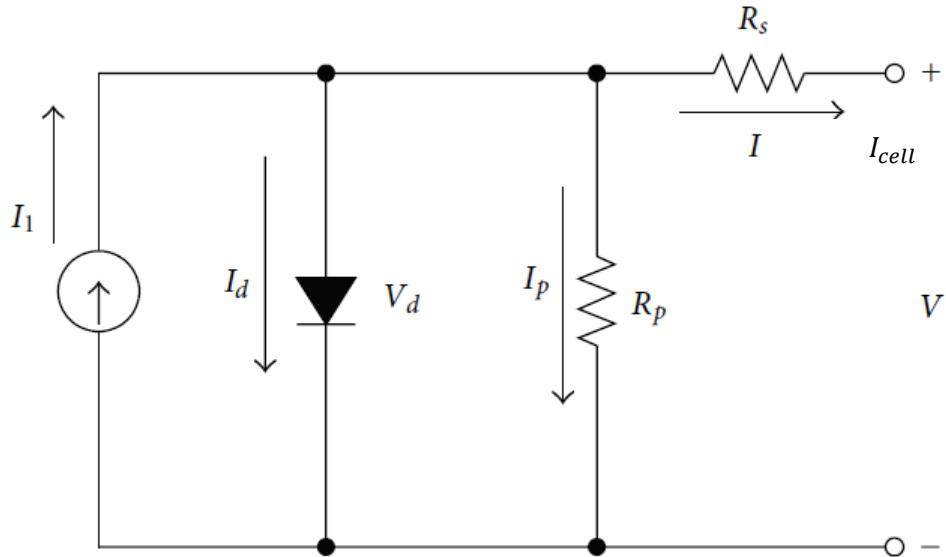


Figure 2-12 - Equivalent Circuit of a Solar Cell [31]

The incident energy in the form of photons from the sun are converted into photocurrent which is the current source  $I_l$ . The electrons in the valence band are given energy from the photons and “jump” up to the conduction band producing a current [35, 36].

The total current which flows out of the solar cell can be calculated by Kirchhoff's Current law at the top node [37]:

$$I_{cell} = I_l - I_d - I_p \quad (2-1)$$

Where:

- $I_{cell}$  - current flowing out of the cell
- $I_l$  - photocurrent source
- $I_d$  - diode current



- $I_p$  - current flowing through a parallel resistor caused by a forward biased P-N junction

The current produced by the photocurrent source is given by the equation [37]:

$$I_l = [I_{SC} + k_i(T_s - T)] \frac{S_i}{1000} \quad (2-2)$$

Where:

- $I_l$  - photocurrent source
- $I_{SC}$  - short circuit current at 1,000W/m<sup>2</sup> and 25°C
- $T_s$  - surface temperature of the solar cell
- $S_i$  - irradiation incident on the solar cell
- $k_i$  - temperature modification coefficient for the short circuit current

In Baetens' studies he utilised the equation below derived from Figure 2-12 - Equivalent Circuit of a Solar Cell [31] for the instantaneous power produced by PV [35-37]:

$$P_{PV,ins} = I_{cell}V \quad (2-3)$$

$$I_{cell} = I_L - I_0 \left[ \exp \left( \frac{V + I_P V R_S}{a_{ref}} \right) - 1 \right] - \frac{V - I_P V R_S}{R_{sh}} \quad (2-4)$$

Where:

- $P_{PV}$  - instantaneous power produced by the cell
- $I_{cell}$  - current produced by the cell
- $V$  - voltage of the cell
- $I_L$  - light generated current
- $I_0$  - reverse saturation current of the diode
- $R_S$  - series resistance of the cells
- $R_{sh}$  - shunt resistance of the cells
- $a_{ref}$  - modified ideal factor for compensation of second-order effects depending on the cell



The equation (2-5) is for the calculation of instantaneous power. The sunlight which drives the independent photocurrent source is continually changing. The variable is the sunlight and it can be modelled using a probability density function (PDF) or measured and averaged. The average solar irradiance measurements are discussed later. Barrios acknowledges that the most common models are the Beta, Weibull, Log-normal and Gamma-Gamma distributions [38]. Instead Borowy in his calculations for average power used the Beta and Weibull functions with the equation [39]:

$$P_{PV,avg} = \int P(S) * f(S). dS \quad (2-5)$$

Where:

- $P_{PV}$  - average power produced over the time-period of integration
- $f(S)$  - irradiance probability density function

While Borowy used the probability function to calculate the average power produced per period. Zahedi used the equation below to calculate the production of kilowatt hours (kWhrs) of energy produced for a solar system. This equation uses the calculated solar irradiance for a given region [40]. The peak sun hour is an hour in which the sunlight intensity is 1,000 watts per square meter. This is converted from the Joules per day of solar irradiance to kilowatts and divided by the 1000 watts per square meter [29].

$$P_{PV,avg}(kW) = size(kW) * PSH * PR \quad (2-6)$$

Where:

- $P_{PV}$  - average power produced in kWhr
- $size$  - size of the system in kW
- $PSH$  - peak sun hours
- $PR$  - production rating and is usually less than 1 due to manufacturers tolerances, dust and dirt and temperature

### 2.3.6 Effects of Shadows on PV

Solar cells are generally installed on rooftops and facades in the domestic environment. This type of solar cell mounting will generally become partially shaded at points during the day.



The shading of one solar cell in a string becomes an issue as this cell can enter into a condition known as reverse bias and cause heating issues [35-37].

When a solar cell becomes shaded it stops being forward biased, stops producing current, it “turns off”, and acts like an open circuit. This unbiased condition effectively produces an open circuit. This is normally not an issue but solar cells are serially connected into a string with each cells voltage being summed to produce the total voltage output of the string [41].

$$I_{substring} = I_{cell} \quad (2-7)$$

$$V_{substring} = N_s * V_{cell} \quad (2-8)$$

Where:

- $N_s$  - is the nth-number of cells in series uniformly irradiated

Therefore, if we have a module comprised of 60 silicon polycrystalline cells with an open circuit voltage of 0.6626 connected serially we would expect [36][42]:

$$V_{substring} = N_s * V_{cell}$$

$$V = 60 * 0.6626$$

$$V = 39.75 \text{ volts}$$

Referencing the datasheet for a standard 250W GEM Series solar module from Sapphire Solar with 60 cells of polycrystalline silicon the open circuit voltage is 37.1 volts [38][36]. This is within three volts of what we expect and demonstrates the series connected system. There will be some losses due to connections. The voltage for the forward biasing of a silicon cell is shown for 33 samples in Figure 2-13 - I-V Characteristic for Silicon 33 Cells Tested without Irradiance (a) Reverse Bias and (b) Forward Bias, at 22 Degrees Celsius [42]. This shows the reverse breakdown voltage and at -20 volts the current is at 5 amps. This is approaching the maximum current of each cell [42].

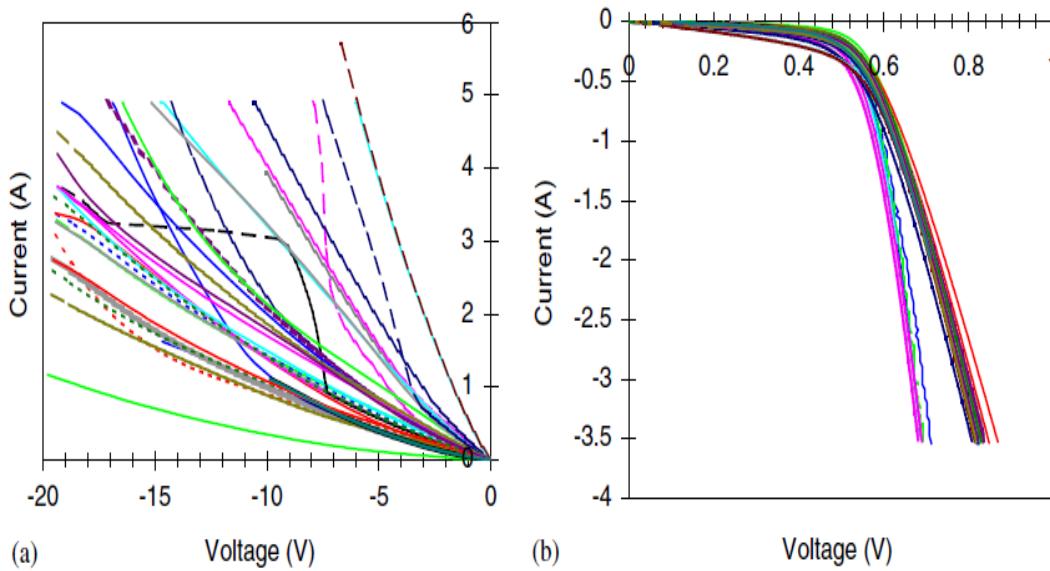


Figure 2-13 - I-V Characteristic for Silicon 33 Cells Tested without Irradiance (a)

Reverse Bias and (b) Forward Bias, at 22 Degrees Celsius [42]

This voltage is what can cause issues when some solar cells are not receiving irradiance, shaded or are faulty. If a solar cell becomes turned off the other solar cells continue to produce the voltage of the string minus that cell. This forces the cell into a conduction known as reverse bias, which dissipates power in the form of heat and creates a hot spot. Mohammed conducted extensive research on hot spot formation and demonstrated that if the power dissipated over the cell exceeds its maximum value it will permanently damage the cell and an open circuit will form. This open circuit in the series connected system stops all flow of current and the PV system will no longer function [36, 41, 43, 44].

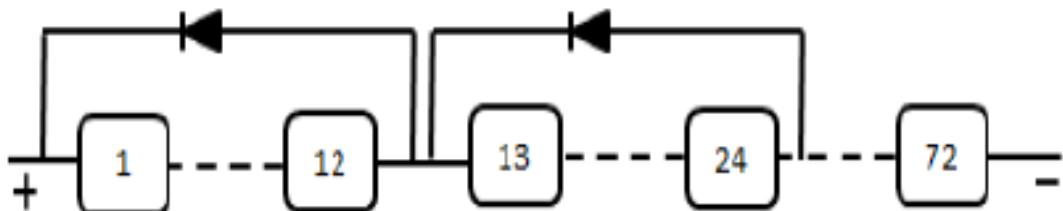


Figure 2-14 - Adding No-Overlapped bypass diodes [43]

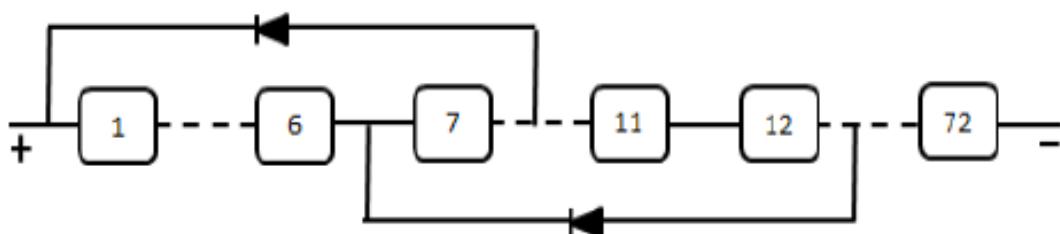


Figure 2-15 - Adding Overlapped bypass diodes [30]



To overcome the issue of solar cells operating in a condition of reverse bias there are different configurations of bypass diodes. There has been several studies by Mohammed, Duong and Silvestre on the correct configuration of bypass diodes [36, 43, 44]. Duong continues by saying that the configuration of the bypass diodes has an important influence on the possibility of a hot spot forming. Two common configurations are shown in Figure 2-14 - Adding No-Overlapped bypass diodes [43] and Figure 2-15 - Adding Overlapped bypass diodes [30].

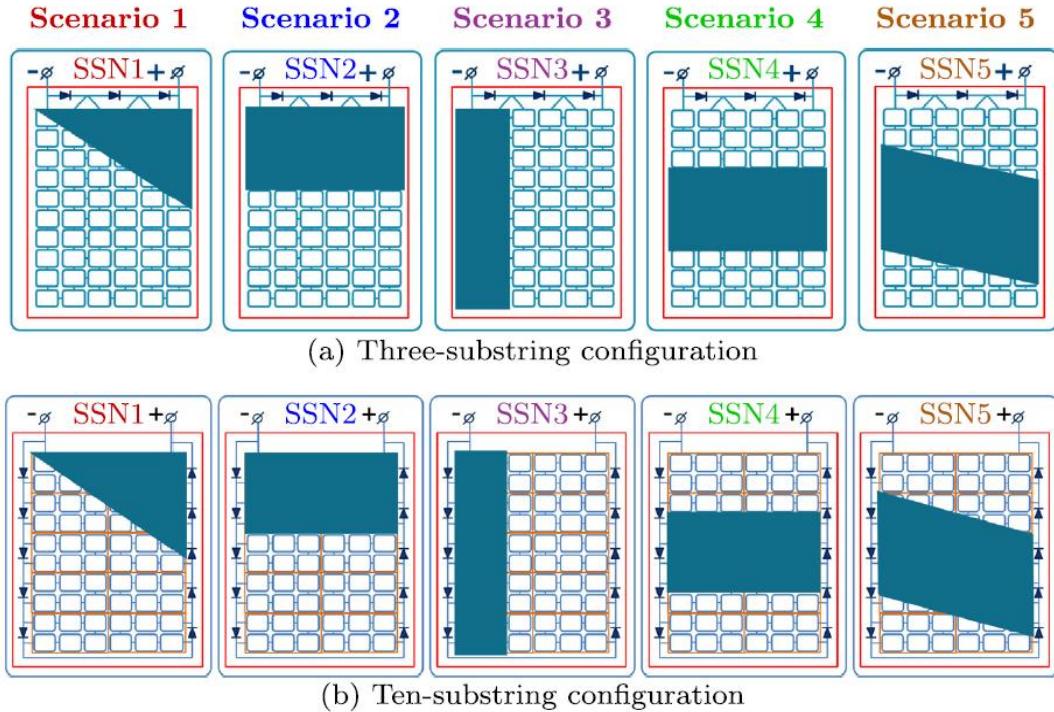


Figure 2-16 - Shading Scenarios used by Mai [44]

Studies conducted by both Silvestre and Mai validated that the configuration and shading location significantly affects the operation and performance of PV modules. They used similar methods, shading techniques of arrays and various scenarios also used by Mai, and are shown above in Figure 2-16 - Shading Scenarios used by Mai [44]. The research showed that the overlapped and not-overlapped configurations had their advantages and disadvantages for PV installation, and therefore, environmental factors must be taken into consideration.

The interesting finding was that for a tropical climate the not-overlapped diode configuration was optimal [44]. In practice, not every cell can have a bypass diode as it is expensive so they are usually connected every 16 cells. Blocking diodes are added to the circuit to prevent reverse flows and serve a different purpose than bypass diodes as shown in Figure 2-17 - Diagram of Bypass and Blocking diode functions [45] [43, 45, 46].

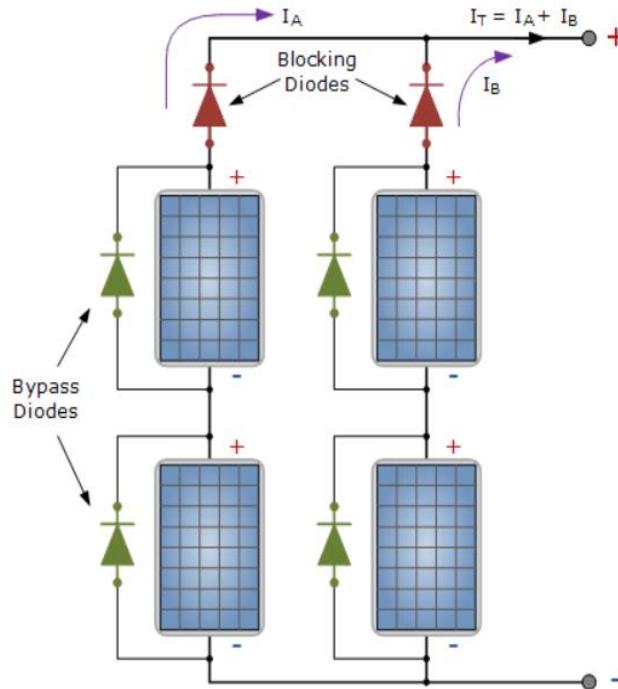


Figure 2-17 - Diagram of Bypass and Blocking diode functions [45]

### 2.3.7 Effects of Dust

Sun and Jiang found that the reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious. It was found that dust pollution had a significant impact on PV module output, corresponding to a reduction of PV output efficiency which grew from 0 to 26% [47]. This evaluation was validated by another study by Mani and Pillai who recorded dust deposition loss of 5.86%, with the winter losses being 4–5% and 6–7% losses in summer [48]. These figures were significantly lower than the maximum of 26% from Sun and Jiang, but validated the reduction in PV output from dust deposition.

### 2.3.8 Costs of PV

The cost of a solar panel installation varies due to three primary factors [49]:

- System Size
  - Generally, a 1.5kW system will produce a third of some household's demands. 3.0kW and 5.0kW systems are becoming more common.
- Installation Type and Labour



- Depending on the type of roof and other factors the cost of installation may be increased. If it is a straight forward installation or if special frames must be installed, this can affect the cost. The system is expected to remain for approximately 25 years. Different companies charge different prices.
- Brand
  - The brand affects the price of system with the more established brands having correspondingly higher price. Generally, with warranty up to 25 years.

From the Australian Government website, it states the approximate cost of a solar system after the rebate and is shown in Table 2-3:

*Table 2-3 - Approximate Cost of PV in QLD [49]*

System Size	Price (AUD)
3kW	\$4,000 - \$6,000
5kW	\$5,000 - \$8,500
10kW	\$12,000 - \$16,000

It then goes on to state that an average 1.5 kW system will generate approximately 6.3 kWhr of electricity per day. The Australian Government uses the number 18 kWhr for the average household, although later in this paper it is re-established at 20 kWhr. Using this number we arrive at a 1/3 reduction in electricity price for a household with irradiance equivalent to Brisbane, Australia [49].

Life cycle costing of PV considers all the costs which will be occurred by an installation over the course of its life. The factors include salvage and maintenance costs. The maintenance costs of PV which also include the cleaning of each panel and inspection costs. These are approximately \$150.00 AUD for an inspection and ranges between \$10.00 - \$20.00 AUD per panel for cleaning. The fixed maintenance costs were summarised by Kumar and Tiwari as 10% of the investment cost [50].

As PV becomes ubiquitous around Australia the salvage value fluctuates and becomes rather difficult to determine in a volatile market. The criteria which McCabe used in a 2011 study identified pricing dependent on the strength of glass, amount of easily recycled aluminium,



and industry reduced average selling price (ASP). It was found that there were ranging values from \$0.04 to \$1.26 / watt [51].

### 2.3.9 Payback of PV

The advent of PV technology gives hope to sever the world's dependence for its energy from fossil fuels. The obligations are outlined in the Kyoto Protocol (1997) for the decrease of carbon dioxide and other gas emissions. While commenting on the allure of renewable technologies Rajoria raised the important factor of energy payback as a main criterion for comparison of energies [52].

Knapp agrees with Rajoria and notes that the query translates into one key elementary question, do they represent a net gain? The net gain being do they produce more energy than it takes to produce them, or are the bigger economies just carbon swapping with poorer countries? A metric used by Fthenakis and other analysts is the Energy Payback Time (EPBT) for comparing sustainable technologies [53]. The EPBT is analogous to financial payback and is defined as the time taken for a solar panel to produce the same amount of energy taken to originally manufacture it. It is a good indication for potential mitigation of carbon emissions summarises Alsema [54, 55].

$$EPBT = \frac{(production\ energy\ requirements)}{(power\ rating)(insolation)} \quad (2-9)$$

Where:

- *production energy requirements* - the gross energy required to produce the product i.e. upstream process and raw materials i.e. silicon
- *power rating* - or efficiency is the rate at which the incoming sunlight is converted into electrical energy and includes system losses
- *insolation* - solar insolation or irradiance but also extends to installation style incorporating roof tilt, orientation, tracking, grid or standalone connection

The first study on PV conducted by Hunt in 1976 yielded a EPBT of 11.6 years. Hay in 1981 arrived with 11.4 years for EPBT. For a multi-crystalline silicon PV rooftop system in 2005 the EPBT was calculated by Peharz at 3 years. Sampaio has validated the figures of 0.7 to 2 years for EPBT of PV subject to technology and location. Sampaio provided the Figure 2-18 - Historical Trend in Times of Energy Return (EPBT) of Photovoltaic Modules of Crystalline Silicon [56] for EPBT decrease [53, 56].

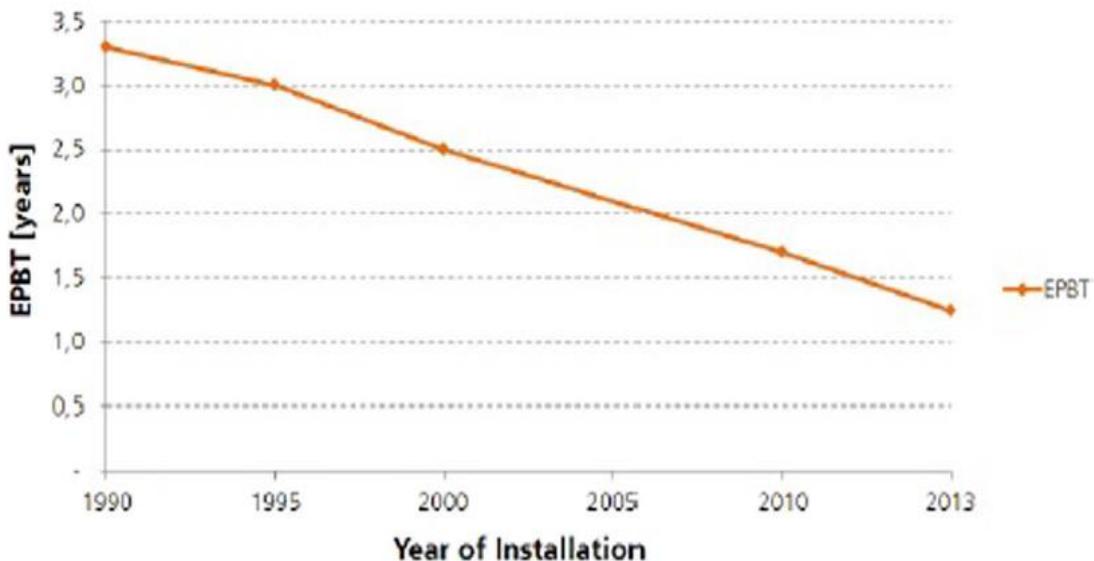


Figure 2-18 - Historical Trend in Times of Energy Return (EPBT) of Photovoltaic Modules of Crystalline Silicon [56]

## 2.4 Inverter System Technologies

An inverter, converter, solar inverter, or PV inverter is an electrical device which converts a DC input signal into a usable AC output signal. The inverter for a solar system converts the DC from the solar panels to AC, which can then be used in the residential household or fed into the commercial electrical grid. The solar inverter usually has additional unique functions when operating as a Distributed Energy Resource (DER) system with PV arrays such as maximum power point tracking (MPPT) and anti-islanding protection [57].

The inverter system in its most basic form can be organised as an astable vibrator circuit or another type of simple oscillator circuit. The principle invoked by the inverter is to create a magnetic field with the DC source. This current induces a voltage in another coil and when the DC source is switched in the opposite direction the induced voltage changes. This creates an oscillation or AC source when the action is repeated. There are three classifications for inverter systems [58]:

- Stand-alone inverters – these inverters are used in isolated systems and convert from batteries charged by PV.
- Grid-tie inverters – these inverters are in DER systems which are designed to match the phase of the supplier's sine wave and shut down upon loss of the network to prevent islanding. They do not run when the network is out.



- Battery backup inverters - these inverters are in DER systems which are designed to match the phase of the supplier's sine wave and do not shut down entirely upon loss of the network. When no network supply is detected they do not feed into the grid to prevent islanding and can be switched to become an Emergency Power Supply (EPS) for small loads including lights and some power.

Solar Inverter Systems generally accommodate:

- Maximum Power Point Tracking (MPPT) – a method utilised by PV inverters to maximise power. The source of power for the inverter is the sunlight and load for the inverter is the household. Through the course of the day both the source and load vary and to ensure the maximum power transfer the inverter must find the maximum efficiency for the system or the “maximum power point” [57].
- Anti-Islanding – the action an inverter takes when it does not detect any network grid. The inverter is connected to the grid to match the phase it is producing with the network. In the event of a blackout there is no power so the inverter shuts down and does not feed power into the electricity grid. If a utility worker were to work on the grid during a black out and anti-islanding was not used he could potentially receive an electric shock. An inverter with an EPS may still power a “microgrid” and feed selected circuits.

Park pointed out that the efficiency of each inverter is dependent on the efficiency curve for that particular inverter [22]. Konsen made the argument that the efficiency of inverters has improved since the mid-1990s from 90% up to 99% efficiency. This was due to new approaches such as MPPT algorithms and realisations, multilevel topologies, soft switching, output filter optimisation and silicon carbide semiconductors. [59]. It should be noted that a study by Carr placed the overall production ratio of the PV systems tested between 0.84 and 0.94 [60].

An inverter system to be installed in Australia must comply with the Electrical Safety Act and Electrical Safety Regulations which include the Australian Standards for inverter systems AS4777. There are two parts for the grid connection of energy systems via inverters and Part 1 deals with installation requirements and Part 2 deals with inverter requirements. The anti-islanding of inverters is specifically referenced stating that they shall incorporate passive forms of anti-islanding protection. The typical installation wiring for a grid tie inverter system as described in AS4777 is given in Appendix E. This protection is in the form of undervoltage,



overvoltage, under-frequency and over-frequency as outlined in the Table 2-4 - Passive Anti-Islanding Set-Point Values [61] [61].

*Table 2-4 - Passive Anti-Islanding Set-Point Values [61]*

Protective Function	Protective Function Limit	Trip Delay Time	Maximum Disconnection Time
Undervoltage (V<)	180 V	1 s	2 s
Overvoltage 1 (V>)	260 V	1 s	2 s
Overvoltage 2 (V>>)	265 V	-	0.2 s
Under-frequency (F<)	47 Hz (Australia) 45 Hz (New Zealand)	1 s	2 s
Over-frequency (F>)	52 Hz	-	0.2 s

## 2.5 Battery Energy Storage (BES) Systems

### 2.5.1 BES Utility & Capital

The shift towards renewable energies is increasing and with it the demand to store this inexhaustible energy. The basis of energy storage is to keep energy produced at one period-of-time and use it later at another period-of-time. Battery banks are used as storage and to allow use of this energy when there is no sunlight. Battery storage technology has been improving and now there are battery energy storage substations which help to improve peak load times. Battery systems can be used for peak shaving, load shifting, backup power, demand response, microgrids, renewable power integration, frequency regulation and voltage control. The battery banks have traditionally been based on lead but have now moved to lithium technology [62].

BES systems are becoming popular in domestic applications for coupling with PV. The improving technology, decreasing cost for a system installation and governmental schemes are set to put BES systems into more common application. The BES system is technology which can offset the use of energy from when it is created to when it is utilised as shown in the Figure 2-19 - Graphical view of potential offset with BES [63] [63].

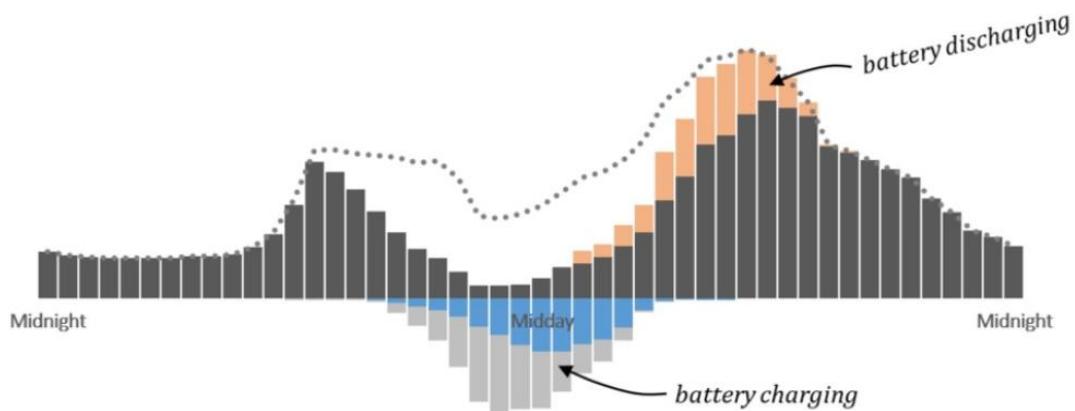


Figure 2-19 - Graphical view of potential offset with BES [63]

The three main solar batteries on the market for purchase in Australia are the LG Chem RESU, Redflow ZBM 2 and the Tesla Powerwall, which was released in 2015. These are lithium-ion and zinc bromide batteries with 4-13.2 kWh ratings depending on the unit. The Powerwall 2 claims 89% round-trip efficiency, the ZBM 80% while the LG RESU claims 95% efficiency. The ZBM 2 promotes 100% capacity use. Rydh in a 2005 study concluded with values of 0.4-0.8 for overall battery efficiency; this seems to contradict the claims made by Telsa and LG but due to the decade in elapsed time it seems reasonable. [64] The retail price for a 10 kWh LG RESU is \$9,700 AUD, a 10 kWh ZBM2 is \$10,600 AUD and a 13.5 kWh Tesla Powerwall 2 is \$8,750 AUD. The typical cost of installation is between \$1,150- \$2900 AUD.

Battery energy storage systems are costly, but with a government subsidy or rebate they readily become economically viable. There are currently schemes in Australia which provide a rebate for BES systems. As of the 1<sup>st</sup> of July 2016, Adelaide in SA have in effect a rebate of 50% of the installed system cost with a maximum cap of \$5,000 for BES systems [65].

### 2.5.2 Modelling of BES

There are many variables which affect the performance of a battery and are discussed below. The recharging time is important during the charging and discharging of a battery. If there is damage due to cell reversal or if a battery is stored in a completely discharged state it may be damaged. The depth of the discharge, humidity, temperature and the lifecycle in number of charge and discharge cycles are factors which affect the performance and life of a battery [66].

The battery life is greatest when the batteries are kept close to 100% of their capacity and after a deep or partial discharge are recharged quickly [39]. Optimal charging and discharging of a



battery is dependent on the battery's characteristics and condition. The following is an explanation of battery factors which affect its production and storage [67].

A PV system is not charging constantly but changes with solar irradiance and temperature. Shen summarised that calculation of the state of charge (SOC) of the battery is difficult and that the system can be assumed to completely (100%) discharge daily [67]. The energy stored on any day is given by the equation:

$$E_B(n) = E_B(n-1) * (1 - \eta_s) + \left( E_{pv}(n) - \frac{E_L(n)}{\eta_{inv}} \right) * \eta_{batt} \quad (2-10)$$

Where:

- $E_B(n)$  – the energy stored in the battery on nth day (present day)
- $E_B(n-1)$  – energy stored in the battery on nth-1 day (day before)
- $\eta_s$  – daily battery self-discharge rate
- $E_{pv}$  – energy generated by the solar array on the nth day
- $\eta_{inv}$  – efficiency of the inverter
- $\eta_{batt}$  – efficiency of the battery

On any nth day, the energy which can be stored in the battery is subject to the condition:

$$E_{B(min)} \leq E_B(n) \leq E_{B(max)} \quad (2-11)$$

Where:

- $E_{B(min)}$  – is the minimum energy level of the battery
- $E_{B(max)}$  – is the maximum energy level of the battery

$E_{B(min)}$  is the minimum energy level the battery can achieve without affecting the specified battery life. This minimum level is the maximum depth of discharge (DOD). The DOD is a measure of the percentage of battery which has been discharged compared to its total maximum capacity. A 80% discharge or DOD is considered a deep discharge [67].



$$E_{B(min)} = (1 - DOD_{max}) * C_{batt} \quad (2-12)$$

$$1 - DOD_{max} = SOC_{min} \quad (2-13)$$

Therefore,

$$E_{B(min)} = SOC_{min} * C_{batt} \quad (2-14)$$

Where:

- $C_{batt} * V_{rated} = E_{B(max)}$  and is the energy capacity of the battery
- $DOD_{max}$  – is the depth of discharge
- $SOC_{min}$  – is the state of charge

SOC is the state of charge of the battery and is a percentage expression which indicates a battery's remaining capacity over its total capacity. It is given by the equation [67, 68]:

$$SOC(n)\% = \frac{E_B(n)}{C_{batt} * V_{rated}} * 100 \quad (2-15)$$

DOD of a battery is linked to the life of the battery. The lower the DOD then the lower the cost of the system and the shorter the battery life.

The difference in the battery technologies affect how they should be operated. The DOD can be shallow or deep and the higher the DOD the lower the cycle life and vice versa [69]. Batteries can suffer from an effect known as “memory” where the output is depressed over time and this fading is indicated by the State of Health (SOH) of the battery. The present full charged capacity of a battery is different from when the battery was new and subsequently declines over time. The following equation can be used to calculate the SOH of the battery [68]:

$$SOH\% = \frac{E_B(n)}{E_{rated}} * 100 \quad (2-16)$$

Where:



- $E_{rated}$  – is the original rated capacity of the battery

## 2.6 North QLD Solar Radiation

Solar PV systems derive their energy directly from the sun. The amount of sunlight hours and its intensity vary; therefore, a measure of potential energy must be established. The diffuse solar irradiance is a measure of the rate of incoming solar energy both directly and diffused on a horizontal plane at a point on the Earth's surface. The device which measures diffuse solar irradiance is the pyranometer. Instruments to measure solar irradiance are complex and special procedures must be adhered to for calibration and measuring [70].

Australia is situated approximately in the middle of the tropic of Capricorn at  $23.5^{\circ}$  latitude. It therefore experiences high degrees of solar irradiance which nominate it as a prime candidate for solar PV systems. The Australian Solar Irradiance is shown in Figure 2-20 - Australian Solar Irradiance [72] and was taken from the Bureau of Meteorology website [71].

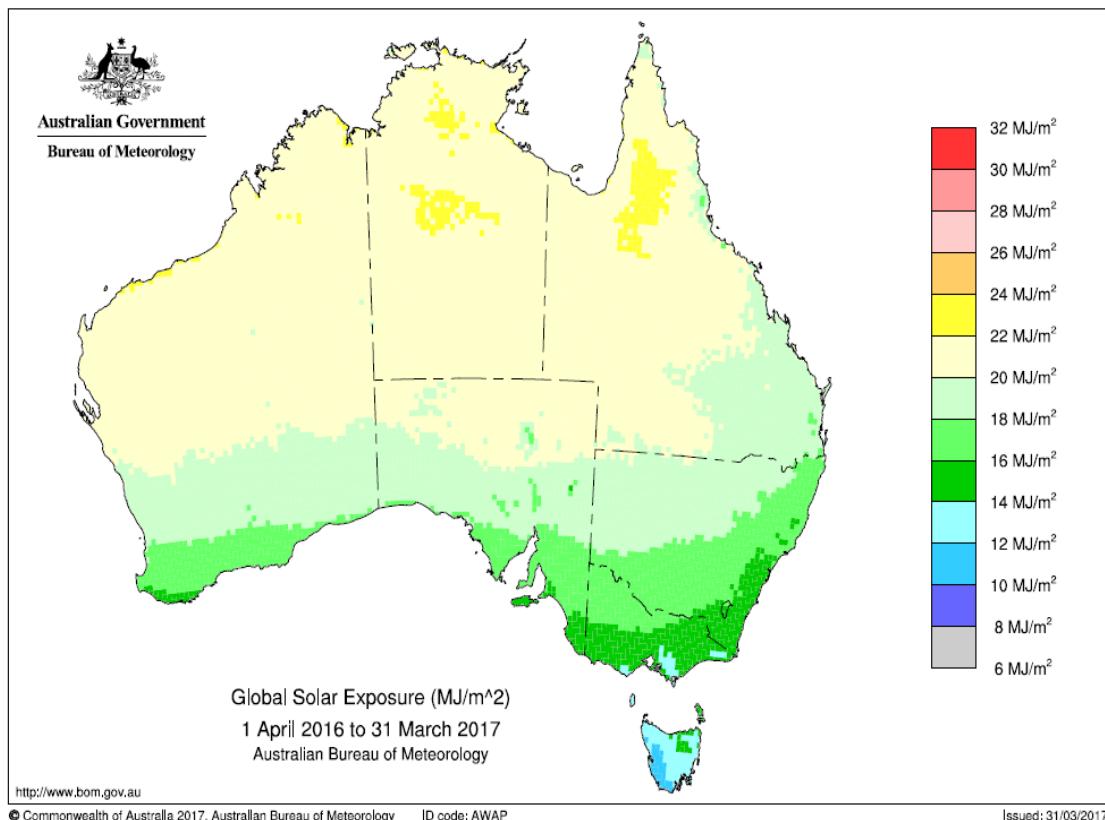


Figure 2-20 - Australian Solar Irradiance [72]



Figure 2-20 - Australian Solar Irradiance [72] shows that Townsville experiences approximately 22 MJ/m<sup>2</sup> of solar energy each year with approximately 300 days of sunlight [72]. Townsville experiences high levels of solar radiation throughout the year due to its high solar elevations and low total ozone columns [73]. This 22 MJ/m<sup>2</sup> is a yearly figure and consequently from the tilt of the Earth's axis it varies as shown in Figure 2-20. This total radiation figure was created in Turkey with a similar latitude to Townsville but in the Northern Hemisphere. It shows the relationship between month and amount of solar radiation and how it varies throughout the year.

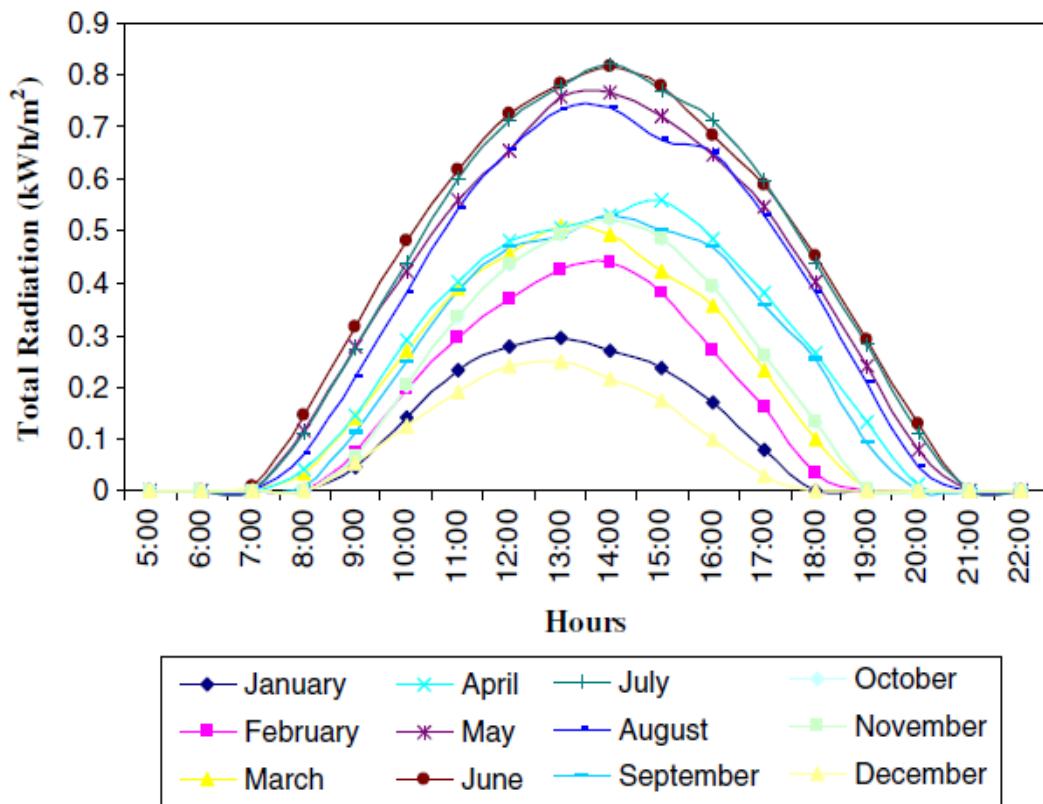


Figure 2-21 - Average Hourly Total Solar Radiation on Horizontal Surface (measured) [73]

### 2.6.1 PSH Conversion

The data which is given in Figure 2-20 - Australian Solar Irradiance [72] is megajoules per meter squared. To convert megajoules per meters squared per day to peak sun hours the following conversions are used:

$$1 \text{ Watt(sec)} = \frac{1 \text{ Joule}}{1 \text{ Second}}$$



$$(1 \text{ W} = \frac{1 \text{ J}}{1 \text{ sec}} * \frac{60 \text{ sec}}{1 \text{ min}} * \frac{60 \text{ min}}{1 \text{ hr}} * \frac{24 \text{ hr}}{1 \text{ day}}) * 1000$$

$$1 \text{ kW(day)} = \frac{8.64 \text{ MJ}}{1 \text{ day}}$$

$$(1 \text{ W} = \frac{1 \text{ J}}{1 \text{ sec}} * \frac{60 \text{ sec}}{1 \text{ min}} * \frac{60 \text{ min}}{1 \text{ hr}}) * 1000$$

$$1 \text{ kW(hour)} = \frac{3.6 \text{ MJ}}{1 \text{ hr}}$$

$$0.277 \text{ kW} * 1 \text{ hr} = 1 \text{ MJ}$$

$$\frac{0.277 \text{ kWhr}}{1 \text{ MJ}} = 1 \quad (2-17)$$

$$\frac{20 \text{ MJ}}{1 \text{ day}} * \frac{0.277 \text{ kWhr}}{1 \text{ MJ}} = 5.55 \frac{\text{kWhr}}{\text{day}}$$

$$\frac{\frac{20 \text{ MJ}}{1 \text{ m}^2} * \frac{0.277 \text{ kWhr}}{1 \text{ MJ}}}{\text{day}} = 5.55 \frac{\text{kWhr}}{\text{m}^2 \text{ day}} = 5.55 \text{ PSH}$$

Therefore, a household in central Northern Territory receiving 20 MJ/m<sup>2</sup>/day is equal to 5.55 peak sun hours (PSH) of solar irradiance.

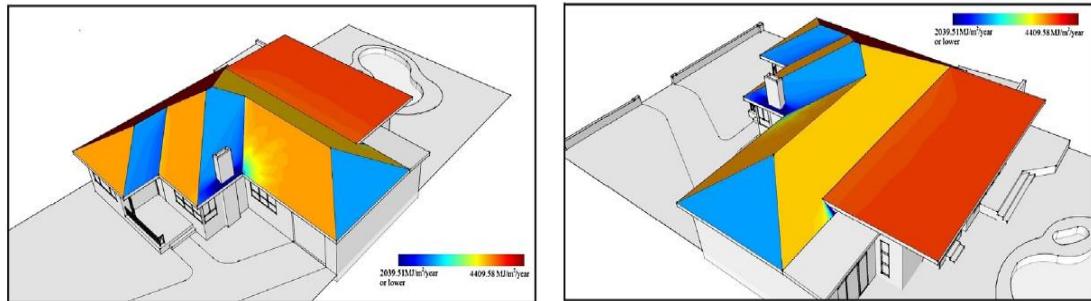
## 2.7 Optimal Roof Tilt Angle & Orientation

Li and Liu conducted a study estimating the solar potentials of pitched roofs. The study demonstrated that the azimuthal angles and surface orientation affected solar yield. It was shown that north facing roofs received more annual solar radiation yields than south facing roofs in the Southern Hemisphere. The shadowing from erected objects showed significant effects on solar radiation yield [9]. The red shades in **Error! Reference source not found.** show higher amounts of solar radiation due to pitch and orientation.

Interestingly, in a study aimed at finding the optimal roof tilt angle for PV, the optimal angle for each month was found and the mean was taken. The study by Ulgen found in winter (December, January, and February) the tilt should be 55.7°, in spring (March, April, and May) 18.3°, in summer (June, July, and August) 4.3°, and in autumn (September, October, and



November) 43°. Thus, the yearly average of these figures was 30.3° and this was the optimum fixed tilt for the year [74]. It should be noted here that the study was conducted in Izmir in Turkey with a latitude of 38.42°.



*Figure 2-22 - 3D annual radiation map of pitched roof from south-eastern view (left) and north-eastern view (right) [75]*

While this method seems reasonable the results of Cheng, Sanchez and Lee concluded that 98.5% of a system's performance with the optimal angle can be achieved using the latitude angle as a reference for the tilted panel in sites located in the Northern Hemisphere. They yielded results with a discrepancy factor of 1.67% in comparison with the data obtained from the computer simulation [75]. This seems to contradict the study by Ulgen, in asserting that the optimal tilt angle in Izmir should have been 30.3°. Perhaps this change of 8° is accountable for the 1.5% loss.

Demirkol, using the optimal roof tilt angles throughout the year and adjusting monthly, found gains in the amount of solar radiation were 1.1% and 3.9%, respectively. A daily average of 29.3% gain in total solar radiation resulted in a daily average of 34.6% gain in generated electricity [76].

As mentioned is it efficient to tilt the module at the angle towards the equator equivalent to the location but to gain another 25% - 35% the solar azimuth can be tracked during the day from east to west. Another 10% can be obtained by adjusting solar declination which is the lowering of the sun in the sky during winter [77]. Figure 2-23 - Solar Azimuth (left) and Solar Declination (right) shows the solar azimuth and solar declination of the sun during a day with reference to perpendicular angle (Note the declination is for the Northern Hemisphere).

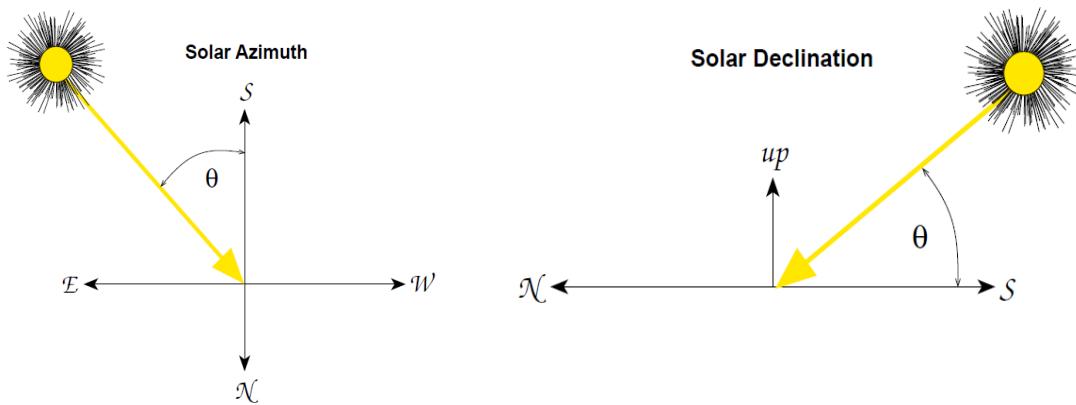
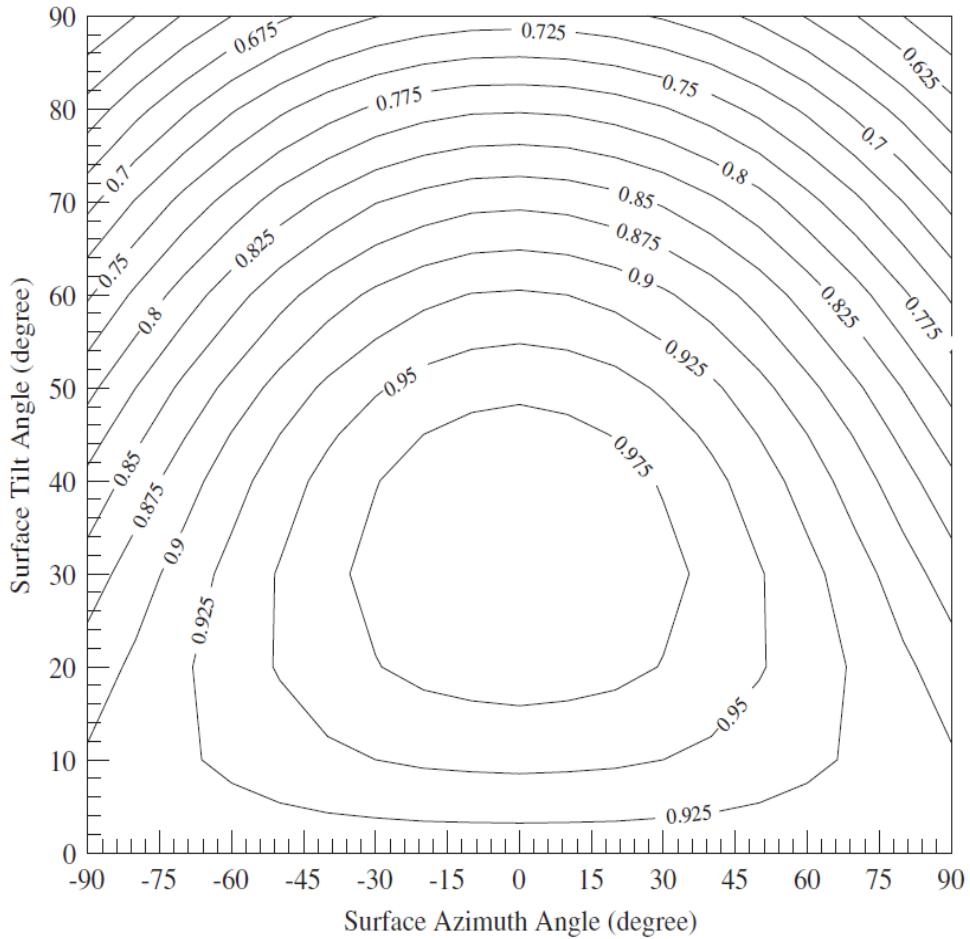


Figure 2-23 - Solar Azimuth (left) and Solar Declination (right) [78]

Mondol's studies on the effect of total insolations as functions of surface azimuths and tilt angles are depicted in Figure 2-24 - Distribution of annual total insolation normalized with respect to the annual total maximum insolation, and they show the maximum annual total insolations for south-facing surfaces. The sun over the day spends equal time in the east and west which describes the symmetrical pattern over the azimuthal angles [74]. It is seen how a deviation in the azimuth angle in either direction will not affect the output until  $25^\circ$ . Note that this location was at  $30^\circ$  latitude. Which is why the optimal tilt angle was  $25^\circ$ , and the efficiency of the PV system decreases as it deviates from this value.



*Figure 2-24 - Distribution of annual total insolation normalized with respect to the annual total maximum insolation [78]*

## 2.8 The Electricity Network (Grid)

The Electricity Network or Electricity Grid is a term used to refer to the network of transmission lines that connect generation to distribution of electricity. The basic operation of a grid consists of stepping the voltage up to a high voltage at the generation side and transmitting it over long distances through transmission lines [27]. There are smaller distribution grids that receive the stepped down voltage from a nearby substation and distribute it around for residential households and commercial businesses.

The Electricity Grid colloquially refers to the grid of the state in which you are presently located, although there are four main grids in Australia. These being:

- WA: South West Interconnected System (SWIS)
- WA: North West Interconnected System (NWIS)
- NT: Darwin-Katherine Electricity Network (DKEN)



- QLD, NSW, ACT, VIC, SA, TAS: National Electricity Market (NEM)

The National Electricity Market (NEM) is the Australian wholesale electricity market which supplies QLD, along with four other states and one territory. The NEM contains over 40,000 km of transmission lines and cables, making it one of the largest interconnected electricity markets in the world. It supplies approximately 200 terawatt hours of electricity to around 9 million customers annually. In 2014-15 \$7.7 billion dollars (AUD) was traded on the NEM.

The Australian Electricity Rules including the Act and the Regulations are maintained by the Australian Energy Regulator which enforce the laws set out for the NEM. The Australian Energy Market Operator (AEMO) manages the NEM and provides critical planning, forecasting and power systems information, security advice, and services to stakeholders [79].

The NEM supplies energy to Ergon Energy who is both a retailer and a distributor and play a relatively minor role in generation. Ergon Energy supplies electricity to QLD with a service area of 97% including Townsville as shown in the Figure 2-25 [80].



Figure 2-25 - Ergon Energy Service Area [80]



## 2.9 Load Profile

The term load profile in electrical engineering relates to the variation of the electrical load over time. The traditional load profile for a residential household sees a peak in the morning when people awaken to prepare breakfast. This then dips down during the day and peaks again after returning home from work and preparing dinner, cleaning and using the lighting and air-conditioning. This spike at the end of the day reduces as they go to bed and this profile repeats daily. The profile changes depending on the number and age of any occupants, if a pool is connected, if gas mains are connected, and the location.

There are many variables which can affect this general load profile such as temperature, living arrangement, holiday seasons and PV [81]. Richardson states that the electricity use in an individual domestic dwelling is highly dependent upon the activities of the occupants and their associated use of electrical appliances.

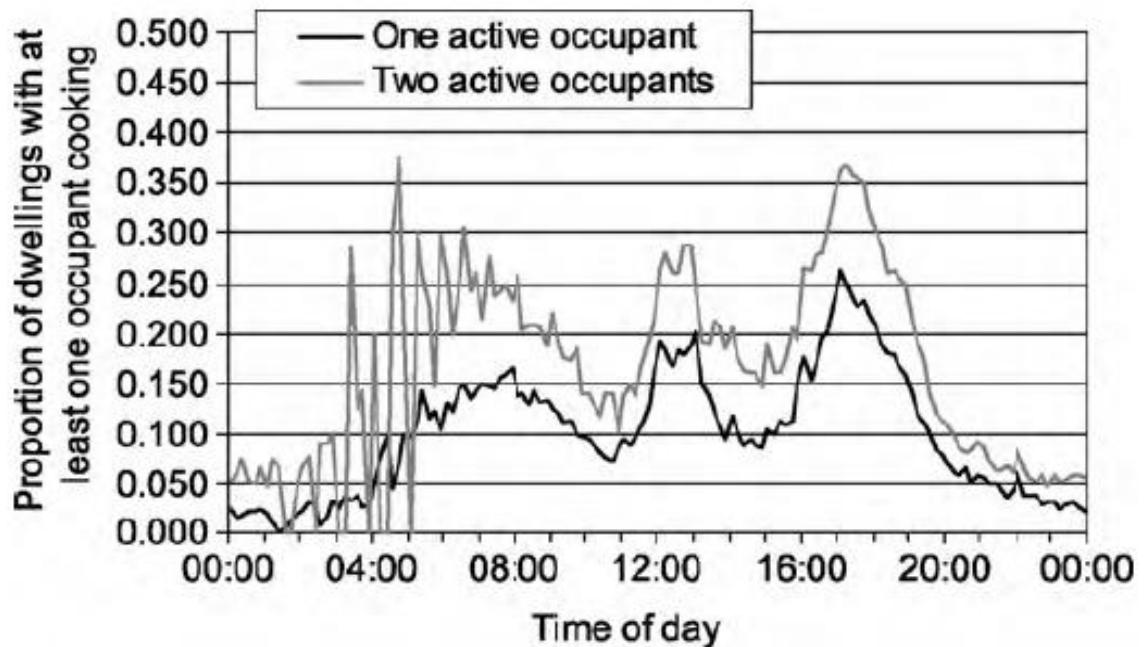


Figure 2-26 - Activity profiles for “cooking”, for one or two active occupants on a week day [81]

From Figure 2-26 - Activity profiles for “cooking”, for one or two active occupants on a week day [81] it shows clearly the peaks and troughs in energy demand from the network. This is the traditional household that does not generate its own electricity. When residences produce, their own electricity, depending on the size of the system, it can potentially feed back into the grid.



The traditional peaks can strain the network and the unpredictability of the independent feed-in's produce more volatility. Hoffmann noted that feed-in energy from PV systems has the potential to disrupt the network and the networks' ability to stabilise itself. Figure 2-27 is the typical load profile during the course of the day for an office building [82].

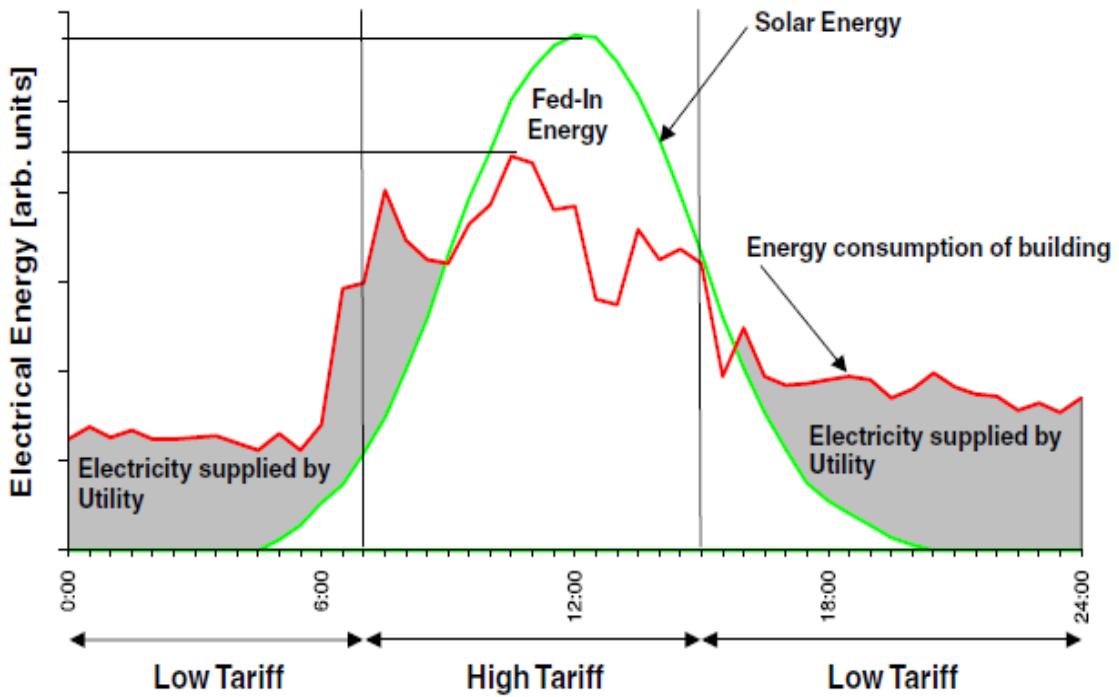
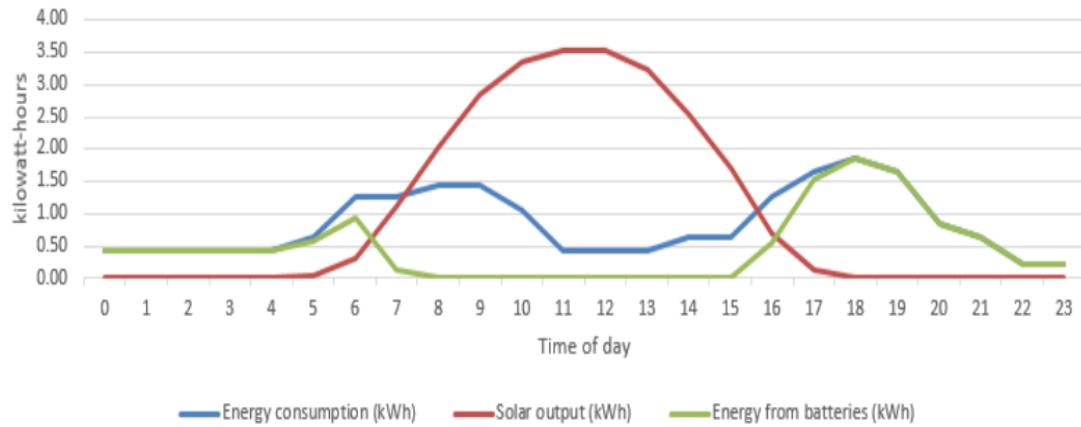


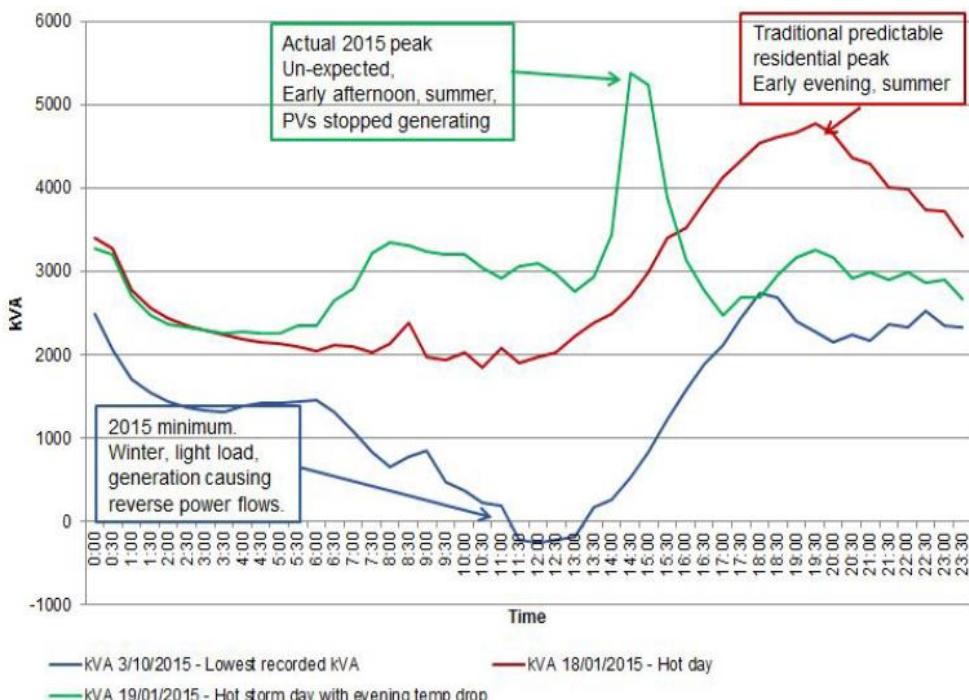
Figure 2-27 – 24-Hour Energy Profile [82]

Figure 2-27 – 24-Hour Energy Profile [82] shows a traditional load profile in red with the new daily solar production shown in green. Now with the advent of BES technology, there is a point where the amount of solar produced during the day can recharge batteries and this energy can be consumed overnight until the next recharge period. The only caveat with this is ensuring that there is adequate supply in the event of clouding for several days. Figure 2-28 - Standalone Household Consumption Load Profile [83] shows the load profile for a house which is entirely stand alone. The red line shows solar output during the day, the green line is the output of the batteries while the blue line refers to the household consumption [83].



## 2.10 Network Demand Challenges

Ergon Energy is constantly monitoring the network to check if extra demand is needed or the load is reduced. The biggest change in this profile over time is the large drop in energy demand in the middle of the day. This is due to solar PV units exporting energy into the grid. The **Error! Reference source not found.** is from Ergon Energy at the Dundowran Feeder in Hervey Bay (QLD) and illustrates how PV has affected the load profile [84]. It shows a reverse flow during the middle of the day at approximately 12:30pm in 2015.





The Planners at Ergon Energy need to identify issues with feeders and disruption which may occur with the grid. **Error! Reference source not found.** the blue line shows this area has high solar PV utility which is meeting the energy requirements during the course of the day and is feeding electricity back into the substation. The red line shows the traditional load profile. The interesting phenomenon is that the green line has an unexpected peak in demand which cannot be met with PV technology and highlights the risks of cloud cover or storms. The sudden losses in power generation must be met and this demand can overload the feeder [84].

## 2.11 Tariffs & Rebate Change

An electricity meter is a device used by Ergon Energy to accurately measure how much electricity is used through that line. A household may have more than one meter if they have several metering schemes. A metering rate is called a tariff and there are different tariff rates which usually vary according to availability or usage. Table 2-5 lists the different residential tariffs: tariff 11, tariff 31, tariff 33 and the solar feed-in tariff [85].

*Table 2-5 - Electricity Pricing Information [85]*

Tariff 11 Residential - 1 Jul to 30 Jun	Price (exc. GST)	Price (inc. GST)
<b>All usage. Anytime.</b>		
All usage	24.61 cents per kWh	27.071 cents per kWh
Daily supply charge	89.572 cents per day	98.5292 cents per day
<b>Controlled load</b>		
<b>Tariff 31 Night rate (super economy)</b>		
All usage	14.423 cents per kWh	15.8653 cents per kWh
Daily supply charge	0.00 cents per day	0.00 cents per day
<b>Tariff 33 Controlled supply (economy)</b>		
All usage	19.96 cents per kWh	21.956 cents per kWh
Daily supply charge	0.00 cents per day	0.00 cents per day
<b>Solar feed-in tariff options</b>		
Solar feed-in tariff for regional Queensland. This amount is not subject to GST. (cents per kWh exported)	7.448	
44 c/kWh solar feed-in tariff. This is not available for new solar PV connections. This amount is not subject to GST. (cents per kWh exported)	44.00	

The QLD Solar Rebate Scheme was an incentive introduced in 2008 for customers who applied before the 9<sup>th</sup> July 2012, and allowed a feed-in tariff rate of 44 c/kWhr [86]. The scheme expired on the 1<sup>st</sup> July 2012 and for persons still receiving the tariff it is substantially higher than the current 7.448 c/kWhr. The current feed in rate is less than one third for what



is paid for the general usage Tariff 11 of 27.071 c/kWhr. The low feed-in tariff rate is beneficial to Ergon the electricity supplier as they are effectively purchasing the power at 7 c/kWhr and selling it to the person next door for 27 c/ kWhr. This is creating them 20 c/kWhr just for maintenance of their network, when it needed to be maintained regardless for supply obligations. Ergon charge 90 cents per day for a person being connected to the grid regardless if electricity is consumed or delivered [86].

Yao and Steemers heavily described the effects of daily residential electricity usage as it varies due to varying factors such as number of occupants and occupancy, cooling appliances, and hours of lighting. Baetens addressed the same sources of energy consumption as Yao and Steemers but additionally included ventilation, space heating, pools, domestic hot water, floor area of the house, number of rooms, water inlet and outlet temperature, volume of water consumed, appliance energy consumption, seasons and weather [37, 87].

Ergon Energy, QLD's Electricity supplier has written that there are a number of factors which affect electricity consumption, but climatic variance is no doubt the most important [88]. They further reinforced this by saying many Northern Districts have up to 73 % more electricity consumption in summer compared to winter and autumn seasons. Figure 2-30 - Tariff 11 kWhr/day - Summer Vs Winter [89] highlights the stark contrast in consumption between winter and summer months.

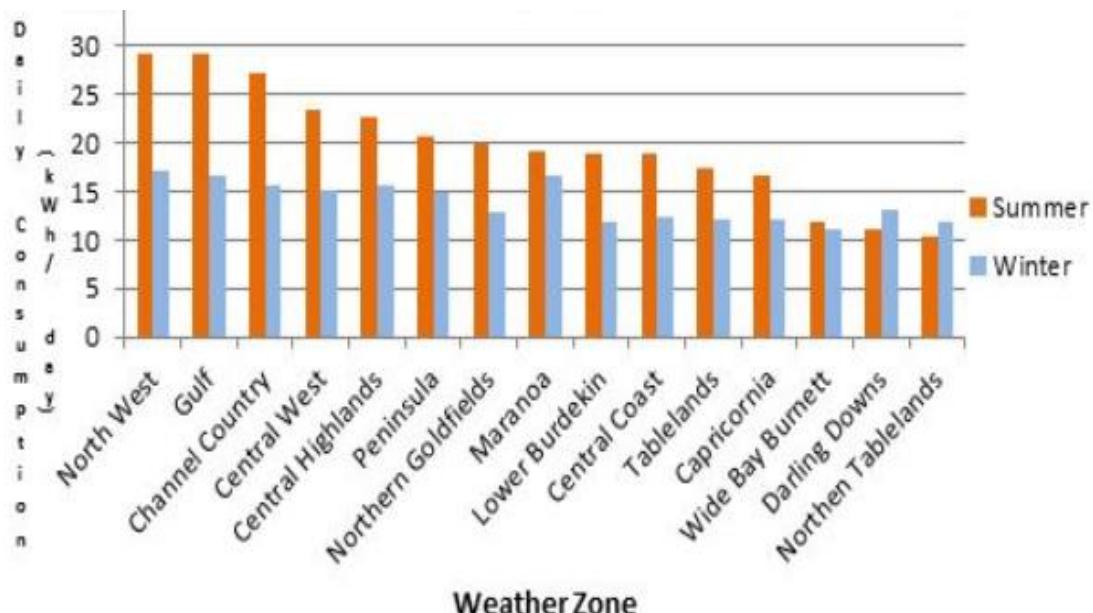


Figure 2-30 - Tariff 11 kWhr/day - Summer Vs Winter [89]



The electricity bill for a residential property in Townsville with the post code 4814, with three occupants, no pool or gas connected main was studied. The billing for a year over the period of 15<sup>th</sup> of August 2015 to the 16<sup>th</sup> of August 2016 with Tariff 11 and 33 was averaged to a 21.01 kWh per day with 2216 kWhs from February to May. This was in accordance with the Australian Government website “Energy Made Easy” that estimated 20 kWh per day and 1804 kWh total in summer for a household under those conditions with that postcode [89].

## 2.12 Economics of PV & BES System

Solar PV/BES technologies give consumers the ability to mitigate the cost of their electricity bills. Although the economics behind PV/BES installations are broad with many underlying variables which may affect the feasibility and returns. There are several models which are available to access and evaluate the performance of PV/BES systems [29, 90, 91]. The importance of modelling applications is due to the margin of variance between domestic households while maintaining a reasonable level of certainty in assessment. Each household varies in load, usage, model of PV/BES, tariff structure and rates [22]. The mains costs and savings can be divided in the associated section of the system. The main costs are listed and illustrated in Figure 2-31 - System Variables and Saving Mechanisms:

- Solar panels
- Inverter
- Battery
- Electricity tariff structure

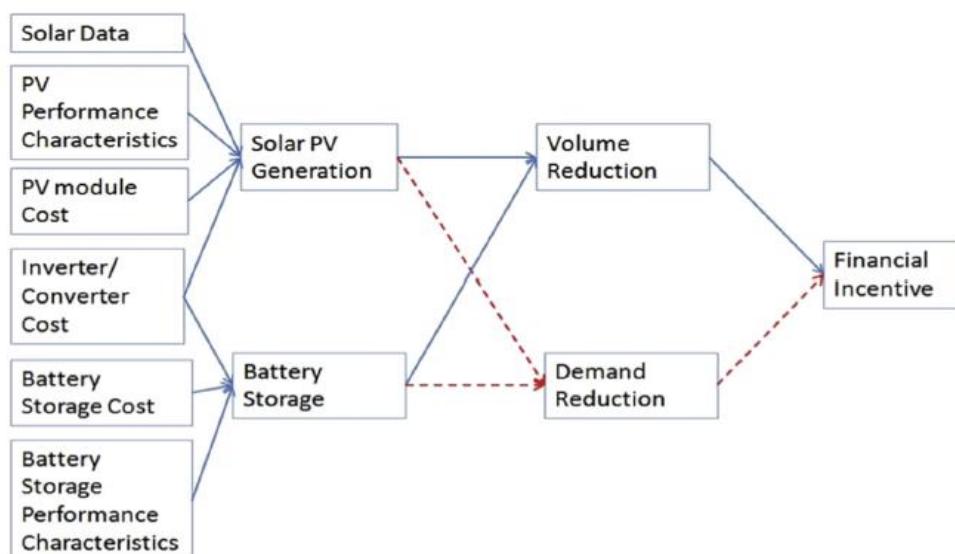


Figure 2-31 - System Variables and Saving Mechanisms [22]



The solar panels, inverter and battery all have their initial cost of capital and depending on the make and model have their associated efficiencies. The performance of the system will be affected by the region and solar irradiance. The performance is affected by the direction of the roof, the angle and if there is any partial shading during the day. The installation cost of the system will vary depending on the installation company and their associated varying rates. The electricity rates will affect the amount of savings as the power is offset from the cost of capital. The feed-in tariff rate will directly affect the payback period. Government rebate schemes for the installation of PV systems will also affect payback periods. The time value of money must be mentioned as a cash lump sum payment against a financed scheme must be assessed for respective returns.

## 2.13 Market Software Competitors

There are software programs currently on the market which utilise past models and data sets to produce outputs which help to indicate to a potential consumer what savings or rate of returns on investments they can expect. They can be used to give indication to a potential customer the metrics for their installation and prospective returns. They incorporate a Graphical User Interface (GUI) in which the user can enter data. There are currently several free programs which are available on the internet.

These programs take input metrics in the form of cost over a billing period, post code, size of PV system, size of battery, tilt of roof, orientation of roof, energy supplier, tariff rates, pool or spa, if there are gas mains and when most of the electricity is consumed. Four of these programs will be analysed below and commented upon for user navigability, accessibility and aesthetic appeal:

### 2.13.1 Solar Power Calculator

This is the best of the three options, offering a visually appealing GUI with simple inputs. It gives the customer a graph and return on investment [92].



Figure 2-32 - Solar Power Calculator GUI [92]

### 2.13.2 Solar Choice Solar Battery Storage Sizing & Payback Calculator

This calculator is perhaps one of the least appealing interfaces but gives the customer easy inputs for the system type and size. It allows the customer to visualise the impacts of battery impacts [83].

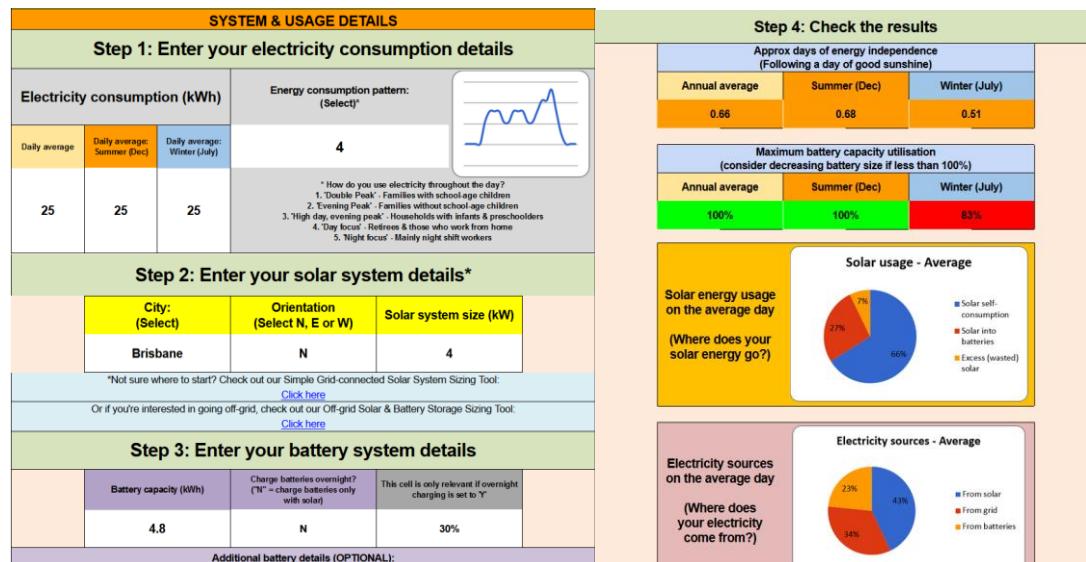


Figure 2-33 - Solar Choice GUI [83]



### 2.13.3 Solar Savings Calculator

This calculator has both simple and advanced options for the customer details. This feature allows a less experienced user to produce a reasonable estimate. The inputs are similar to the other previously analysed programs and has a good GUI [93].

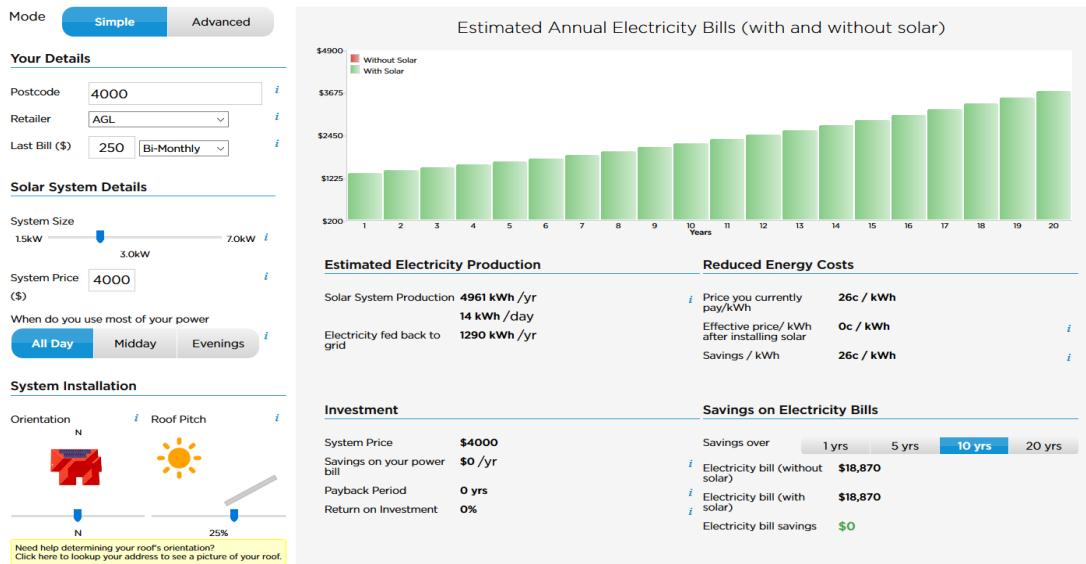


Figure 2-34 - Solar Savings GUI [93]

### 2.13.4 Hybrid Optimisation Model for Multiple Energy Resources

The current market leader for modelling of renewable technology systems is a design tool called the Hybrid Optimisation Model for Multiple Energy Resources (HOMER) [24]. HOMER is a microgrid software developed by HOMER Energy and is currently the global standard for optimising microgrids. HOMER has been successfully implemented in the design and optimisation of military bases, grid connected campuses, island communities and village power.

HOMER allows the comparison of thousands of possibilities to compare and assess impacts of multiple variables such as wind speed, fuel costs, solar irradiance and demand changes. There are heuristic techniques and algorithms embedded into the system which aid analysis. HOMER is a bulk processing tools which allows the simulation of a micro-grid from time intervals of one minute for an entire year [94]. The interface for HOMER is shown in Figure 2-35 - HOMER GUI [24].

There are several modules which can be customised according to the simulation, these include:



- Biomass
- Hydro
- Combined Heat and Power
- Advanced Load
- Advanced Grid
- Hydrogen
- Advanced Storage
- Multi-Year
- MATLAB Link

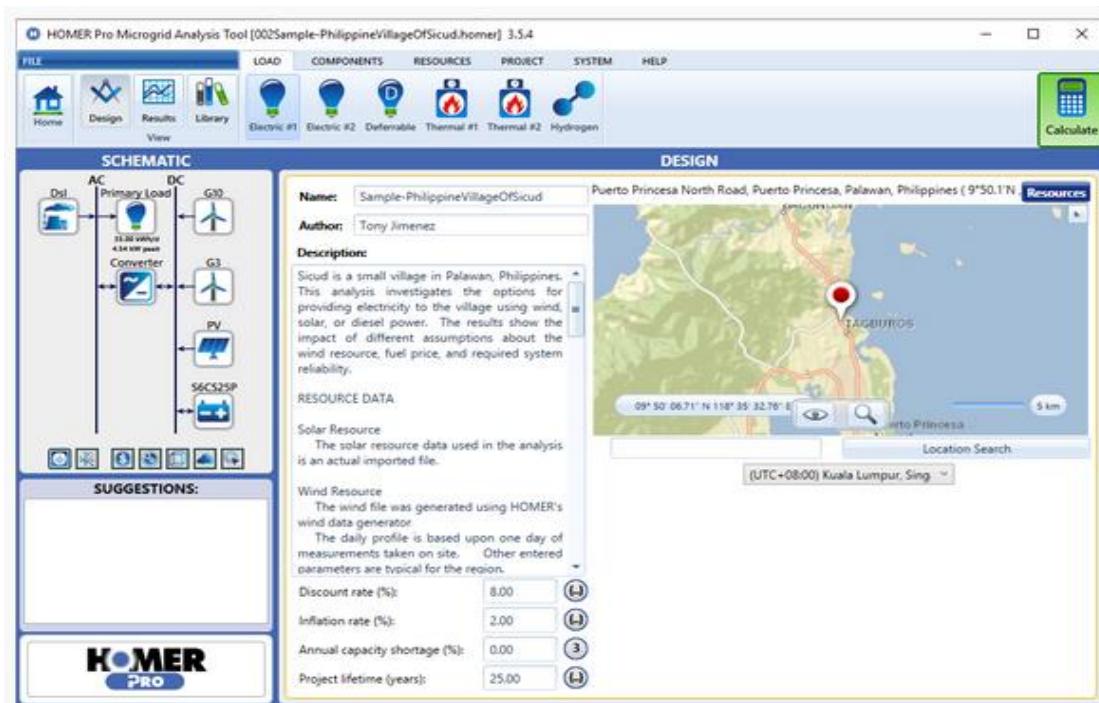


Figure 2-35 - HOMER GUI [24]

## 2.14 Summary of Findings

The Literature Reviewed in this document closely examines and analyses key issues, concepts, and technologies affecting the residential consumer, electricity network, and the electricity supplier. The key aspects of both current and future issues have been addressed with PV technologies, BES technologies, inverter systems, irradiance exposure, load profiles, tariff structures, network issues, shading effects, bypass diodes, energy payback, logistics and economics. The support that PV/BES hybrid systems can give to the electricity network to minimise strain and stabilise demand peaks, has enormous potential. The next question is what is the optimal size for reasonable stability with positive maximised economic return?

There is extensive literature covering the myriad of models which analyses different facets of solar PV installations and operation. Both Bernard and Li have modelled the amount of solar



irradiance a roof will receive annually [9, 73]. While Jardini, Tonkoski, and Paatero have each conducted studies for the load profiles of domestic residential households and annual daily power consumptions [95-97]. Individually Faxas and Riahi made models for priority load control algorithms optimising energy management systems [90, 98]. The efficiencies of different types of solar cells were explored by Edalati [99]. There was limited information on the effects of orientation on PV production. There were no derating factors or equations for how degree change in both azimuth or declination affect PV production.

The efficiencies of both inverter systems and BES systems have been modelled by Kandatsu [100]. Zahedi submitted an interesting paper on the effects of different tariff schemes in Australia [101]. There has been extensive work with the life cycle assessment and economic analysis of low concentrating PV systems by De Feo and Petitio [102].

The current market leaders for a user interface of solar power calculators were visited and commented upon over several metrics. There was not extensive coverage of optimised stages where a consumer could select certain levels of PV autonomy. The software for customers was difficult to access for checks, and updates were disjointed. It appears that there was and continues to be a breakdown in the market for user friendly software and reliable feedback for potential PV customers. There was not an option in these programs for existing PV installation holders to upgrade or find an optimised operating point. Lappas says that there is an essential requirement for a simulation which functions under different locations, loads and financial circumstances. He goes on to state that there is no such model within an Australian context that provides a correctly represented characteristic applied to the commercial sale of electricity [22].

The disruptive voltage spikes that DER put to the grid during hours of peak production were shown to be an issue for the energy provider. The literature was not very supportive of adequate corrective measures to prevent or circumvent these reverse power flows. If there was an option or a rebate scheme for a level of battery capacity in a hybridised system which helped reduce peak demand and stabilised the grid from a DER level, then this has the potential to become endorsed by Ergon and other suppliers, and it may reach a governmental level with another rebate scheme for BES technology in QLD. There is a need for a platform to inform potential customers of the benefits of such an installation.

The potential for export of electricity from areas with higher solar insolation to areas which suffer high cloud cover or less solar radiation is becoming a possibility. The feasibility study conducted by Blakers and Luther on the large-scale transmission of solar electricity to



Southeast Asia from Australia found that it appears to be both technically and economically feasible over the next 40 years. They concluded by stating it's possible for the Southeast Asian electricity system to be supported by up to one third by 2050; one third from Australian solar energy, one third from indigenous solar energy, and one third from conventional energy sources [103].

Despite the limited literature and access to programs for optimisation and upgrades this thesis will investigate the optimisation and deployment of sufficient models to size and optimise PV/BES systems. These models and program will be suitable for different residential households to provide maximum return on investments and minimise disruptive outputs to the grid. Three models will be created in a GUI for a MATLAB program, with each having varying levels of return and customer PV autonomy. There currently is no program which allows for dual array in varying directions as an input criterion. Furthermore, no programs currently have the option to allow for sub-circuit breakdown of various tariff structures. This appears to be a promising area with a high potential to create savings for customers at a domestic household level, as Lappas thought, the need exists as a major portion of electricity bills are due to peak demand times. This has the ability to help energy suppliers reduce peak demand to create a more stabilised and reliable electricity network for Australia [22].



# CHAPTER 3: METHODOLOGY

The aim of this chapter is to discuss the methodology and techniques which were employed to address the issues raised in the Literature Review. There was extensive research into the field of PV/BES technologies throughout the Literature Review to find the gaps in the existing body of knowledge, and where improvements and further research was necessary. This thesis calculated production and estimated costs for PV/BES installations with a modelling program using GUI in MATLAB. This methodology depicts the development and criteria for the programs testability and was selected from several proposed methods. The layout was split into several different phases for ease of explanation and measurable progress milestones. The program was host to varying inputs for subsequent outputs while creating three graphs which will be addressed in greater detail in the ensuing chapter. One of the outputs from the program was an economic assessment of the conditions with a corresponding economic climate.

The project was modelled and verified where possible against existing pools of data and structures for analysis. Due to the capital cost of a PV installation, battery and inverter, it was deemed economically unfeasible to purchase and to conduct physical tests to verify the results of the program. There were other factors which limited the possibility of physical trials such as time constraints, experience, electrical licenses/permits, premises for conducting experiments and test equipment. Future trials and tests for the program are recommended in Chapter 7. The substitution for simulations and comparative analysis was a reasonable trade off as there was a minimal loss of accuracy and this technique has been utilised often and reduces external errors. The development of the program is illustrated in Figure 3-1 - Illustrated Scope of Works for Program Design and shows how each section can be developed individually and incorporated into the finished working program.

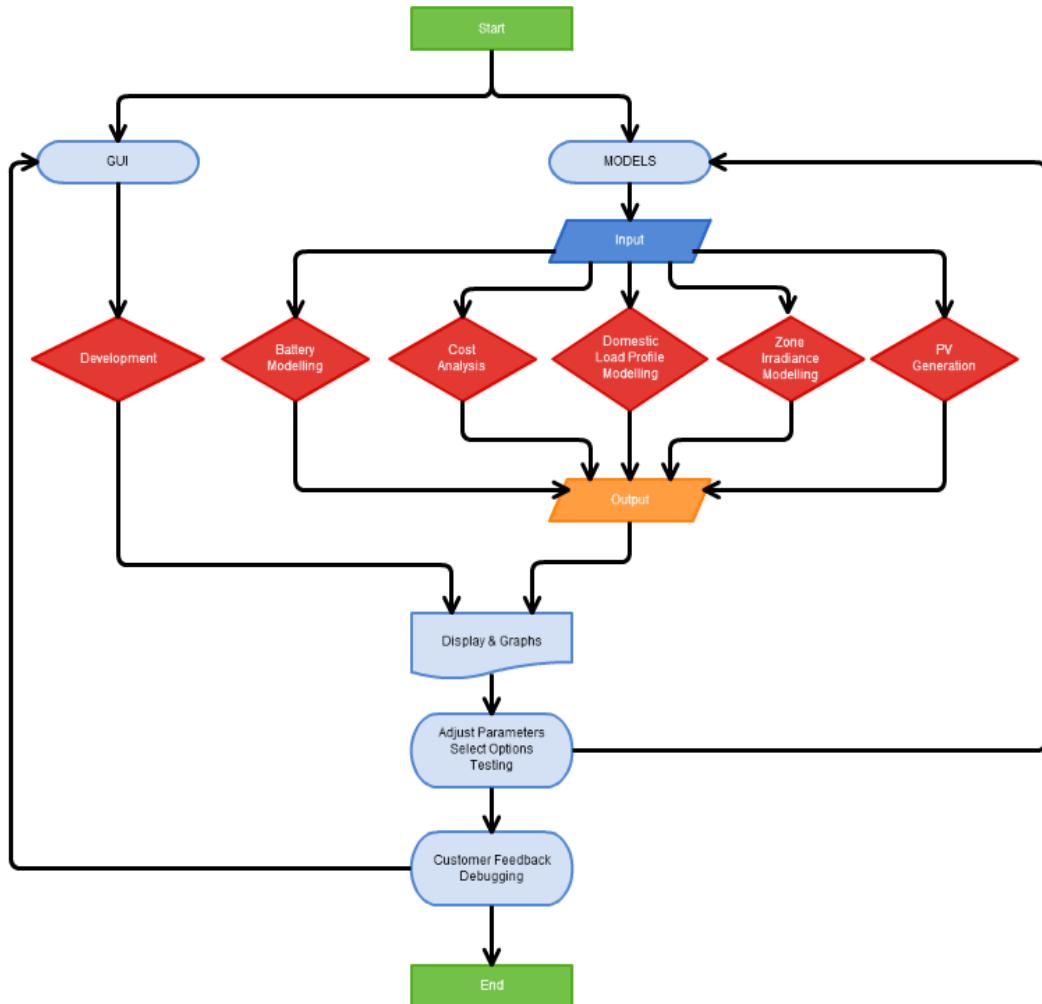


Figure 3-1 - Illustrated Scope of Works for Program Design

### 3.1 Matrix Laboratory (MATLAB)

MATLAB or (Matrix Laboratory) is a high-performance, multi-paradigm language environment which is currently in its fourth generation. MATLAB was created by MathWorks and integrates computation, easy-to-use programming, matrix manipulations, graphing and plotting capabilities, interfaces and algorithms. MATLAB can interface with other languages including C, C++, Java and Python. As of 2014 there are currently over 5 million users of MATLAB.

MATLAB also has the capabilities of:

- Scientific and engineering graphics
- Graphical user interfaces
- Perform complex fast algorithms



- Prototyping, simulation and modelling
- Standard math and computation

Given the capabilities, computational speed, modelling and simulation proficiencies, online technical blog, tutorials and support guides of MATLAB, it was naturally selected as the program with which to conduct this thesis. MATLAB will be used to realise the different phases of this paper and host the GUI for operation.

### 3.2 Graphical User Interface

The Graphical User Interface was designed with an initial screen which to be visually appealing to entice users through aesthetics. The inputs were delivered on a prompt basis to the user which made it easily navigable. There were drop down boxes for options where available, and auto corrects. If a value fell outside an allowable range then warnings would appear. Where possible there were scaling options. For the roof pitch, there was variable angle and for the orientation it was set to north.

### 3.3 Description of Functionality

The aim of this thesis was to develop a program to size and optimise PV/BES systems for different configurations of household demand, to maximise savings and minimise disruptive outputs to the LV grid network. The cost of electricity for a domestic situation from a PV/BES system, up front capital expenditure and lifetime payback are to be modelled. The program hereafter will be referred to as the “Solar Solution”.

Four model screens were created in a GUI for the Solar Solution, each with varying levels of return and customer PV autonomy. This appears to be a promising area with a high potential to create savings for customers at a domestic household level and help Ergon reduce peak demand to create a more stabilised and reliable electricity network for Australia. **Error! Reference source not found.** shows the layout of functionality for the Solar Solution in its various phases: inputs, modelling, and outputs.

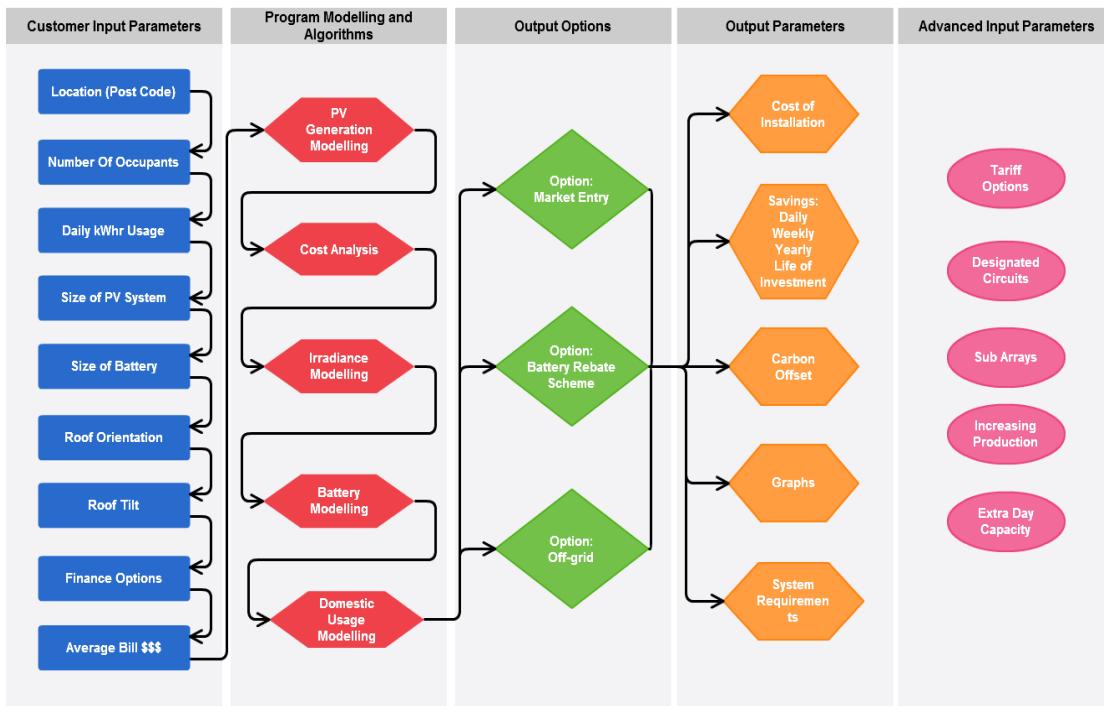


Figure 3-2 - Program Overview

### 3.4 Data Sourcing

The Solar Solution collected raw data from several sources and stored them in a source folder as a .mat file for access on processing. The data was manually entered into the containing files from the prospective websites. The postcode and geographical coordinates of cities around Australia was made available to the Solar Solution through LatLong [104].

The data for the average usage in households around Australia was found from the Australian Government [105]. This data was particularly useful as it contained daily average kWh usage for households from one to four people. The data contained information for if gas mains or a pool were connected while not all the locations had data for gas connected main offsets.

The data for monthly averaged radiation incident on an equator-pointed tilted surface was found from NASA. NASA supplied data for PSH for differing angles of equator pointed surfaces [106]. The MathWorks help information was referenced during the coding process. To create the tab display the source data “Multiple Tab GUI” by James Willmann was sourced and modified accordingly [107].



## 3.5 User Parameters

### 3.5.1 Input Parameters

The input parameters are values which are entered into the Solar Solution via the GUI. This allows an individualised assessment of every system to allow for unique differences. The input parameters are sub-divided into a basic and advanced option. This allows for a browsing user to check possibilities readily and for an evaluating customer to make serious decisions and commitments.

The value which is input first is the area post code. This allows for the Solar Solution to check the average irradiance value. This has the second feature of checking tariff rates and the energy provider. The next input is the average daily kWh or instead a quarterly bill can be input. This average was checked and if it was out of a certain tolerance an alarm is displayed to the user. The next input is for the solar array; what size and price. The next inputs are roof pitch and orientation. If there are two arrays, there is an option for two arrays with two orientations. Other inputs include if there is any shading during the day and for how long. The next input is if battery storage is wanted; what size and cost.

The advanced input parameters are comprised of several different additional inputs and are described below. There is provision to allow for different tariff structures according to sub-circuit arrangement and peak demand. Other inputs include: annual bill inflation, feed-in tariff kw from solar, opportunity cost and inverter replacement and battery replacement. There are different financing options such as solar loan, mortgage or upfront cash payment. The last inputs include the options for the maximum rate of return, or optimal grid stabilisation for a battery rebate and for a standalone system.

### 3.5.2 Output Parameters

The output parameters will be indicative of what is selected on the input screen and will vary due to the available input values or availability. These will include graphs which indicate time to pay off and daily, monthly and yearly savings. The optimum point for each type of system will be displayed. The output parameters are explained in the following section.



## 3.6 Production Calculations

This section focuses on the calculation of the production values associated with each installation. The methods which are used in the ensuing sections are based off the findings in the Literature Review and produce the most commonly used indicators for analysis.

### 3.6.1 Linear Tilt Approximation

The data from NASA held the values for PSH at different tilt angles. The Solar Solution would access the source data and find the tilt values. Using the input value for the tilt angle it would find the next highest and lowest tilt angle. By taking a ratio between the highest and lowest of the different between the max and min it would multiply this by the PSH. This PSH was then used in the calculations and the data was indexed by columns while the state code used a switch statement which added to the row for referencing.

### 3.6.2 kWhr Production

The kWhr production of the system was found using the equation from the Literature Review and the PSH which was indexed from NASA data. The production ratio was input from the user and the recommended values are stated in the Literature Review. The value of 0.85 was used in the Solar Solution and will be justified later in the Discussion.

## 3.7 Risk Assessment

The risk assessment (Appendix B) was completed as per the JCU procedure on the website. It is attached and all possible risks associated with the project we considered. The signed approved form is attached in Appendix C.

## 3.8 Project Funding

The project is limited in its allowable budget and scope for the works of testing and were downgraded to comply with budget constraints. The primary costs of the project are with licenses for the computer software. The MATLAB Student Version was \$115 AUD. Functions such as the “IRR” function were not included in the MATLAB Student Version. The cost of the added tool box was \$35 AUD.



### 3.9 Gantt Chart

The Gantt chart was created to give an overview and scope for the works. Milestones were marked to ensure adequate progress was being achieved. The Gantt chart is attached in Appendix A and was reviewed throughout the project lifetime.



### 3.10 Economic Calculations

This section will focus on the methods used to predict the financial outcomes associated with each installation. The methods used are the most common indicators to determine profitability and are: Present Value (PV), Net Present Value (NPV), Life Cycle Cost (LCC), Annualised Life Cycle Cost (ALCC), Internal Rate of Return (IRR), Annual Payment (ANN-PMT), Electricity Price (EP), Simple Payback (SPB) and Benefit to Cost Ratio (B/C) [91, 108]. Abdul summarised the merits and limitations of the economic tools in Table 3-1.

*Table 3-1 - Merits and Limitations of Economic Tools for Calculation of LCC [108]*

Economic Tools	Merits	Limitations	Comments
Net Present Value (NPV)	Takes the time value of money into account. Generates the return equal to the market rate of interest.	Not usable when the comparing alternatives have different life length. Not easy to interpret.	Most LCC models utilise the NPV method. Not usable if the alternatives have different life length.
Annualised Life Cycle Cost (ALCC)	Different alternatives with different life lengths can be compared.	Gives a mean value and doesn't specify the actual cost during each year of the LCC.	Comparing different alternatives with different life's length.
Simple Payback (SPB)	Easily calculated and interpreted.	Does not take inflation, interest or cash flow into account.	Rough estimation if the investment is profitable.
Discount Payback Method (DPB)	Taking the time value of money.	Ignores all cash flow outside the payback period.	Only useful for screening but not decision making.
Internal Rate of Return (IRR)	Results are presented in percent which gives an obvious interpretation.	Calculations need a trial and error procedure. Determined when the investments will generate an income.	Can only be sued if the investments generate an income.
Net Savings (NS)	Investment can be easily decided and compared.	Can be used if the investment generates an income.	Can be used to compare investment options, if the investment generates an income.



### 3.10.1 Life Cycle Costing

The LCC is a sensible means for evaluating all the costs or total cost of a system over its associated lifetime and purchasing options. It is an important tool for ranking and selecting between alternative investments. It is the sum of all the net present worth [29, 109, 110]. All types of projected costs such as maintenance, repair, operation, replacements and residual value are discounted to their present value for LCC of the project. The initial cost of the system consists of the individual component prices such as PV panels, inverter, batteries, electronic control and battery charger, the cost of civil work, installation. Operation and maintenance cost includes taxes, insurance, maintenance, recurring costs, etc. The LCC is determined by [40]:

$$LCC = \frac{(I_{pc} + I_c + M_c + R_c + P_c) - R_v}{E} \quad (3-1)$$

Where:

- $I_{pc}$  – initial purchasing cost of equipment
- $I_c$  – installation cost
- $M_c$  – operation and maintenance cost
- $R_c$  – replacement of system components cost
- $P_c$  – environment pollution mitigation and disposal cost of residues
- $R_v$  – salvage value of remaining materials
- $E$  – energy produced by the system

The money for a project cannot always be paid upfront but is usually financed from a bank. The inflation and discount rates can affect a project as the value of the money is constantly changing. The inflation rate considers the depreciation of the money while the discount rate relates to the amount of interest that can be earned on the principal that is saved. The projected costs for an entire project's lifetime can be converted into a present worth value and evaluated. The present worth factor is shown in the equation [40]:

$$x = \frac{1+i}{1+d} \quad (3-2)$$

Where:

- $x$  – present worth factor (a dimensionless quantity)
- $i$  – inflation rate



- $d$  – discount rate

We can now calculate the present worth for costs at the beginning of the year and at the end of the year. Costs at the end of the year are usually for maintenance and operation. There are two present worth factors which are used to help calculate the cost of a project. These are shown [40]:

$$P_a = \frac{1-x^n}{1-x} \quad (3-3)$$

$$P_{a1} = X P_a \quad (3-4)$$

Where:

- $n$  – lifetime of the project
- $P_a$  – cumulative present worth factor at the start of the year
- $P_{a1}$  – present worth factor at the end of the year

Using the two factors for present worth we can calculate the entire LCC for the project [40]:

$$LCC = \sum_{k=0}^{k=\infty} P_a C_n + \sum_{m=0}^{m=\infty} P_{a1} C_o \quad (3-5)$$

Where:

- $C_n$  – expense occurred at the beginning of the year
- $C_o$  – expense occurred at the end of the year

### 3.10.2 Annualised Life Cycle Cost

The ALCC is useful for comparing two projects that do not have the same life span, making the LCC's incomparable; so, a comparison on an annualised basis is necessary. The ALCC would be assumed to be simply the LCC divided by the amount of years of the project. This is assuming an unchanging cost per year, which is not the case due to inflation and discount rates. Instead the ALCC is determined by [40]:

$$ALCC = \frac{LCC}{P_a} \quad (3-6)$$



### 3.10.3 Annual Payment

The ANN-PMT is how much is paid back yearly on loaned money. If the money for a project is borrowed then the mortgage rate will affect the amount to be repaid. The rate at which the money is borrowed from the bank has a significant effect on the annual cost. For the calculation of the ANN-PMT for a project is determined by [40, 111]:

$$ANNPMT = LCC * j * \left[ \frac{(1+j)^n}{(1+j)^n - 1} \right] \quad (3-7)$$

Where:

- $ANNPMT$  – annual payment
- $j$  – mortgage rate set by the banking institution

The electricity price can be calculated from the ANN-PMT and ALCC for a generating system. The calculation of the price for generation from a system is important to compare for viability of the project. To calculate the price of electricity two equations are used [40]:

$$Electricity Cost (ALCC) \$/kWhr = \frac{ALCC}{kWhr/year} \quad (3-8)$$

$$Electricity Cost (ANNPMT) \$/kWhr = \frac{ANNPMT}{kWhr/year} \quad (3-9)$$

Where:

- $kWhr/year$  – power produced by the project per year in kilowatts

### 3.10.4 Present Value

The PV takes the present value of the money into consideration and is the most accepted standard of assessment for financial investment. PV is determined by [108]:

$$P_v = \frac{F_n}{(1+d)^n} \quad (3-10)$$

Where:

- $n$  – number of years



- $P_v$  – present value
- $d$  – discount rate
- $F_n$  – constant dollar cash flow

### 3.10.5 Net Present Value

The NPV takes the present value of the money into consideration and is an extension of PV value by adding up several years of cash flows. The NPV is determined by [108]:

$$NPV = -C_0 + \frac{C_1}{(1+d)^1} + \frac{C_2}{(1+d)^2} + \cdots + \frac{C_n}{(1+d)^n} \quad (3-11)$$

Where:

- $n$  – number of years
- $NPV$  – Net Present Value
- $d$  – discount rate
- $C_n$  – dollar cash flow for the nth year

### 3.10.6 Internal Rate of Return

The IRR is mathematically defined as the interest rate that allows the NPV to be equal to zero with a series of cash flows and is common economic tool for assessment. It is used for accepting or rejecting projects and is often viewed as a measure of efficiency. The IRR is determined by [112]:

$$0 = -NPV + \frac{C_1}{(1+IRR)^1} + \frac{C_2}{(1+IRR)^2} + \cdots + \frac{C_n}{(1+IRR)^n} \quad (3-12)$$

Where:

- $n$  – number of years
- $NPV$  – Net Present Value
- $IRR$  – internal rate of return
- $C_n$  – dollar cash flow for the nth year

### 3.10.7 Return on Investment

The ROI is calculated as ratio of the earnings or profits of a project to the investment cost. There are different methods to calculate the profits of a project which are the total summed



(Simple ROI) or the discounted present value (Discounted ROI). The Simple ROI does not take into account the assumed future discount rates. The simple ROI is determined by [112]:

$$\text{Simple ROI} = \frac{\text{Overall Financial Gain}}{\text{Total Investment Cost}} \quad (3-13)$$

### 3.10.8 Simple Payback Period

The SPB period is determined by dividing the total investment cost by annual cash flow. The initial cash flow is extrapolated for every year. This fails to take into account the discount rate of money which is included in the Discounted Payback (DPB) period. The SPB period is determined by [112]:

$$\text{SPB Period} = \frac{\text{Total Investment}}{\text{Estimated Annual Net Cash Flow}} \quad (3-14)$$



# CHAPTER 4: MATLAB GUI PROGRAM

The previous section highlighted the important variables which are critical for the operation of a program to efficiently model the operation of a solar hybrid system. This section will outline an example calculation from the Solar Solution and how it can be used to size a household. The Solar Solution was coded into the MATLAB workspace with user information entered through a prompting system. This method was selected to allow the user sufficient time to source the correct information, for accurate simulations, and to facilitate smooth navigation.

The Solar Solution was split into 5 different tabs which were Data Acquisition, Input Data, Estimated Production, Finance Options, and Display. This design was selected as it gave the user the ability to switch between options and created a user-friendly environment. The following section will explore the Solar Solution and provide snapshots of how the user could input data.

## 4.1 Data Acquisition

The inputs were entered in the Data Acquisition phase using a prompted style option. Figure 4-1 - Entry Screen to GUI prompt shows the first screen upon entry to the Solar Solution.



Figure 4-1 - Entry Screen to GUI prompt



Figure 4-2 and Figure 4-3 - Data Acquisition phase of GUI prompting (continued) show the

**Figure 4-2 - Data Acquisition phase of GUI prompting**

The following table summarizes the data collected from the screens in Figure 4-2:

Screen	Question	Response	Progress (%)
1	Do you have gas connected mains?	Yes	8%
2	Do you have a pool?	No	15%
3	What percentage of your electricity do you use during the day?	20	23%
4	What is your performance ratio of the solar system?	0.7	31%
5	Do you have a solar system?	Yes	38%
6	What is the size of your solar system (kW)?	1	38%
7	How much did your solar system cost (\$)?	8	44%
8	Do you have a battery energy storage (BES) system?	Yes	46%



succession of user prompts.



What is the size of your BES system (kWhr)?

6

Next

18:54 Progress: 46% E X Reset

How much did your BES system cost (\$)?

6000

Next

18:54 Progress: 52% E X Reset

What is the angle of your roof (Degrees)?

20

Next

19:16 Progress: 54% E X Reset

Which orientation is your roof?

North

Next

19:35 Progress: 62% E X Reset

What is your post code?

4814

Townsville, QLD

Postcode Location

4814 Townsville, QLD  
4825 Mount Isa, QLD  
800 Darwin, NT  
6000 Perth, WA  
3000 Melbourne, VIC  
7000 Hobart, TAS  
2000 Sydney, NSW

Data Error  
Error: No data or less than one data point for this postcode. No data or less than one data point for this postcode.

OK

Next

19:35 Progress: 77% E X Reset

Cost of last quarter bill (\$)?

Skip

18:56 Progress: 85% E X Reset

How many occupants are in the residence?

1

Next

16:53 Progress: 92% E X Reset

*Figure 4-3 - Data Acquisition phase of GUI prompting (continued)*



## 4.2 Input Data

The Input Data tab is automatically selected after the final prompt has been answered on the Data Acquisition tab. This displays to the user all the information which has been entered and allows verification before checking the results. This tab is shown in Figure 4-4 - Input Data tab.

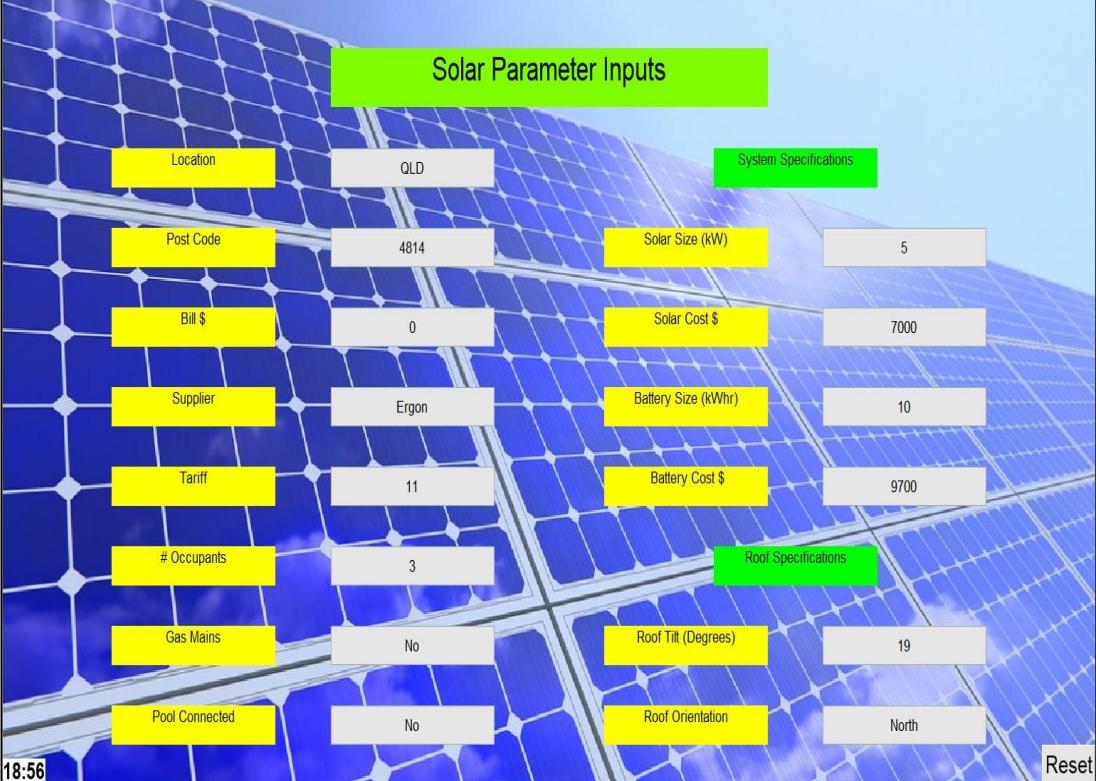
Data Aquisition	Input Data	Estimated Production	Finance Options	Display	2x Production Graph	2x Yearly Graph	5x Pie Graph																																
 <p><b>Solar Parameter Inputs</b></p> <table><tr><td>Location</td><td>QLD</td><td colspan="2">System Specifications</td></tr><tr><td>Post Code</td><td>4814</td><td>Solar Size (kW)</td><td>5</td></tr><tr><td>Bill \$</td><td>0</td><td>Solar Cost \$</td><td>7000</td></tr><tr><td>Supplier</td><td>Ergon</td><td>Battery Size (kWhr)</td><td>10</td></tr><tr><td>Tariff</td><td>11</td><td>Battery Cost \$</td><td>9700</td></tr><tr><td># Occupants</td><td>3</td><td colspan="2">Roof Specifications</td></tr><tr><td>Gas Mains</td><td>No</td><td>Roof Tilt (Degrees)</td><td>19</td></tr><tr><td>Pool Connected</td><td>No</td><td>Roof Orientation</td><td>North</td></tr></table> <p>18:56      <b>Reset</b></p>								Location	QLD	System Specifications		Post Code	4814	Solar Size (kW)	5	Bill \$	0	Solar Cost \$	7000	Supplier	Ergon	Battery Size (kWhr)	10	Tariff	11	Battery Cost \$	9700	# Occupants	3	Roof Specifications		Gas Mains	No	Roof Tilt (Degrees)	19	Pool Connected	No	Roof Orientation	North
Location	QLD	System Specifications																																					
Post Code	4814	Solar Size (kW)	5																																				
Bill \$	0	Solar Cost \$	7000																																				
Supplier	Ergon	Battery Size (kWhr)	10																																				
Tariff	11	Battery Cost \$	9700																																				
# Occupants	3	Roof Specifications																																					
Gas Mains	No	Roof Tilt (Degrees)	19																																				
Pool Connected	No	Roof Orientation	North																																				

Figure 4-4 - Input Data tab



### 4.3 Estimated Production

The Estimated Production tab shows the estimated daily production for the solar system by the solar panels, the storage from the batteries and how much electricity will be imported. The daily cost headings allow the user to compare how much they are spending per day on import and export and their actual savings for a day. This allows an easy comparison and effective savings. The Monthly Average kWh Production graph shows how much they can expect their solar system to produce per day per month. This tab is shown in Figure 4-5 - Estimated Production tab.

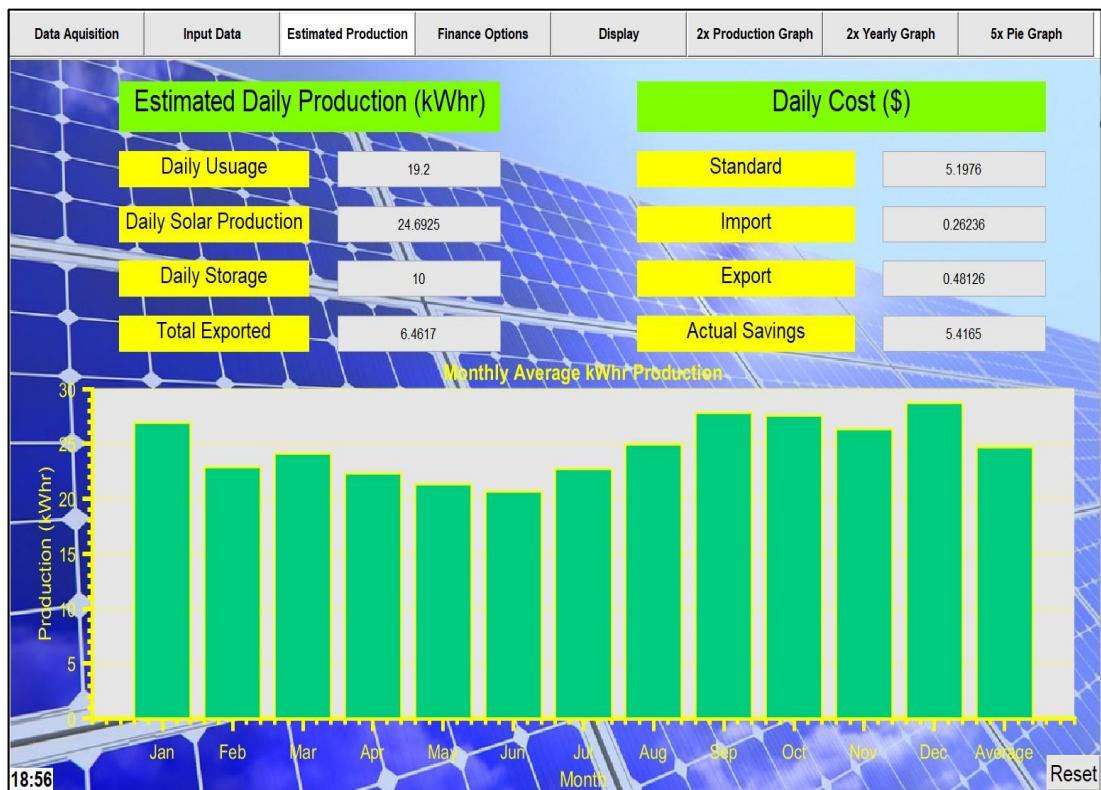


Figure 4-5 - Estimated Production tab



## 4.4 Finance Options

The Finance Options tab (Figure 4-6 - Finance Options tab) displays to the user their finance options based on ALCC and ANN-PMT calculations. There is an IIR calculation and ROI calculation.

The expected savings heading displays to the user easily readable expected savings for a month, year, 10-year and 20-year period. This heading also contains a SPB period calculation and NPV calculation.

Note in Figure 4-6 - Finance Options tab the normal plot (red) represents the cost of electricity for a household without solar i.e. normal, while the Solar/Battery (green) is the expected cost of supplying the household with electricity when a PV/BES system is installed.



Figure 4-6 - Finance Options tab



## 4.5 Display

The Display tab (Figure 4-7 - Display tab) allows the user to visualise what is occurring in their household. This tab has a solar panel, solar inverter, battery inverter, main panel, grid and home icon. Green coloured headings display what is created, stored or exported. The red coloured headings showed import and usage. The blue headings showed import and usage.

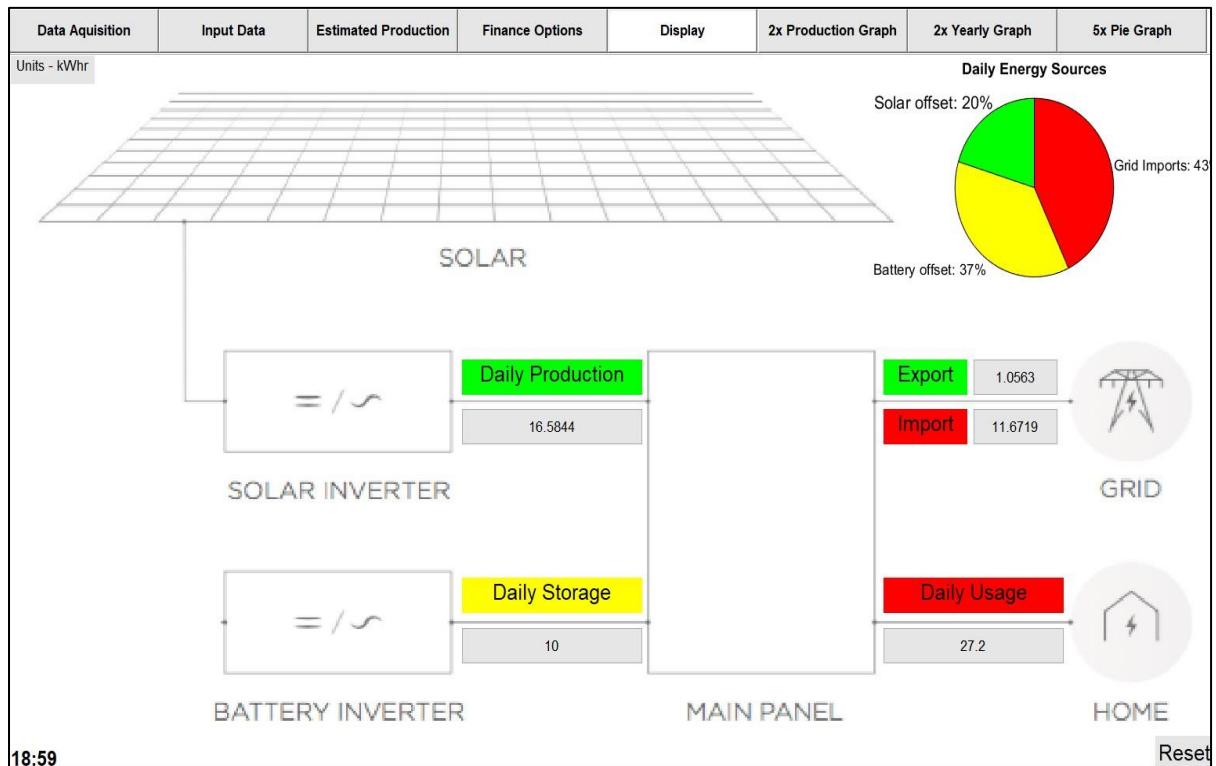


Figure 4-7 - Display tab

## 4.6 Additional Features

Several additional features were added to the Solar Solution for aesthetics and to facilitate rapid operation. Firstly, a clock feature was added to the South-West corner. Secondly, a reset button was added to the South-East corner giving the user the ability to reset if any incorrect information was inadvertently entered. Thirdly, error message dialogues were included which gave extra information, errors or warnings when entering information or if it was not available. Figure 4-3 demonstrates an error dialogue being generated indicating that gas main data was not available for that specified location.

Two graphs were included, one to depict expected daily production per month for the solar system, and the second was to show the calculated saving per year for the installed solar system over a 20-year period. These two graphs were visual aids to help relay the possible savings to



the user. A progress bar was added to the design to allow the user to gauge progress while entering the input information. When the Solar Solution was loading a “loading bar” was added to give indication of the time to completion for the calculations.



# CHAPTER 5: RESULTS

The Solar Solution was tested by selecting three different locations: Darwin; NT, Townsville; QLD and Hobart; TAS, and analysing the outputs from the Solar Solution against set criteria and expected results. Several parameters were kept constant to analyse the desired figures. The stars in Figure 5-1 - Locations Selected for Analysis [105] illustrate the locations which were selected for testing (a gold star denotes location).



Figure 5-1 - Locations Selected for Analysis [105]

These locations were selected due to their diversity in location around Australia and variance in latitude which are specified in Table 5-1. The equator tilted panels were equal to the latitude of the location to provide maximum solar irradiance. The GPS locations were specified from the source LatLong [104]. The latitudes are negative due to being in the Southern Hemisphere.

Table 5-1 - Locations Selected

City	Location		
City	Townsville	Darwin	Hobart
Post Code	4814	800	7000



Latitude (°)	-19.259	-12.463	-42.882
Longitude (°)	146.817	130.846	147.327
Equator Titled Panels (°)	-19	-12	-42

## 5.1 Constant Parameters

To successfully test the Solar Solution several parameters were kept constant to order to provide a basis to examine the output from the Solar Solution at the prospective locations. The inputs which were kept constant are listed in Table 5-2.

*Table 5-2 - Constant Parameters*

Constant Variables	Value
Gas Mains Connected	No
Pool Connection	No
Electricity Load Profile (%)	30%
Performance Ratio	0.85
Solar Size (kW)	5
Solar Cost (\$)	7000
Battery Size (kWhr)	10
Battery Cost (\$)	9700
Roof Tilt (°)	Equator tilted
Roof Orientation	North
Bill Entry (\$)	-
Number of Occupants (people)	3



## 5.2 Output Production Figures

The output production figures were retrieved from the Solar Solution and are shown in Table 5-3 for each prospective location. Energy Sources Analysis (ESA) shows from what sources the household supplies its electricity.

*Table 5-3 - Output Production Figures*

City	Townsville	Darwin	Hobart
Daily Usage (kWhr)	19.2	18.5	27.2
Daily Production (kWhr)	24.692	26.945	17.722
Daily Storage (kWhr)	10	10	10
Total Exported (kWhr)	6.461	7.963	1.815
Daily Cost – Standard (\$)	5.326	5.131	7.545
Daily Cost – Import (\$)	0.268	-0.133	3.132
Daily Cost – Export (\$)	0.500	0.616	0.140
Daily Cost - Actual Savings (\$)	5.557	5.881	4.553
ESA - Solar Offset (%)	42.9	47.3	21.7
ESA - Battery Offset (%)	52.1	52.7	36.8
ESA - Grid Imports (%)	5.1	0.0	41.5



## 5.3 Output Finance Figures

The output finance figures were retrieved from the Solar Solution and are shown in Table 5-4 for each prospective location

*Table 5-4 - Output Finance Figures*

City	Townsville	Darwin	Hobart
Annualised Life Cycle Cost (\$/kWhr)	0.1603	0.1469	0.2233
Annual Payment - Optimistic (\$/kWhr)	0.1623	0.1488	0.2262
Annual Payment - Likely (\$/kWhr)	0.2061	0.1889	0.2872
Annual Payment - Pessimistic (\$/kWhr)	0.2554	0.234	0.3558
Internal Rate of Return (%)	4.596	5.333	2.132
Return on Investment (%)	-1.840	-1.261	-3.634
Expected Savings – Monthly (\$)	166.721	176.456	136.596
Expected Savings – Yearly (\$)	2028.4	2146.9	1661.9
Expected Savings - 10 Year Period (\$)	20284	21469	16619
Expected Savings - 20 Year Period (\$)	40569	42938	33239
Payback Period (years)	13.014	12.296	15.885
Net Present Value (\$)	16682	19742	7212.1



## 5.4 Monthly Power Production Graphs

The average monthly kWhr per day expected production for each location is shown in Figure 5-2, Figure 5-3 and Figure 5-4.

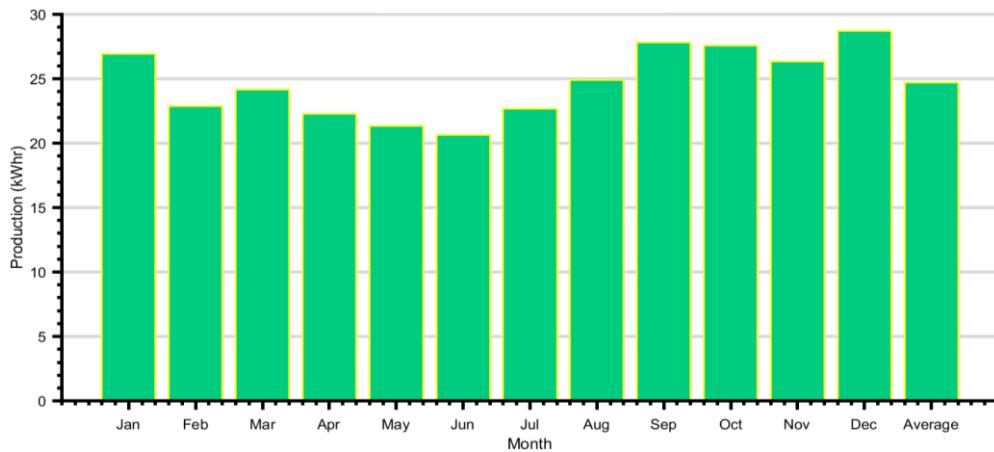


Figure 5-2 - Monthly Power Production - Townsville

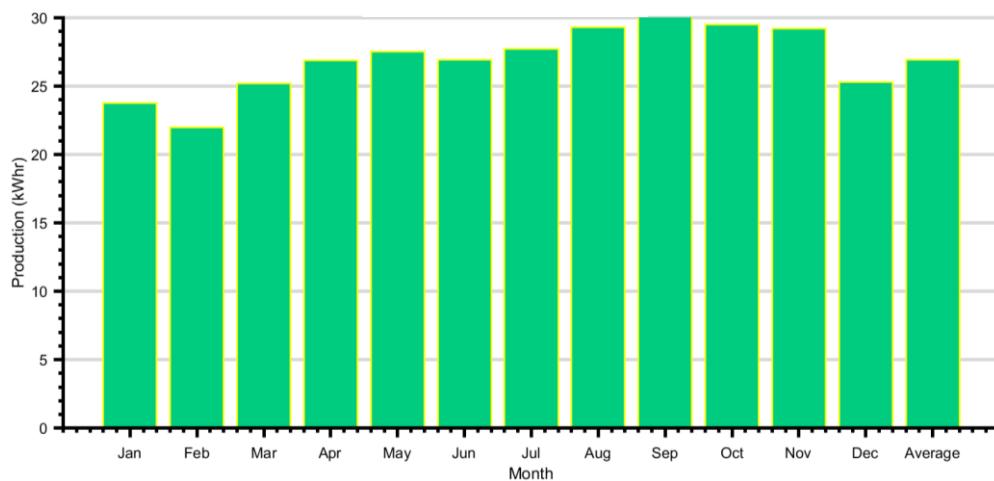


Figure 5-3 - Monthly Power Production - Darwin

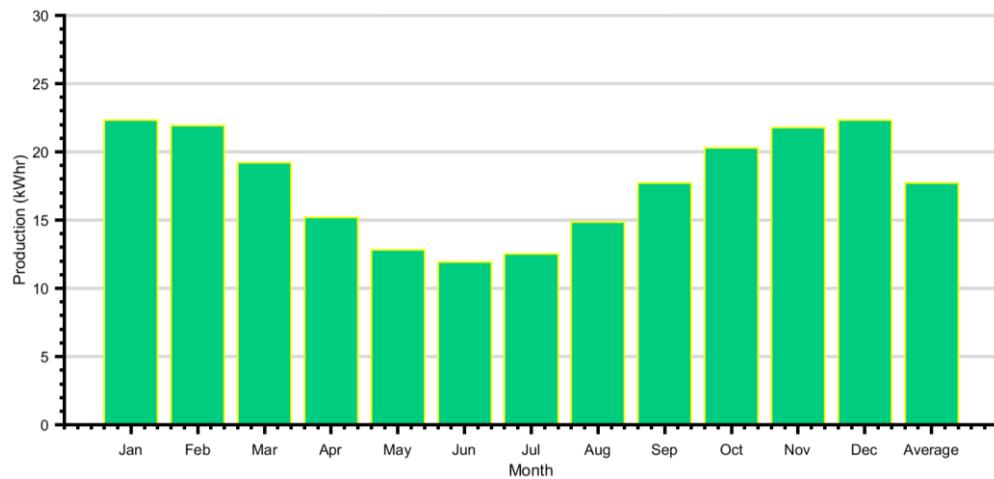


Figure 5-4 - Monthly Power Production - Hobart



## 5.5 Yearly Saving Plots

The yearly cost of electricity for installations with PV/BES and without are shown for each location in Figure 5-5, Figure 5-6 and Figure 5-7.

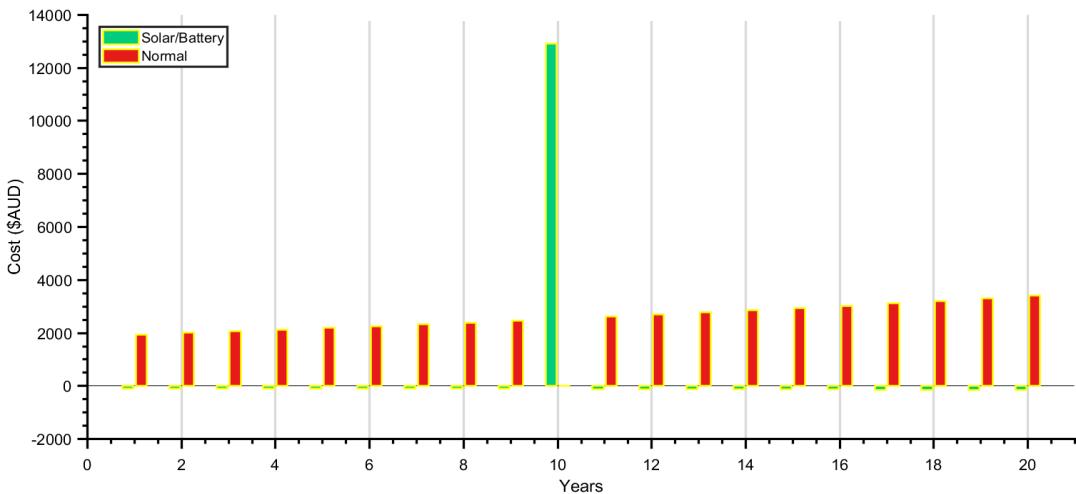


Figure 5-5 - Yearly Savings with Solar Vs. Normal Rate - Townsville

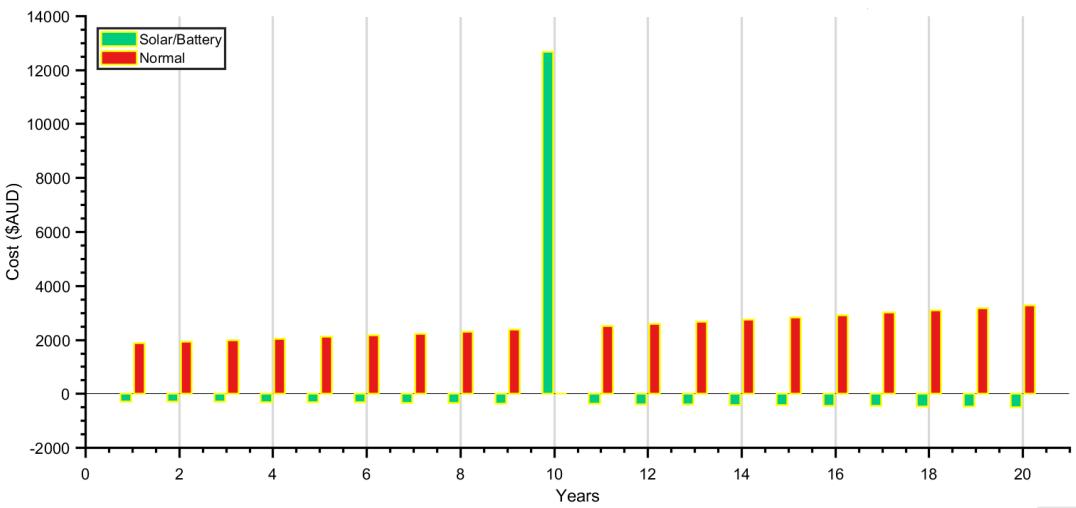


Figure 5-6 - Yearly Savings with Solar Vs. Normal Rate - Darwin

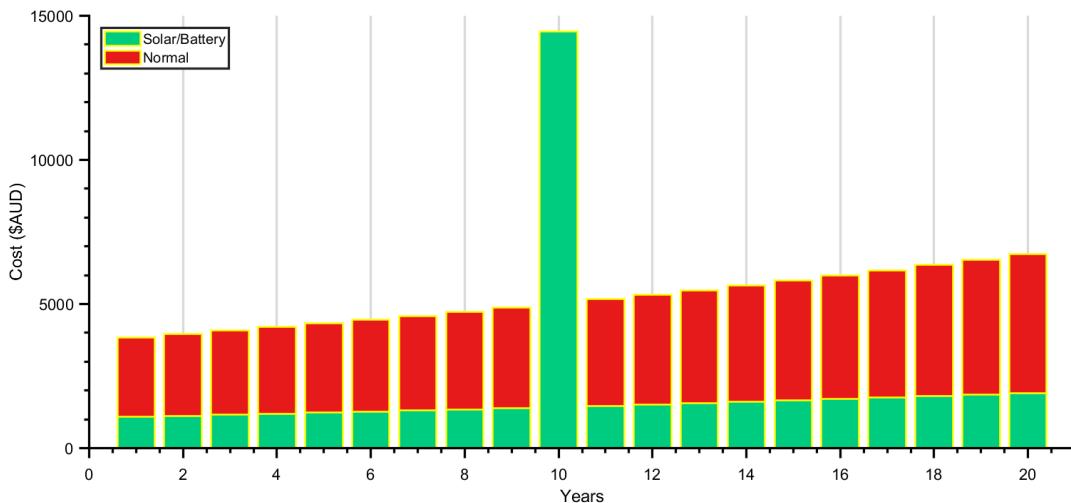


Figure 5-7 - Yearly Savings with Solar Vs. Normal Rate - Hobart



## 5.6 Daily Energy Sources Charts

The daily energy sources for each location are shown in Figure 5-8, Figure 5-9 and Figure 5-10.

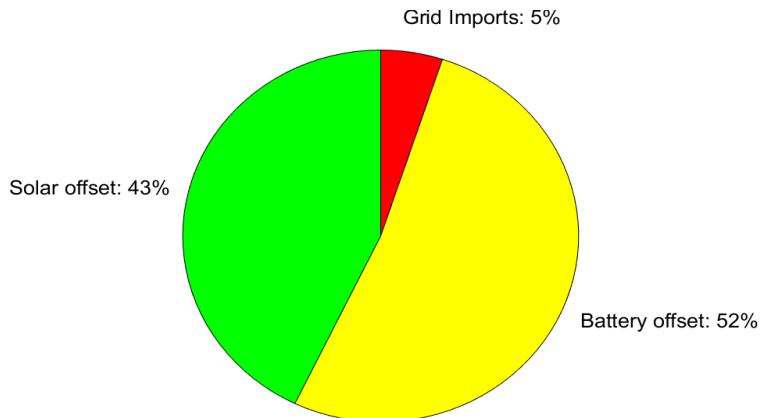


Figure 5-8 - Household Energy Sources - Townsville

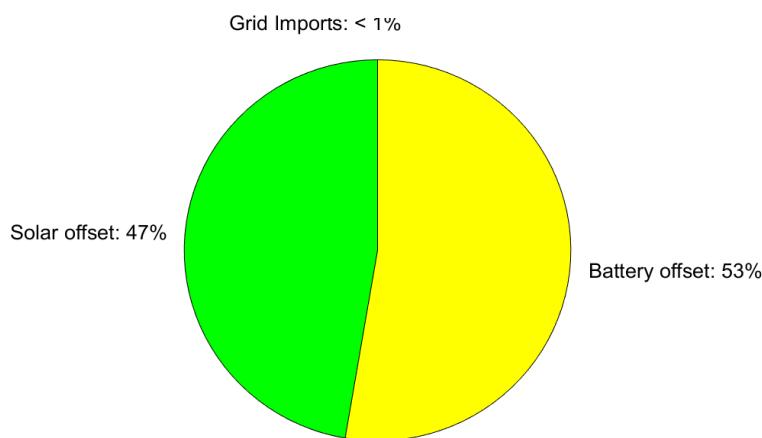


Figure 5-9 - Household Energy Sources - Darwin

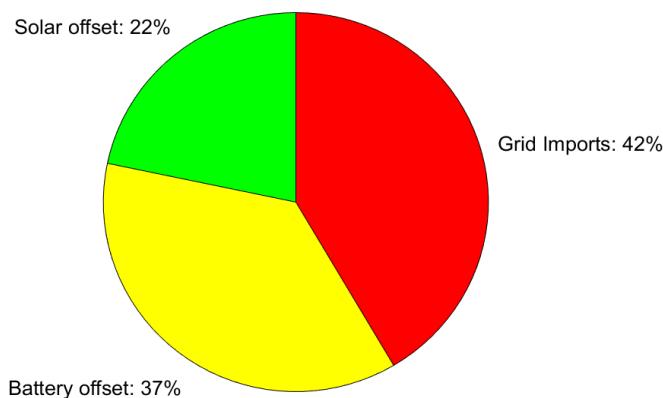


Figure 5-10 - Household Energy Sources - Hobart



# CHAPTER 6: DISCUSSION

The Solar Solution has the ability to handle many scenarios while incorporating robust error checking properties. The results and following discussion only consider the situation for a residential household at three different locations without gas mains or pool connection. In reality, the Solar Solution has the capacity to facilitate results for non-battery applications, non-solar applications and with the inclusion of the former and later combined, and excluded. The provision for different lifespan projects and financial calculations is also possible. All the monetary values stated in this discussion are based in Australian Dollars (AUD) and the indication for currency will be omitted henceforth.

## 6.1 Effects of Location & Parameters

The locations which were selected for analysis around Australia were: Townsville; Queensland, Darwin; Northern Territory and Hobart; Tasmania, as shown in Table 5-1. These locations were selected due to their variance in latitude from the equator. Darwin has a latitude of -12° from the equator, Townsville -19° and Hobart -42° from the equator in the Southern Hemisphere. The varying latitudes were expected to give a decreasing value of production with higher degrees - and validate the Solar Solution. The postcode for each location was entered into the Solar Solution as Townsville; 4814, Darwin; 0800 and Hobart; 7000.

The decision to exclude a gas mains connection and pool connection was done to increase the accuracy of the calculations. This was due to the availability of information and benchmark data by the Australian Government to accurately compare gas and pool daily usage figures. The electricity load profile was set at 30% of daily usage during the day, to identify how much electricity would be used in the household after production. The performance ratio was assigned the value of 0.85 for the simulations, as was stated in the Literature Review, and is an accurate depiction of the overall efficiency of a PV/BES system.

The solar size and cost of 5kW and \$7000 were based off average values for combined cost and install, as stated in the Table 2-3 in the Literature Review; therefore, the brand and style were not relevant. The battery size and cost of 10 kWh and \$9700 were based on the LG Chem RESU, with a cost price of \$8222.50 and installation ranging from \$1000-\$2000. The numeric value of \$9700 was deemed acceptable for both procurement and installation price of battery. The roof orientation was set in a north facing direction and the roof tilt was given the



latitude value of the respective location i.e. Townsville was set at 19° roof tilt due to the latitude location of -19°.

The monetary value of the bill input was set at zero in order to allow the Solar Solution to calculate the average usage from the post code entry and the internal imported database. The number of people was set at three for an arbitrary value which allowed the correct indexing of the Australian Government data. This indexing cross-referenced the tariff and solar feed-in rates. These values were held constant and prices varied due to demand, supply, population, environment, access, and time. In order to create a suitable simulation, the tariff rate of 27.74 c/kWhr and solar feed-in rate of 7.448 c/kWhr were assigned. These rates are similar to the tariff rate of 27.071 c/kWhr and solar feed-in rate of 7.74 c/kWhr hour assigned by Ergon Energy as seen in Table.

## 6.2 Energy Production Feasibility Calculations

The following section discusses and analyses the output production figures shown in Table 5-3 for each location. The daily usage in kWhr which was output from the simulations for Townsville, Darwin and Hobart were 19.2, 18.5, and 27.2 respectively. Ranking these from lowest to highest corresponds with Darwin, Townsville and Hobart, which shows corollary with increasing degrees of latitude at -12, -19 and -42 – this aligns with what we would expect for usage. This higher usage at the higher latitudes is an effect of heating from ambient inside atmosphere and water.

The PSHs were calculated from data supplied by NASA for monthly averaged radiation incident on an equator-pointed tilted surface (kWh/m<sup>2</sup>/day) and are shown in Appendix G. The amount of solar irradiance the Earth receives was outlined in the Literature Review. Using the conversion equation (2-18) to PSH, it was expected that higher concentrations would appear at lower latitudes. This was confirmed by the Daily Production (kWhr) values: 24.692 for Townsville, 26.945 for Darwin, and 17.772 for Hobart.

The angle of the solar panels was set at their respective latitudes for maximum solar irradiance at each location. The values validate the fact that lower latitudes receive the most solar irradiance/PSH. The daily production values were calculated using the equation (2-7) in the Literature Review with the size of the solar system at 5 kW and with a performance ratio of 0.85. The change per month for Townsville, Darwin and Hobart is shown in Figure 5-2, Figure 5-3, and Figure 5-4. From these graphs, a clear change throughout the year across all three is obvious. The production peaks over the sunny summer season months and then dips in



production over the winter season months. This dip is due to the tilt of the Earth as it orbits the Sun.

Figure 5-4 for Hobart displays the best example of the trend hypothesised, with a clear increase and decrease through the solstice-equinox-solstice-equinox; here this progression is quite apparent. The Townsville production graph Figure 5-2 shows a dip during the winter season but has lower than expected production months for November and March. This nonuniformity is again observed in the production graph Figure 5-3 of Darwin for the months of February and December.

The daily storage was calculated from the size of the battery and was considered fully charged at the end of the day by either solar production and imports, or both. In all three locations, the charge of the battery was 10 kWhr and equalled the size of the battery.

The total exported in kWhr was the net result of the kilowatts produced daily minus the kWhrs used in the household and the daily storage. The kilowatts produced daily and daily storage have been mentioned above while the kWhrs used from the solar during the day was a percentage of what was produced. This percentage was a constant parameter and was set to 30%. Therefore, the total exported in kWhr for Townsville, Darwin and Hobart was 6.461, 7.963 and 1.815 respectively.

It can be seen that the location Darwin has 7.963 kWhr of exports while Hobart only has 1.815 kWhr. This is due to Darwin having more peak sun hours, and consequently, higher production of 26.945 kWhr to Hobart's 17.722 kWhr. This means that a larger amount produced minus the battery and 30% internal usage will yield a larger surplus of energy to be exported to the grid.

The "Daily Cost – Standard" for each location was based on the tariff rate of 27.071 c/kWhr which was multiplied by the daily usage of kilowatts for each location. Townsville was \$5.3261, Darwin was \$5.1319, and Hobart was \$7.5453, which corresponded to the higher import of kWhrs paying the most - due to cost being associated with rate multiplied by the amount of kWhrs used. These daily values represent the normal cost of electricity for the customer without solar or battery offset.

The "Daily Cost – Standard" is the benchmark for cost of electricity at each representative location and was utilised for the calculation of "Daily Cost – Actual Savings". The "Daily Imported" was found by subtracting the daily storage and how much solar was used in the



residence from the average usage. The “Daily Cost – Imported” was created by multiplying the amount of kWhrs imported by the import tariff rate stipulated. The “Daily Cost – Export” was created by multiplying the amount of kWhrs exported by the stipulated solar feed-in rate.

The result of the PV/BES system was having the household supplied or partially supplied electricity at a new rate. The actual savings were calculated by subtracting the cost of imports from the standard rate and adding the cost of exports. The actual savings for each location was \$5.5574, \$5.8819 and \$4.5532 for Townsville, Darwin and Hobart. The saving value for Hobart was \$4.55 per day off the household electricity cost. This was increased when examining Townsville at \$5.55 and Darwin at \$5.88.

Despite these figures, it was noted that the standard cost of electricity for Darwin was \$5.13 and the amount of savings from the installation of a PV/BES system was \$5.88. These figures are apparently incorrect, yet it must be taken into account that the PV/BES system supply the entire households electricity needs. The surplus of this electricity is then sold back to the grid; thus, this electricity is earning money. Hence, there is a gain larger than the cost price of electricity for this region. The same effect was observed in Townsville with a cost price of \$5.32, while the actual savings were \$5.55.

Figure 5-8, Figure 5-9, and Figure 5-10 show the percentages of how each location sources its energy in a chart. The solar offset percentage (green) for Townsville, Darwin and Hobart is 42.9%, 47.3% and 21.7% respectively. The battery offset percentage (yellow) for Townsville, Darwin and Hobart is 52.1%, 52.7% and 36.8% respectively. The grid imports percentage (red) for Townsville, Darwin and Hobart is 5.1%, 0% and 41.5% respectively. It is noted that Darwin does not import any electricity from the grid with 0.00% grid imports.

It is affirmed that this 0.00% grid importation of electricity is due to the high solar electricity production which covers the household usage, battery recharging and exports to the grid. This production covers the household as seen in the load profiles in [2.8] from between 6:00am to 6:00pm. The average kilowatt usage in Darwin for this type of residence is such that outside of the solar production period the 10 kWhr of the battery is sufficient to cover demand.

Moreover, the values of 42.9% and 47.3% for solar offset in the locations of Townsville and Darwin are approximately the 30% of the load profile which was established earlier. The offset at these two locations are in the forties, while Hobart at 21.7% is lower as a consequence of two reasons. Firstly, the higher daily kWhr usage for a domestic residence; and secondly, the lower PSH and subsequent decreased solar production.



## 6.3 Economic Payback Potential

The following section discusses and analyses the output financial figures shown in Table 5-4 for each location. The methods and equations outlined in the Methodology – Economic Calculations (3.10) section are used below.

The ALCC (\$/kWhr) was calculated using the LCC outlined in the Methodology (3.10.3) and the equation (3-6). The ALCC is a means to compare two projects that do not have the same lifespan, making the LCC's incomparable; so, a comparison on an annualised basis is necessary. The ALCC was used instead of the LCC to compare these projects, as the provision for different lifespans of projects was incorporated into the Solar Solution; hence, the ALCC was selected as output from the Solar Solution. The ALCC in these instances incorporated a battery replacement at 10 years which was fused into the LCC.

The ANN-PMT was selected as an output for financial analysis and incorporated three different mortgage rates of 1%, 3.5% and 6%. The rates were split into optimistic (1%), likely (3.5%) and pessimistic (6%) to give a broad analysis of potential payment schemes and mortgage climates, as these significantly affect the cost of electricity.

The ANN-PMT and ALCC were calculated on a \$/kWhr basis over their lifetimes using the equations (3-6, 3-7) outlined in the Literature Review for the generating systems. The ALCC for Townsville, Darwin and Hobart was \$0.1603, \$0.1469 and \$0.2233 respectively. The optimistic ANN-PMT for Townsville, Darwin and Hobart \$0.1623, \$0.1488 and \$0.2262. The likely ANN-PMT for Townsville, Darwin and Hobart \$0.2061, \$0.1889 and \$0.2872. The pessimistic ANN-PMT for Townsville, Darwin and Hobart \$0.2554, \$0.234 and \$0.3558.

Considering that QLD's energy provider (Ergon Energy) charges \$0.27071/kWhr, it sets the benchmark for the cost of electricity comparisons in QLD. Using this as a reference, it disqualifies the likely and pessimistic values for ANN-PMT in Hobart, which are above at \$0.27071 at \$0.2872 and \$0.3558.

The ALCC cost price of electricity is for money that is not financed from a bank i.e. cash or savings; it is an economically viable production strategy for the locations, as they are all below \$0.23, which is \$0.04/kWhr below the benchmark of \$0.27071. The ALCC cost price in Darwin is \$0.1469 which is approximately half the cost of the benchmark cost of electricity.



Table 6-1 - Average Financial Figures for Each Location

Economic Option	Average
Annualised Life Cycle Cost (\$/kWhr)	0.1768
Annual Payment - Optimistic (\$/kWhr)	0.1791
Annual Payment - Likely (\$/kWhr)	0.2274
Annual Payment - Pessimistic (\$/kWhr)	0.2817

Table 6-1 shows the average for each location in ALCC, and ANN-PMT with optimistic, likely and pessimistic mortgage rates. The average ALCC \$0.1768/kWhr while the average ANN-PMT for an optimistic mortgage rate is \$0.1791/kWhr; this is a difference of 0.023 c/kWhr. Under these economic conditions, it is apparent that the difference in cost of electricity is minimal between ALCC and ANN-PMT options, and both are applicable and below the national benchmark cost.

Results from Table 5-34 show that as the mortgage rate increases the cost of electricity increases in an ANN-PMT option. The average for ANN-PMT option with a likely rate is \$0.2274/kWhr and a pessimistic rate is \$0.2817/kWhr. The likely ANN-PMT is still below the benchmark but the pessimistic ANNMT rate is \$0.01099/kWhr over.

The expected savings or Net Savings (NS) were calculated using the daily savings figure and extrapolated to one month, year, 10 years and 20 years by a linear expansion, e.g. daily savings multiplied by 30 for a month, 365 for a year, etc. These values were not adjusted for inflation or discount rate, they are linear extrapolations for analysis. These values represent what would be saved from a normal bill without PV/BES system installed. They incorporate the net gain from the cost of electricity offset by the PV/BES system. These values do not take into account the cost of the investment or replacement costs.

The Expected Savings – Monthly for Townsville, Darwin and Hobart was \$166.721, \$176.456 and \$136.596; the Expected Savings – Yearly was \$2,028.4, \$21,46.9 and \$1,661.9; the Expected Savings – 10 Year Period was \$20,284, \$21,469 and \$16,619; and the Expected Savings – 20 Year Period was \$40,569, \$42,938 and \$33,239. These figures seem high, as for Townsville after a 20-year period the expected savings are \$40,569, which appears optimistic and will be discussed in-depth in the next section.



Figure 5-5, Figure 5-6, and Figure 7-7 in the results show the plots of the yearly savings for Townsville, Darwin and Hobart. All three figures show how the cost of electricity is going to rise through inflation and this trend is clearly depicted (red). Figure 5-5 and Figure 5-6 have increasing negative values (green) for the cost of PV/BES – this indicates savings to the customer. This is due to the exportation and the solar feed-in rates which are shown as a negative value and cash inflow. Figure 5-7 shows the green PV/BES cost with the red overlapping it, which indicates the cost of the supply of the household with and without the system.

SPB period is the length of time required for an investment to recover its initial outlay in terms of profits or savings. This was calculated from the equation (3-14) in the Literature Review, which was the cost of the investment divided by the cash flow for one year. Townsville, Darwin and Hobart each had 13.014, 12.296, and 15.885-year payback periods respectively. Hobart was the longest payback period due to the lower latitude causing poor production while coupled with higher daily kWhr usage - which increased imports and subsequently costs.

Whilst the potential savings of a project are critical, it is important to consider the value in the present sum of money, in contrast to some future value it will have when it has been invested at compound interest; this is usually the difference between cash inflows and outflows all discounted from the future. This was why the cost of the project was depicted in the NPV, to give a monetary value of the present worth. The NPV of Townsville, Darwin and Hobart was \$16,682.00, \$19,742.00, and \$7,212.10 correspondingly. This clearly identifies Darwin as having the highest present-day worth; while Hobart was less than 50% of both Townsville's and Darwin's NPVs.

Measuring the profitability was important for budgeting the capital in potential investments for possible clients, which is why the IRR was incorporated into the Solar Solution. The syntax and function to solve for IRR in MATLAB code is “Return = irr(CashFlow)”. This function is not included in most MATLAB versions, so it was coded manually, but the upshot is the compatibility across all editions. The equation (3-12) which was coded was outlined in the Methodology. In brief, the IRR is the discount rate that makes the NPV of all cash flows from a particular project equal to zero.

Through simulations the Solar Solution yielded for Townsville, Darwin and Hobart an IRR of 4.5967%, 5.3334%, and 2.132%. Remembering that the IRR is often defined as the theoretical discount rate at which the NPV of a cash flow stream becomes zero, and that the discount rate



assumed in this paper was 4%, the values from 2.1-5.3% are realistic. This is within  $\pm$  2% of the assumed value, and validates the supposition.

The discounted ROI is another common tool for evaluating the efficiency of investments, and Townsville, Darwin and Hobart had ROI's of -1.8406%, -1.261%, and -3.6341% respectively. All the ROI's are negative values with the most negative value corresponding to Hobart. These values were negative due to three factors; firstly, the assumed discount rate of 4%; secondly, the assumed inflation rate of 3%; thirdly, the assumed cost of the batteries and other components. The decision to use the discounted ROI, and not Simple ROI and the accumulation of the net savings (NS), was due to deciding the time value of money was crucial for accuracy. The change in value of money is important and by not accounting for potential shifts can lead to disingenuous data and results. If a Simple ROI approach was undertaken, then the values would have been positive.

## 6.4 Assumptions

As mentioned previously in the 6.3 Economic Payback Potential section, the values for the discount rate, mortgage rates and inflation rate were assumed. The inflation rate was set to 3%, the mortgage rate was 1%, 3.5% and 6%, and the discount rate was 4%.

Performance and efficiencies were described in the Literature Review with the batteries between 80-95% efficiency, PV panels ranging from 25.6-37.9%, and inverters between 90-99% efficiency. Thus, with the loss in cabling and assuming some degradation a system efficiency of 85% is practical.

Lifetime expectancy for the solar system was set at 20 years for the simulations but the Solar Solution could be changed to 25 years. This assumption was derived from 2.3.8 Costs of PV from the Literature Review which stated that systems generally last 25 years. 20 years was deemed an acceptable assumption as the batteries were only guaranteed for 20 years, and thus, this incorporated an offset for PV operating degradation which was not included.

The tariff rate was arbitrarily assigned the value of 27.74 c/kWhr as this was similar to Ergon Energy's tariff 11 rate of 27.071 c/ kWhr. The solar feed-in rate was similarly based off Ergon Energy's 7.448 c/kWhr at 7.774 c/kWhr. This rate was assumed to not change over the 20-year period which is not likely the case. This was why a small increase was combined into the rates.



The assumption of the battery being replaced at 10 years was founded in the data sheet for the Tesla Powerwall 2 and the 10-year guarantee. This gives the customer a guarantee of 20 years for the assumed cost price of the batteries. The cost of the second battery was not discounted, inflated or trended for the tenth year, but instead assumed to be equal to the cost of the initial battery. This assumption was used in the ALCC. The decreasing cost of a battery was assumed to offset the inflation rate. The battery was assumed to be fully charged to its capacity at the end of each day.

Equal cash inflows for the calculation of the SPB period were assumed. The cash flows were not adjusted due to the difficulty in assuming the change in price of electricity rates, inflation, discount, and future costs. Thus, the SPB was selected to minimise necessary assumptions and potential margins of error.

Whilst calculating the LCC for the project, several assumptions and trade-offs were made. The salvage cost of the PV/BES system were assumed to be equal to the degradation costs for the system; as the viability of the salvage of PV systems is not well established. The maintenance costs of PV and the battery were assumed to be equal to the recyclability costs. Figures for the salvage costs and recyclability costs are hard to estimate, which is why the trade-offs were opted over unreliable data. The degradation of the PV/BES system was factored into the unadjusted cost of the second battery, as a precautionary measure.

## 6.5 Limitations in MATLAB Modelling

The Solar Solution has several limitations which could not be circumvented due to access restrictions, data, time, and resource constraints. These limitations are highlighted in the following section.

The data which was used from NASA [106] for the PSH is not an updating resource. The data is static and saved in a.mat file. If the data were updated then the Solar Solution would not have access and lose accuracy. A solution would be to have the Solar Solution continually updating periodically. This solution would be applicable to the daily usage data from the Australian Government [89]. This data is subject to the same static nature as the NASA data; a similar solution would be recommended.

The data from the Australian Government [89] did not benchmark data for gas mains in many locations. This is not an issue with the Solar Solution but access to reliable data for gas connected residential households around Australia was non-existent. Access to the most recent



data for irradiance, prices, efficiencies and sizes may be an issue and will affect the outcomes associated with the Solar Solution.

Accuracy is important for all estimations and by using a set tariff rate for each location it was affected. By tailoring the input data to each location, energy supplier and tariff, an enhanced estimation would be affected. This set tariff rate would allow the amount entered in the bill entry prompt to accurately back calculate the average usage.

Although tailoring each location for the energy provider would render estimations improved, the reality is that the Solar Solution only works with flat-rate tariffs. If all rates could be used for time of use, block tariffs and fixed daily ‘supply charges’ or electricity retailer discounts (e.g. ‘pay on time’ and ‘direct debit’ discounts) then the Solar Solution would have a reduced margin of error.

Load profiling of households is a method to predict the expenditure of electricity during the day. The Solar Solution currently only judges the electricity used daily by the amount entered by the user. If several scenarios were predicated (e.g. peak at night, peak at morning, double peak or constant) then perhaps the accuracy could be improved.

Despite this study only using a northern orientation for each location, the Solar Solution did not possess the ability to use arrays with differing orientations. This was partly due to the data supplied from NASA, which was north-orientated. The Literature Review (Section 2.3) examined the lack of information for differing orientations and their effects on PV performance.

Dual arrays were capable of being entered into the Solar Solution, but as mentioned above the ability to have different orientations was not possible; if two arrays were installed in a household then the total combined kilowattage would be used for the sizing, e.g. two 2.5 kW arrays would be combined to a 5kW system. This is only a true approximation if they were both orientated true north.

A linear approximation was used to calculate the PSH from the NASA data for households with differing roof tilt angles. This approximation may not be entirely valid as it is mapping a degree based value to a linear value. Although not entirely correct, the net result of error would be negligible as the optimum tilt angles are recorded in the NASA data.



## 6.6 Solar Solution Comparison Table

Table 6-2 - Solar Solution Comparison is a comparison of the Solar Solution to other solar sizing software which is currently on the market. The table displays the Solar Solution (blue), the Solar Choice (green), the Solar Power Calculator (red) and the Solar Savings (orange). The left column lists allowable inputs to the programs and the ticks indicate if the program has the capacity to facilitate the input parameter.

*Table 6-2 - Solar Solution Comparison*

FEATURES	The Solar Solution	Solar Choice	Solar Power Calculator	Solar Savings
Allowable Inputs				
Prompted Entry	✓	✗	✗	✗
Gas Mains Connected	✓	✓	✗	✗
Pool Connection	✓	✓	✗	✗
Electricity Load Profile	✓	✓	✓	✓
Performance Ratio	✓	✓	✗	✓
Solar Size	✓	✓	✓	✓
Solar Cost	✓	✓	✓	✓
Battery Size	✓	✓	✓	✗
Battery Cost	✓	✓	✓	✗
Roof Tilt	✓	✓	✓	✓
Roof Orientation	✓	✓	✓	✓
Post Code Entry	✓	✓	✓	✓
Bill Entry	✓	✓	✓	✓
Number of Occupants	✓	✗	✗	✗



# CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS

## 6.7 Conclusions

The optimisation and estimation of solar photovoltaic and storage for domestic use was investigated in this thesis; through the creation of a GUI in the workspace of MATLAB and proceeding analysis of output data through extensive simulation. It has successfully created a modelling program both for production and economic output from PV/BES systems. The economic analysis included life cycle costing and cost of electricity, to provide a readily comparable figure. Whilst solar calculation programs have been created previously, no program hosts the features which are utilised in the Solar Solution.

The primary focus of this work was on creating a model which compiles recent data, existing theories, trends, and methods, and incorporating them into a syntax in the modelling workspace of MATLAB. To achieve this objective, it was necessary to analyse every variable which affects PV/BES systems. In so far, it was necessary to set certain parameters at values deemed reasonable in accordance with the literature. Thus, the Solar Solution with its features and parameters was tested and analysed by the selection of several locations with varying latitudes throughout Australia. The selected sites of assessment were Townsville, Darwin, and Hobart.

Based on the simulation results obtained and analysis conducted, the following conclusions can be drawn:

- 1) Based on the results from the output data of the Solar Solution, it was shown that due to the lower latitudes receiving higher PSH, the kWhr production per day for a given PV system was increased.
- 2) It was found that data for domestic residential households for kWhr usage, namely gas connected configurations, was not sufficient.
- 3) Households with combined installation of PV/BES in each location produced a reduced cost of electricity per kWhr with respect to the Australian benchmark cost.
- 4) A Darwin residence supplied with the sizing specified in this document of PV/BES was found to be self-supportive - without the importation of electricity from the grid.



- 5) The annual payment costs of a PV/BES system were found to be economically feasible in the mortgage climate rates of optimistic and likely, while the pessimistic figures were viable in most situations with a lower latitude.
- 6) All simple payback periods were within the lifetime of the projects and net savings were substantial compared to investment cost.
- 7) Discounted return on investment yields were calculated at negative integer values, due to the methodology used in assuming a higher discount rate against lower inflation rates.
- 8) Whilst syntax and programming capability in the MATLAB workspace allows mathematical freedom, it was found aesthetics and time consumption were a disadvantage of using this style of coding language.

Excitement for the economic and production capabilities of PV/BES technologies is rapidly growing throughout Australia. This paper has validated the potential for export and self-production capacity for locations of low latitudes in Australia and the ability of the Solar Solution to size PV/BES installations. The transmission of solar electricity from lower latitudes in Australia is both technically and economically feasible over the next 40 years using PV/BES systems.

## 6.8 Recommendations for Further Research

There is opportunity to further expand on the results of this thesis. The current code and modelling can be refined and expanded in both scope and resource. Limitations and assumptions of the Solar Solution were mentioned in the preceding sections. Hitherto, if further research were to be conducted on solar photovoltaic and storage for domestic use and principally, the simulation and estimation of cost and production; the following recommendations should be considered:

- Further testing and debugging of the Solar Solution should be performed for all scenarios for every combination to try and find issues which can be rectified.
- Different orientations should be allowed as input parameters both for a primary, primary-auxiliary combo, or dual combination of arrays.
- Studies on salvage, maintenance and recycle costs in QLD need to be established.
- Benchmark data for households throughout Australia is not well known and needs to be accrued.
- Carbon offset calculations and indication.



- Creation of three modes or options for the user is recommended to be included in the Solar Solution:

- Market Entry – Maximum Return

The Market Entry option is effectively an enticer or market entry for persons whose sole incentive is an investment with maximised returns. This will evaluate the cheapest installation costs and equipment.

- Incentivised Grid Stabilisation Scheme

The second option is the grid stabilisation scheme which will be proposed to energy suppliers and at a governmental level for prospective budget or backing. The underlying goal of this recommendation is to provide a sound basis for a proposal to the Government and energy suppliers for the funding of rebates for consumers. This is an acceptable proposition for QLD, since as of the 1<sup>st</sup> of July, 2016, Adelaide; SA have in effect a rebate of 50% of the installed system cost for BES systems [65].

- Three Day – Standalone Grid Autonomy

The third option will be for the user to completely disconnect from the electricity network. This is for people who wish to become completely electrically independent and operate on renewable energies. This option will be most costly due to current technological limitations, but a shift has commenced towards standalone systems. There are currently many rural and remote small low power operations which are entirely run on renewable energy. The days of autonomy for each installation should be displayed.



# REFERENCES

- [1] L. Rekha, M. M. Vijayalakshmi, and E. Natarajan, "Photovoltaic thermal hybrid solar system for residential applications," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 38, no. 7, pp. 951-959, 2016/04/02 2016.
- [2] S. Shafiee and E. Topal, "When will fossil fuel reserves be diminished?," *Energy Policy*, vol. 37, no. 1, pp. 181-189, 1// 2009.
- [3] J. E. Cohen, "Human Population: The Next Half Century," *Science*, vol. 302, no. 5648, pp. 1172-1175, 2003.
- [4] G. J. Abel, B. Barakat, K. Samir, and W. Lutz, "Meeting the Sustainable Development Goals leads to lower world population growth," *Proceedings of the National Academy of Sciences*, vol. 113, no. 50, pp. 14294-14299, 2016.
- [5] T. M. Razikov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, and H. M. Upadhyaya, "Solar photovoltaic electricity: Current status and future prospects," *Solar Energy*, vol. 85, no. 8, pp. 1580-1608, 8// 2011.
- [6] N. Kannan and D. Vakeesan, "Solar energy for future world: - A review," *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 1092-1105, 9// 2016.
- [7] A. Zahedi, "Developing a method to accurately estimate the electricity cost of grid-connected solar PV in Bangkok," in *2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE)*, 2014, pp. 1-4.
- [8] S. V. Valentine, "Understanding the variability of wind power costs," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 8, pp. 3632-3639, 10// 2011.
- [9] Y. Li and C. Liu, "Estimating solar energy potentials on pitched roofs," *Energy and Buildings*, vol. 139, pp. 101-107, 3/15/ 2017.
- [10] I. MacGill, "Electricity market design for facilitating the integration of wind energy: Experience and prospects with the Australian National Electricity Market," *Energy Policy*, vol. 38, no. 7, pp. 3180-3191, 7// 2010.
- [11] C. Ma, M. Polyakov, and R. Pandit, "Capitalisation of residential solar photovoltaic systems in Western Australia," *Australian Journal of Agricultural and Resource Economics*, vol. 60, no. 3, pp. 366-385, 2016.
- [12] P. Jahangiri and D. C. Aliprantis, "Distributed Volt/VAr Control by PV Inverters," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3429-3439, 2013.
- [13] A. Zahedi, "A review on feed-in tariff in Australia, what it is now and what it should be," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3252-3255, 12// 2010.
- [14] J. v. Appen, M. Braun, and R. Estrella, "A framework for different storage use cases in distribution systems," in *CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid*, 2012, pp. 1-4.
- [15] J. v. Appen, T. Stetz, M. Braun, and A. Schmiegel, "Local Voltage Control Strategies for PV Storage Systems in Distribution Grids," *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 1002-1009, 2014.
- [16] J. D. Farmer and F. Lafond, "How predictable is technological progress?," *Research Policy*, vol. 45, no. 3, pp. 647-665, 4// 2016.
- [17] SavOnSolar. (2017, CA LIC #998752). *How Does Solar Power Work?* [Website]. Available: <http://savonsolar.com/how-solar-works/>
- [18] M. Grätzel, "Photovoltaic and photoelectrochemical conversion of solar energy," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 365, no. 1853, pp. 993-1005, 2007.



- [19] P. G. V. Sampaio and M. O. A. González, "Photovoltaic solar energy: Conceptual framework," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 590-601, 7// 2017.
- [20] L. El Chaar, L. A. lamont, and N. El Zein, "Review of photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 5, pp. 2165-2175, 6// 2011.
- [21] S. Yilmaz, H. R. Ozcalik, S. Kesler, F. Dincer, and B. Yelmen, "The analysis of different PV power systems for the determination of optimal PV panels and system installation—A case study in Kahramanmaraş, Turkey," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1015-1024, 12// 2015.
- [22] A. Park and P. Lappas, "Evaluating demand charge reduction for commercial-scale solar PV coupled with battery storage," *Renewable Energy*, vol. 108, pp. 523-532, 8// 2017.
- [23] S. Voltaics. (2017, 9/16). *Standard Test Conditions*. Available: <http://sinovoltaics.com/solar-basics/measuring-the-temperature-coefficients-of-a-pv-module/>
- [24] H. Energy. (2017). *HOMER PRO*. Available: [http://www.homerenergy.com/HOMER\\_pro.html](http://www.homerenergy.com/HOMER_pro.html)
- [25] D. L. King, J. A. Kratochvil, and W. E. Boyson, "Temperature coefficients for PV modules and arrays: measurement methods, difficulties, and results," presented at the Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference - 1997, Available: <http://dx.doi.org/10.1109/pvsc.1997.654300>
- [26] Deloitte, "US Solar Power Growth through 2040 Exponential or inconsequential?," September 2015 2015.
- [27] C. E. Council, "Clean Energy Australia Report 2015," 2015. Printed by Complete Colour Printing.
- [28] REN21, "Renewables 2016 Global Status Report," no. REN21. 2016., 2016 2016.
- [29] I. Güney, N. Onat, and G. Koçyiğit, "Cost calculation algorithm for stand-alone photovoltaic systems," *WSEAS Transactions on Systems*, vol. 8, no. 7, pp. 835-844, 2009.
- [30] I. T. R. f. Photovoltaic, "International Technology Roadmap for Photovoltaic (ITRPV) 2014 Results," 2015.
- [31] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (Version 45)," *Progress in Photovoltaics: Research and Applications*, vol. 23, no. 1, pp. 1-9, 2015.
- [32] V. Sharma and S. S. Chandel, "Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 753-767, 2013/11/01/ 2013.
- [33] E. L. Meyer and E. E. v. Dyk, "Assessing the reliability and degradation of photovoltaic module performance parameters," *IEEE Transactions on Reliability*, vol. 53, no. 1, pp. 83-92, 2004.
- [34] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation rates—an analytical review," *Progress in photovoltaics: Research and Applications*, vol. 21, no. 1, pp. 12-29, 2013.
- [35] Ö. Özden, Y. Duru, S. Zengin, and M. Boztepe, "Design and implementation of programmable PV simulator," in *Fundamentals of Electrical Engineering (ISFEE), 2016 International Symposium on*, 2016, pp. 1-5: IEEE.
- [36] S. Silvestre, A. Boronat, and A. Chouder, "Study of bypass diodes configuration on PV modules," *Applied Energy*, vol. 86, no. 9, pp. 1632-1640, 2009.
- [37] R. Baetens, R. De Coninck, L. Helsen, and D. Saelens, "The impact of domestic load profiles on the grid-interaction of building integrated photovoltaic (BIPV) systems in extremely low-energy dwellings," in *Zero Emission Buildings*, 2010, pp. 3-14.
- [38] R. Barrios and F. Dios, "Exponentiated Weibull model for the irradiance probability density function of a laser beam propagating through atmospheric turbulence," *Optics & Laser Technology*, vol. 45, pp. 13-20, 2// 2013.



- [39] B. S. Borowy and Z. M. Salameh, "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system," *IEEE Transactions on Energy Conversion*, vol. 11, no. 2, pp. 367-375, 1996.
- [40] A. Zahedi, "Economic Aspects of energy systems, calculations of system's capital and electricity cost considering time value of money. (LECTURE NOTES)," *Lectures*, 2013.
- [41] T. D. Mai, S. De Breucker, K. Baert, and J. Driesen, "Reconfigurable emulator for photovoltaic modules under static partial shading conditions," *Solar Energy*, vol. 141, pp. 256-265, 1/1/ 2017.
- [42] M. C. Alonso-García, J. M. Ruiz, and F. Chenlo, "Experimental study of mismatch and shading effects in the I-V characteristic of a photovoltaic module," *Solar Energy Materials and Solar Cells*, vol. 90, no. 3, pp. 329-340, 2/15/ 2006.
- [43] S. S. Mohammed, D. Devaraj, and T. I. Ahamed, "Modeling, simulation and analysis of photovoltaic modules under partially shaded conditions," *Indian Journal of Science and Technology*, vol. 9, no. 16, 2016.
- [44] M. Q. Duong, K. H. Le, T. S. Dinh, M. Mussetta, and G. N. Sava, "Effects of bypass diode configurations on solar photovoltaic modules suffering from shading phenomenon," in *2017 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, 2017, pp. 731-735.
- [45] W. Herrmann, W. Wiesner, and W. Vaassen, "Hot spot investigations on PV modules-new concepts for a test standard and consequences for module design with respect to bypass diodes," in *Photovoltaic Specialists Conference, 1997., Conference Record of the Twenty-Sixth IEEE*, 1997, pp. 1129-1132: IEEE.
- [46] I. AspenCore, "Bypass Diodes in Solar," Electronic Tutorials 2017. AspenCore, Inc
- [47] H. Jiang, L. Lu, and K. Sun, "Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules," *Atmospheric Environment*, vol. 45, no. 25, pp. 4299-4304, 2011/08/01/ 2011.
- [48] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3124-3131, 2010/12/01/ 2010.
- [49] A. Government, "Average Solar Usage and Generation Statistics," 2017.
- [50] S. Kumar and G. N. Tiwari, "Life cycle cost analysis of single slope hybrid (PV/T) active solar still," *Applied Energy*, vol. 86, no. 10, pp. 1995-2004, 2009/10/01/ 2009.
- [51] J. McCabe, "Salvage Value of Photovoltaic Systems," in *World Renewable Energy Forum. Littleton, CO*, 2011.
- [52] C. Rajoria, S. Agrawal, A. K. Dash, G. Tiwari, and M. Sodha, "A newer approach on cash flow diagram to investigate the effect of energy payback time and earned carbon credits on life cycle cost of different photovoltaic thermal array systems," *Solar Energy*, vol. 124, pp. 254-267, 2016.
- [53] K. Knapp and T. Jester, "Empirical investigation of the energy payback time for photovoltaic modules," *Solar Energy*, vol. 71, no. 3, pp. 165-172, 2001.
- [54] E. A. Alsema, "Energy pay-back time and CO<sub>2</sub> emissions of PV systems," *Progress in Photovoltaics: Research and Applications*, vol. 8, no. 1, pp. 17-25, 2000.
- [55] A. Ganguly and D. N. Basu, "Analysis of a solar photovoltaic-assisted absorption refrigeration system for domestic air conditioning," *International Journal of Green Energy*, vol. 13, no. 6, pp. 585-594, 2016/05/02 2016.
- [56] G. Peharz and F. Dimroth, "Energy payback time of the high-concentration PV system FLATCON®, " *Progress in Photovoltaics: Research and Applications*, vol. 13, no. 7, pp. 627-634, 2005.
- [57] S. Jain and V. Agarwal, "A Single-Stage Grid Connected Inverter Topology for Solar PV Systems With Maximum Power Point Tracking," *IEEE Transactions on Power Electronics*, vol. 22, no. 5, pp. 1928-1940, 2007.
- [58] M. Solar, "Schematic and Operation of an Inverter," 2017.



- [59] L. Aarniovuori, A. Kosonen, P. Sillanpää, and M. Niemelä, "High-Power Solar Inverter Efficiency Measurements by Calorimetric and Electric Methods," *IEEE Transactions on Power Electronics*, vol. 28, no. 6, pp. 2798-2805, 2013.
- [60] A. J. Carr and T. L. Pryor, "A comparison of the performance of different PV module types in temperate climates," *Solar Energy*, vol. 76, no. 1, pp. 285-294, 2004/01/01/2004.
- [61] A. N. Z. Standard, "Grid connection of energy systems via inverters, Part 1: Installation requirements," p. 12, 2016, Art. no. 1. SAI Global Limited
- [62] H. Kirchsteiger, P. Rechberger, and G. Steinmauer, "Cost-optimal Control of Photovoltaic Systems with Battery Storage under Variable Electricity Tariffs," *e & i Elektrotechnik und Informationstechnik*, journal article vol. 133, no. 8, pp. 371-380, 2016.
- [63] M. Energy. (2017, 3). *Energy future: Understanding your load profile*. Available: <https://www.mojopower.com.au/blogs-energy-future-understanding-your-load-profile/>
- [64] C. J. Rydh and B. A. Sandén, "Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies," *Energy Conversion and Management*, vol. 46, no. 11–12, pp. 1980-2000, 7// 2005.
- [65] A. C. Council, "Sustainability Incentives Scheme," 2017.
- [66] J. H. Teng, S. W. Luan, D. J. Lee, and Y. Q. Huang, "Optimal Charging/Discharging Scheduling of Battery Storage Systems for Distribution Systems Interconnected With Sizeable PV Generation Systems," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1425-1433, 2013.
- [67] W. X. Shen, "Optimally sizing of solar array and battery in a standalone photovoltaic system in Malaysia," *Renewable Energy*, vol. 34, no. 1, pp. 348-352, 1// 2009.
- [68] K. S. Ng, C.-S. Moo, Y.-P. Chen, and Y.-C. Hsieh, "Enhanced coulomb counting method for estimating state-of-charge and state-of-health of lithium-ion batteries," *Applied Energy*, vol. 86, no. 9, pp. 1506-1511, 9// 2009.
- [69] M. Muselli, G. Notton, P. Poggi, and A. Louche, "PV-hybrid power systems sizing incorporating battery storage: an analysis via simulation calculations," *Renewable Energy*, vol. 20, no. 1, pp. 1-7, 5// 2000.
- [70] R. L. McKenzie *et al.*, "First southern hemisphere intercomparison of measured solar UV spectra," *Geophysical Research Letters*, vol. 20, no. 20, pp. 2223-2226, 1993.
- [71] A. B. o. M. (BOM). (2017). *Average Solar Radiation for Australia*. Available: [http://www.bom.gov.au/climate/averages/climatology/solar\\_radiation/IDCJCM0019\\_solar\\_exposure.shtml](http://www.bom.gov.au/climate/averages/climatology/solar_radiation/IDCJCM0019_solar_exposure.shtml).
- [72] A. Zahedi, "Australian renewable energy progress," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 8, pp. 2208-2213, 10// 2010.
- [73] G. Bernhard, B. Mayer, G. Seckmeyer, and A. Moise, "Measurements of spectral solar UV irradiance in tropical-Australia," *JOURNAL OF GEOPHYSICAL RESEARCH-ALL SERIES-*, vol. 102, pp. 8719-8730, 1997.
- [74] K. Ulgen, "Optimum Tilt Angle for Solar Collectors," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 28, no. 13, pp. 1171-1180, 2006/09/01 2006.
- [75] C. L. Cheng, C. S. Sanchez Jimenez, and M.-C. Lee, "Research of BIPV optimal tilted angle, use of latitude concept for south orientated plans," *Renewable Energy*, vol. 34, no. 6, pp. 1644-1650, 2009/06/01/ 2009.
- [76] M. Kacira, M. Simsek, Y. Babur, and S. Demirkol, "Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey," *Renewable energy*, vol. 29, no. 8, pp. 1265-1275, 2004.
- [77] R. Perez and S. Coleman, "PV module angles," *Home Power*, vol. 36, pp. 14-16, 1993.



- [78] J. D. Mondol, Y. G. Yohanis, and B. Norton, "The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system," *Renewable Energy*, vol. 32, no. 1, pp. 118-140, 2007/01/01/ 2007.
- [79] A. E. M. Operator. (2017). *National Electricity Market (NEM)*. Available: <https://www.aemo.com.au/About-AEMO>
- [80] E. Energy, "An Overview Our Regulatory Proposal," 2015.
- [81] I. Richardson, M. Thomson, D. Infield, and C. Clifford, "Domestic electricity use: A high-resolution energy demand model," *Energy and Buildings*, vol. 42, no. 10, pp. 1878-1887, 10// 2010.
- [82] W. Hoffmann, "PV solar electricity industry: Market growth and perspective," *Solar Energy Materials and Solar Cells*, vol. 90, no. 18-19, pp. 3285-3311, 11/23/ 2006.
- [83] S. Choice. (2017). *Can you go off grid*. Available: <https://www.solarchoice.net.au/blog/can-you-go-off-grid-solar-energy-storage>
- [84] E. Energy, "Solar Inquiry Submission Report," 2017.
- [85] E. Energy, "Energy Price Fact Sheet," 2017.
- [86] A. Government, "Queensland Solar Bonus Scheme," 2015.
- [87] R. Yao and K. Steemers, "A method of formulating energy load profile for domestic buildings in the UK," *Energy and Buildings*, vol. 37, no. 6, pp. 663-671, 6// 2005.
- [88] E. Energy. (2017). *Talking Energy*. Available: <https://www.ergon.com.au/about-us/news-hub/talking-energy/electricity-industry/consumption-vs-price>
- [89] A. Government, "Energy Made Easy," 2017.
- [90] J. Faxas-Guzmán, R. García-Valverde, L. Serrano-Luján, and A. Urbina, "Priority load control algorithm for optimal energy management in stand-alone photovoltaic systems," *Renewable Energy*, vol. 68, pp. 156-162, 8// 2014.
- [91] M. Castillo-Cagigal *et al.*, "PV self-consumption optimization with storage and Active DSM for the residential sector," *Solar Energy*, vol. 85, no. 9, pp. 2338-2348, 9// 2011.
- [92] S. Calculator. (2017, 9/9). *Solar Calculator*. Available: <https://solarcalculator.com.au/>
- [93] T. Q. Company. (2017, 2/10). *Solar Savings Calculator*. Available: <https://www.solarmarket.com.au/solar-savings-calculator/>
- [94] H. Yang, W. Zhou, L. Lu, and Z. Fang, "Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm," *Solar Energy*, vol. 82, no. 4, pp. 354-367, 4// 2008.
- [95] J. A. Jardini, C. M. V. Tahan, M. R. Gouvea, S. U. Ahn, and F. M. Figueiredo, "Daily load profiles for residential, commercial and industrial low voltage consumers," *IEEE Transactions on Power Delivery*, vol. 15, no. 1, pp. 375-380, 2000.
- [96] R. Tonkoski, D. Turcotte, and T. H. M. E.-. Fouly, "Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 3, pp. 518-527, 2012.
- [97] J. V. Paatero and P. D. Lund, "A model for generating household electricity load profiles," *International Journal of Energy Research*, vol. 30, no. 5, pp. 273-290, 2006.
- [98] M. Hazami, A. Riahi, F. Mehdaoui, O. Nouicer, and A. Farhat, "Energetic and exergetic performances analysis of a PV/T (photovoltaic thermal) solar system tested and simulated under to Tunisian (North Africa) climatic conditions," *Energy*, vol. 107, pp. 78-94, 7/15/ 2016.
- [99] S. Edalati, M. Ameri, and M. Iranmanesh, "Comparative performance investigation of mono- and poly-crystalline silicon photovoltaic modules for use in grid-connected photovoltaic systems in dry climates," *Applied Energy*, vol. 160, pp. 255-265, 12/15/ 2015.
- [100] Y. Kandatsu, "DC/AC inverter controller for solar cell, including maximum power point tracking function," ed: Google Patents, 1993.
- [101] A. Zahedi, "Development of an economical model to determine an appropriate feed-in tariff for grid-connected solar PV electricity in all states of Australia," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 4, pp. 871-878, 5// 2009.



- [102] G. De Feo, M. Forni, F. Petito, and C. Renno, "Life cycle assessment and economic analysis of a low concentrating photovoltaic system," *Environmental Technology*, vol. 37, no. 19, pp. 2473-2482, 2016/10/01 2016.
- [103] B. Andrew, L. Joachim, and N. Anna, "Asia Pacific Super Grid–Solar electricity generation, storage and distribution," *Green*, vol. 2, no. 4, pp. 189-202, 2012.
- [104] LatLong. (2017, 8/8/17). *Latitude and Longitude Finder*. Available: <http://www.latlong.net/>
- [105] A. Government. (2017, 10/8/17). *Energy Sourcing For Domestic Households*. Available: <https://www.energymadeeasy.gov.au/benchmark>
- [106] NASA. (2017, 3/7/17). *Surface meteorology and Solar Energy*. Available: <https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?skip@larc.nasa.gov>
- [107] MathWorks. (2017, 3/3/17). *Matlab Help*. Available: <https://au.mathworks.com/help/matlab/examples/creating-a-user-interface-with-tab-panels.html>
- [108] S. Rodrigues *et al.*, "Economic feasibility analysis of small scale PV systems in different countries," *Solar Energy*, vol. 131, pp. 81-95, 6// 2016.
- [109] A. Q. Jakhrani, A. K. Othman, A. R. H. Rigit, S. R. Samo, L. P. Ling, and R. Baini, "Cost estimation of a standalone photovoltaic power system in remote areas of Sarawak, Malaysia," (in English), *NED University Journal of Research*, Report p. 15+, 2012/01/01 2012.
- [110] A. Q. Jakhrani, A. R. H. Rigit, A. K. Othman, S. R. Samo, and S. A. Kamboh, "Life cycle cost analysis of a standalone PV system," in *2012 International Conference on Green and Ubiquitous Technology*, 2012, pp. 82-85.
- [111] A. Zahedi, "Developing a Method to Accurately Estimate the Electricity Cost of Grid-Connected Solar PV in Doha."
- [112] J. C. Hartman and I. C. Schaftrick, "THE RELEVANT INTERNAL RATE OF RETURN," *The Engineering Economist*, vol. 49, no. 2, pp. 139-158, 2004/01/01 2004.

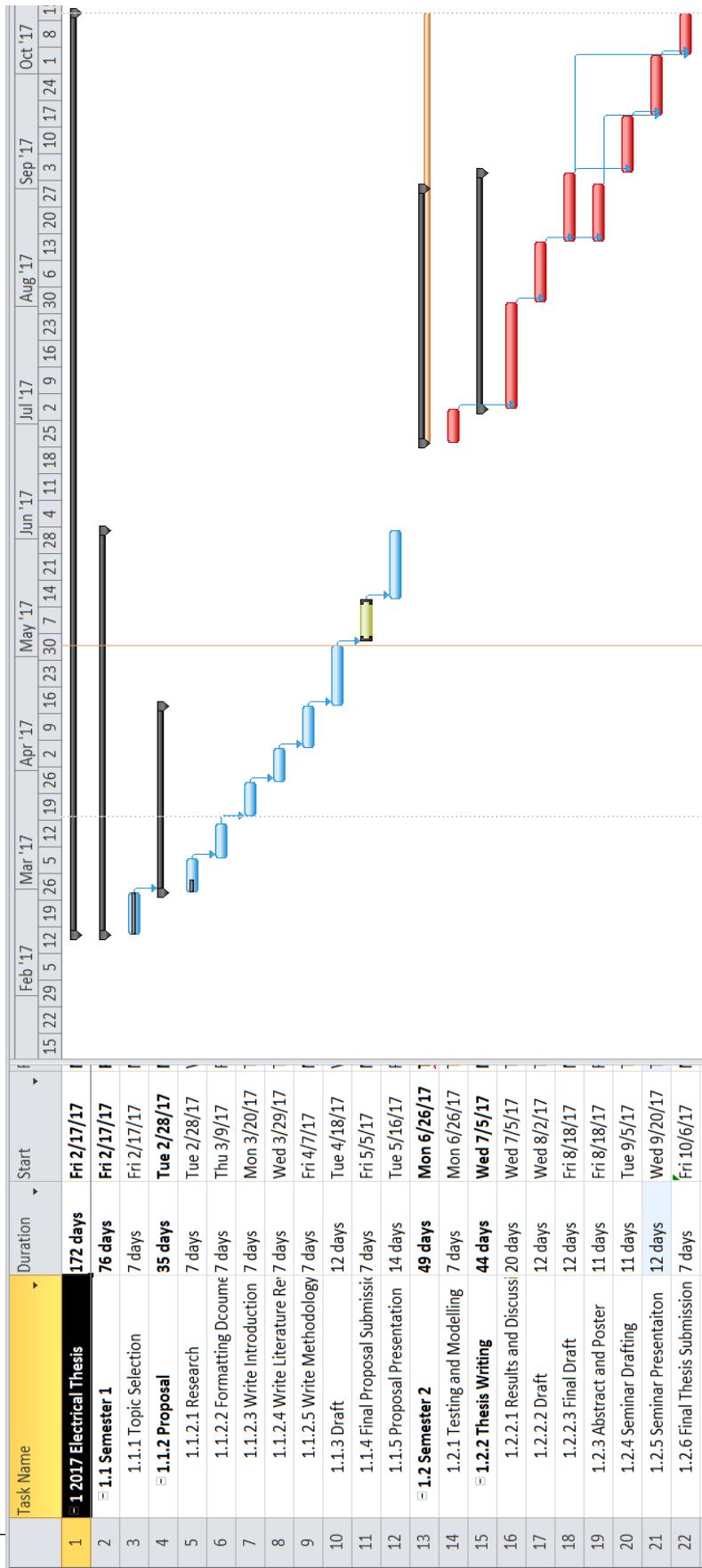


# APPENDICES

APPENDIX A – PROGRESS GANTT CHART	100
APPENDIX B – RISK ASSESSMENT	101
APPENDIX C – RISK ASSESSMENT (APPROVAL)	102
APPENDIX D – PROGRAM OVERVIEW	103
APPENDIX E – TYPICAL INSTALLATION WIRING OF INVERTER	104
APPENDIX F – PROJECT CODE & TITLE	106
APPENDIX G – NASA PEAK SUN HOUR DATA	107
APPENDIX H – ENERGY CONSUMPTION DATA	110
APPENDIX I – MATLAB SOURCE CODE	114



## APPENDIX A – PROGRESS GANTT CHART





## APPENDIX B – RISK ASSESSMENT

NUMBER	RISK DESCRIPTION		TREND	INHERENT	CURRENT	RESIDUAL
501	EG4011 - Thesis - Clinton Elliott - Solar Energy		⬆️	Not Assessed	Medium	Low
RISK OWNER	RISK IDENTIFIED ON		LAST REVIEWED ON	NEXT SCHEDULED REVIEW		
EG4011 Thesis Students	18/04/2017	18/04/2017	18/10/2017			
RISK CONSEQUENCE	RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER	DUE DATE	
On campus after hours	Control: Let administration know what I am working after hours.  Control: Have them call every 30 minutes to check if I am ok.	Control: Report suspicious activity	Ahmad Zahedi	20/04/2017		
Working with electrical appliances 230v mains <u>electricity printers</u> computers	Control: Correct guards Test and tagged	Control: Isolate power if unsure	Ahmad Zahedi	20/04/2017		
Low periods of sitting at desk eye strain carpal tunnel back strain	Control: Correct setup workstation regular breaks stretching	Control: Adjust workstation see Medial specialist if any real concerns	Ahmad Zahedi	20/04/2017		
Air condition removing moisture Periods without water consumption can cause headaches	Control: Hydration Panadol Adjust temperature	Control: Set up a timer, to consume water	Ahmad Zahedi	20/04/2017		



## APPENDIX C – RISK ASSESSMENT (APPROVAL)

### Risk Assessment [Ref Number: 567]

Date Printed: Friday, 5 May 2017

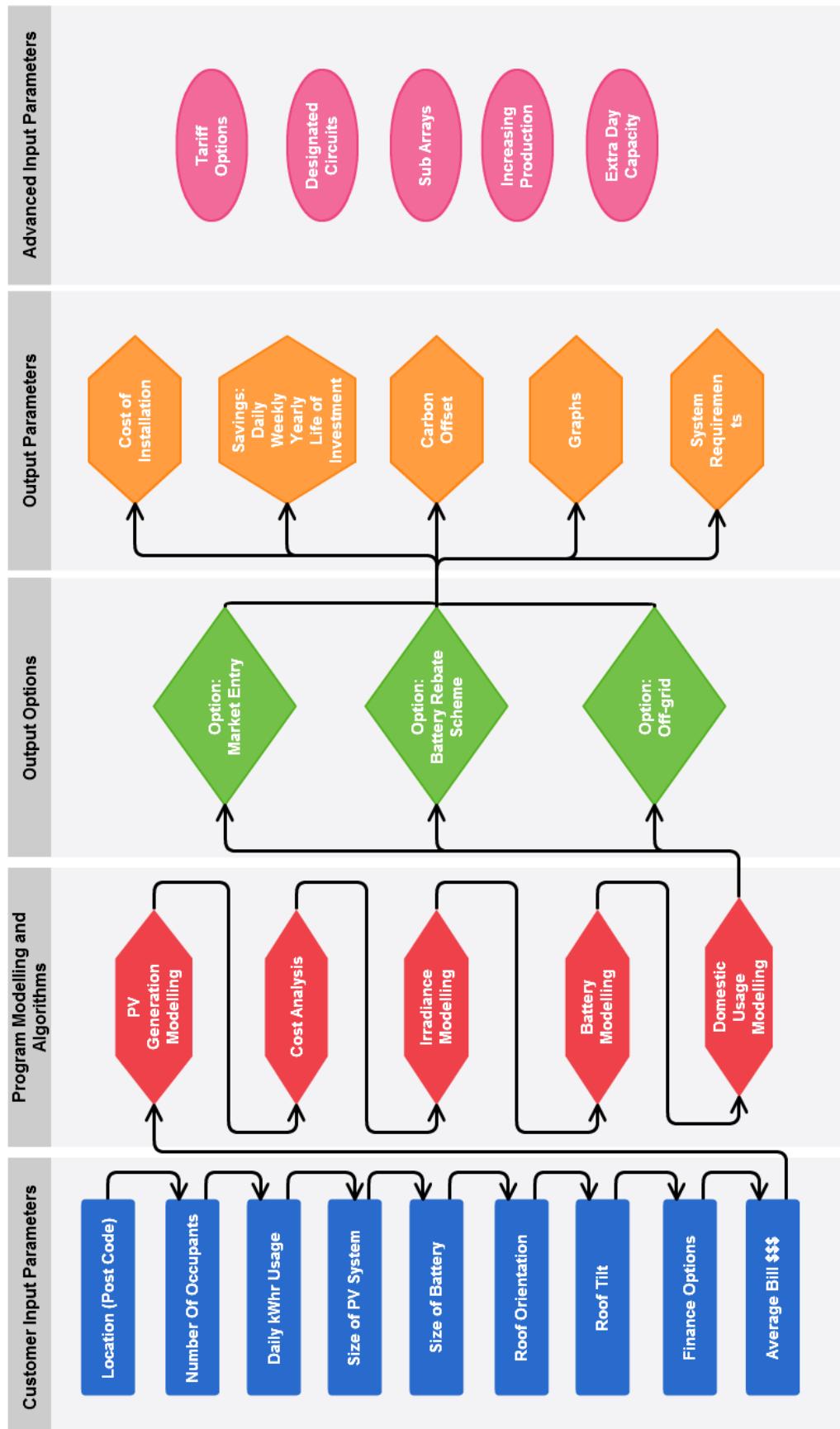
#### Risk Assessment Approval

Description of Role	Signature	Date	Contact Number
Operator			
Supervisor <u>Amna Zahed</u> <u>John Rencher</u> Safety Advisor	<u>R. Zahed</u> <u>J. Rencher</u>	<u>5/5/2017</u> <u>5/5/17</u>	<u>16907</u> <u>14459</u>
Head of Discipline	<u>J. Rencher</u>	<u>8/5/17</u>	<u>X4422</u>

THIS FORM IS TO BE DISPLAYED IN THE IMMEDIATE VICINITY OF THE EXPERIMENT BEING UNDERTAKEN



## APPENDIX D – PROGRAM OVERVIEW





## APPENDIX E – TYPICAL INSTALLATION WIRING OF INVERTER

AS/NZS 4777.1:2016

12

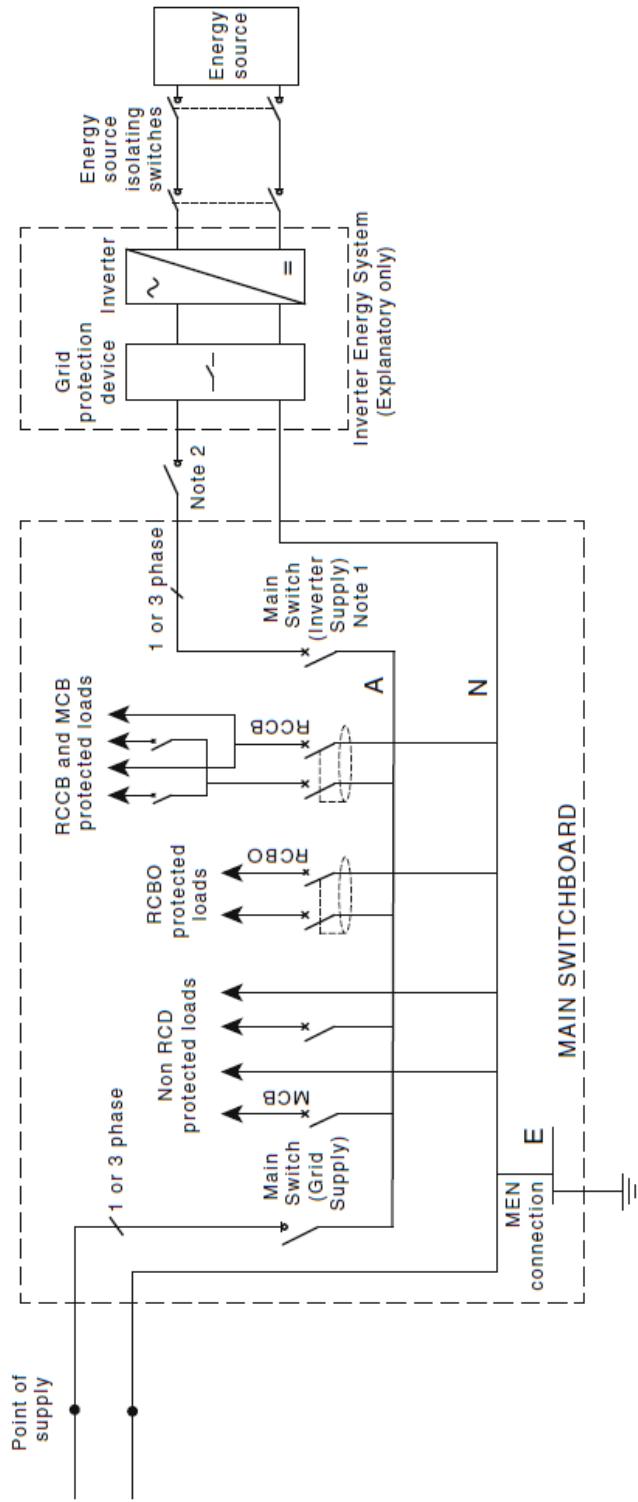


FIGURE 1 TYPICAL INSTALLATION OF AN INVERTER ENERGY SYSTEM TO A MAIN SWITCHBOARD





## APPENDIX F – PROJECT CODE & TITLE

ProjectCode
AZ2
Title: SolarPhotovoltaicand storage for domestic use

### Description

Solar photovoltaic (PV) electricity is receiving a significant attention. This is mainly because of its ability to directly convert sun energy into electricity. One of the weaknesses of solar PV electricity is that it can rarely provide immediate response to the changing load. Recently, an important attention has been turned to the use of an energy storage technology. Combing with storage makes solar PV system more attractive. Smart battery management can create a more effective way of electricity into the power grid. At domestic level a battery of an electric vehicle can provide such a system.

The objectives of this project is to design, optimize the size, and calculate the cost of electricity from a PV/Storage for domestic application.



## APPENDIX G – NASA PEAK SUN HOUR DATA

Townsville	Tilt 0	0	6.35	5.56	5.56	4.79	4.27	4.0	4.39	5.13	6.18	6.59	6.62	6.71	5.51
	Tilt 4	4	6.39	5.55	5.62	4.92	4.46	4.21	4.62	5.32	6.3	6.61	6.57	6.76	5.61
	Tilt 19	19	6.33	5.38	5.68	5.24	5.02	4.86	5.34	5.86	6.54	6.49	6.2	6.76	5.81
	Tilt 34	34	5.97	4.96	5.45	5.29	5.31	5.24	5.77	6.08	6.43	6.02	5.53	6.42	5.71
	Tilt 90	90	2.55	1.94	2.57	3.26	3.92	4.08	4.5	4.08	3.28	2.17	1.76	2.82	3.09
Mount Isa	Tilt 0	0	6.84	6.3	6.11	5.56	4.83	4.32	4.54	5.46	6.11	6.57	6.88	6.96	5.87
	Tilt 5	4	6.88	6.3	6.21	5.79	5.16	4.65	4.86	5.75	6.27	6.6	6.82	7.02	6.02
	Tilt 20	19	6.79	6.1	6.3	6.25	5.93	5.45	5.63	6.4	6.52	6.48	6.39	6.98	6.27
	Tilt 35	34	6.36	5.6	6.06	6.38	6.37	5.94	6.08	6.69	6.42	6.03	5.64	6.58	6.19
	Tilt 90	90	2.59	2.07	2.86	4.01	4.88	4.78	4.73	4.61	3.38	2.28	1.84	2.81	3.41
Darwin	Tilt 0	0	5.52	5.2	5.9	5.99	5.82	5.55	5.76	6.36	6.87	7.07	6.79	5.84	6.06
	Tilt 12	12	5.59	5.17	5.93	6.32	6.47	6.34	6.52	6.9	7.06	6.94	6.87	5.95	6.34
	Tilt 27	27	5.43	4.92	5.71	6.44	6.96	6.99	7.12	7.21	6.96	6.44	6.65	5.82	6.4
	Tilt 90	90	2.43	1.94	2.23	3.46	4.75	5.29	5.16	4.3	2.9	1.72	2.6	2.65	3.29
	Tilt space	95	2.43	1.94	2.23	3.46	4.75	5.29	5.16	4.3	2.9	1.72	2.6	2.65	3.29
Perth	Tilt 0	0	8.41	7.49	5.93	4.34	3.09	2.62	2.82	3.62	5.04	6.41	7.71	8.45	5.49
	Tilt 16	16	8.18	7.62	6.43	5.07	3.82	3.37	3.56	4.3	5.59	6.67	7.59	8.14	5.85
	Tilt 31	31	7.51	7.31	6.54	5.46	4.3	3.89	4.06	4.7	5.8	6.54	7.06	7.39	5.87



	Tilt 46	46	6.47	6.61	6.29	5.56	4.53	4.19	4.33	4.84	5.7	6.07	6.17	6.28	5.58
	Tilt 90	90	2.46	3.09	3.76	4.13	3.78	3.69	3.72	3.75	3.75	3.1	2.55	2.3	3.34
Melbourne	Tilt 0	0	6.31	5.81	4.53	3.26	2.27	1.84	2.03	2.7	3.67	4.77	5.68	6.17	4.08
	Tilt 22	22	6.17	5.98	5.03	4.02	3.06	2.63	2.83	3.42	4.18	5.01	5.61	5.97	4.48
	Tilt 37	37	5.71	5.72	5.07	4.27	3.41	3.01	3.19	3.69	4.27	4.87	5.25	5.48	4.49
	Tilt 52	52	4.99	5.19	4.84	4.31	3.57	3.21	3.38	3.77	4.15	4.5	4.64	4.76	4.27
	Tilt 90	90	2.61	2.99	3.26	3.39	3.11	2.92	3.02	3.08	2.98	2.75	2.55	2.48	2.93
Hobart	Tilt 0	0	5.78	5.18	3.92	2.61	1.8	1.46	1.62	2.33	3.39	4.62	5.52	6	3.68
	Tilt 27	27	5.68	5.4	4.51	3.39	2.71	2.44	2.59	3.23	4.08	4.94	5.49	5.72	4.18
	Tilt 42	42	5.25	5.16	4.52	3.58	3.02	2.81	2.95	3.5	4.17	4.78	5.12	5.25	4.17
	Tilt 57	57	4.59	4.67	4.31	3.59	3.16	3.02	3.13	3.58	4.06	4.4	4.51	4.54	3.96
	Tilt 90	90	2.73	3	3.12	2.95	2.85	2.85	2.9	3.07	3.1	2.94	2.74	2.69	2.91
Sydney	Tilt 0	0	5.91	5.25	4.48	3.56	2.73	2.49	2.68	3.49	4.6	5.41	5.88	6.24	4.39
	Tilt 18	18	5.78	5.32	4.82	4.16	3.46	3.37	3.54	4.28	5.15	5.63	5.8	6.04	4.78
	Tilt 33	33	5.38	5.11	4.84	4.42	3.87	3.89	4.04	4.68	5.32	5.5	5.43	5.57	4.84
	Tilt 48	48	4.73	4.66	4.62	4.45	4.07	4.2	4.31	4.82	5.21	5.1	4.82	4.85	4.65
	Tilt 90	90	2.34	2.55	2.93	3.35	3.43	3.77	3.77	3.82	3.54	2.83	2.4	2.31	3.09
Brisbane	Tilt 0	0	6.19	5.39	4.95	3.98	3.23	3.02	3.22	4.04	5.12	5.52	6.07	6.35	4.75
	Tilt 12	12	6.06	5.41	5.15	4.34	3.71	3.59	3.78	4.56	5.47	5.62	5.98	6.18	4.99



	Tilt 27	27	5.65	5.22	5.19	4.6	4.12	4.13	4.29	4.99	5.65	5.5	5.61	5.71	5.05
	Tilt 42	42	4.98	4.78	4.96	4.63	4.32	4.43	4.57	5.15	5.54	5.11	4.99	4.97	4.87
	Tilt 90	90	2.09	2.28	2.81	3.22	3.41	3.75	3.76	3.84	3.38	2.49	2.13	2.04	2.94



## APPENDIX H – ENERGY CONSUMPTION DATA

City	Post Code	# People	Pool	Gas	kWhr/day	Annual	Tariff #	Tariff Rate	Solar Rate
Townsville	4814	4	0	0	24.6	8979	11	0.27071	0.07448
	4814	4	0	1	24.6	8979	11	0.27071	0.07448
	4814	4	1	0	32.5	11862.5	11	0.27071	0.07448
	4814	4	1	1	32.5	11862.5	11	0.27071	0.07448
	4814	3	0	0	19.2	7008	11	0.27071	0.07448
	4814	3	0	1	19.2	7008	11	0.27071	0.07448
	4814	3	1	0	27	9855	11	0.27071	0.07448
	4814	3	1	1	27	9855	11	0.27071	0.07448
	4814	2	0	0	16.8	6132	11	0.27071	0.07448
	4814	2	0	1	16.8	6132	11	0.27071	0.07448
	4814	2	1	0	24.6	8979	11	0.27071	0.07448
	4814	2	1	1	24.6	8979	11	0.27071	0.07448
	4814	1	0	0	10.8	3942	11	0.27071	0.07448
	4814	1	0	1	10.8	3942	11	0.27071	0.07448
	4814	1	1	0	18.7	6825.5	11	0.27071	0.07448
	4814	1	1	1	18.7	6825.5	11	0.27071	0.07448
Mount Isa	4825	4	0	0	25.2	9198	11	0.27071	0.07448
	4825	4	0	1	25.2	9198	11	0.27071	0.07448
	4825	4	1	0	33.3	12154.5	11	0.27071	0.07448
	4825	4	1	1	33.3	12154.5	11	0.27071	0.07448
	4825	3	0	0	19.6	7154	11	0.27071	0.07448
	4825	3	0	1	19.6	7154	11	0.27071	0.07448
	4825	3	1	0	27.7	10110.5	11	0.27071	0.07448
	4825	3	1	1	27.7	10110.5	11	0.27071	0.07448
	4825	2	0	0	17.2	6278	11	0.27071	0.07448
	4825	2	0	1	17.2	6278	11	0.27071	0.07448
	4825	2	1	0	25.2	9198	11	0.27071	0.07448
	4825	2	1	1	25.2	9198	11	0.27071	0.07448
	4825	1	0	0	11.1	4051.5	11	0.27071	0.07448
	4825	1	0	1	11.1	4051.5	11	0.27071	0.07448
	4825	1	1	0	19.1	6971.5	11	0.27071	0.07448



	4825	1	1	1	19.1	6971.5	11	0.27071	0.07448
Darwin	800	4	0	0	20.5	7482.5	11	0.27071	0.07448
	800	4	0	1	20.5	7482.5	11	0.27071	0.07448
	800	4	1	0	26.6	9709	11	0.27071	0.07448
	800	4	1	1	26.6	9709	11	0.27071	0.07448
	800	3	0	0	18.5	6752.5	11	0.27071	0.07448
	800	3	0	1	18.5	6752.5	11	0.27071	0.07448
	800	3	1	0	24.6	8979	11	0.27071	0.07448
	800	3	1	1	24.6	8979	11	0.27071	0.07448
	800	2	0	0	18.6	6789	11	0.27071	0.07448
	800	2	0	1	18.6	6789	11	0.27071	0.07448
	800	2	1	0	24.7	9015.5	11	0.27071	0.07448
	800	2	1	1	24.7	9015.5	11	0.27071	0.07448
	800	1	0	0	9.6	3504	11	0.27071	0.07448
	800	1	0	1	9.6	3504	11	0.27071	0.07448
	800	1	1	0	15.8	5767	11	0.27071	0.07448
	800	1	1	1	15.8	5767	11	0.27071	0.07448
Perth	6000	4	0	0	20	7300	11	0.27071	0.07448
	6000	4	0	1	20	7300	11	0.27071	0.07448
	6000	4	1	0	20	7300	11	0.27071	0.07448
	6000	4	1	1	20	7300	11	0.27071	0.07448
	6000	3	0	0	17	6205	11	0.27071	0.07448
	6000	3	0	1	17	6205	11	0.27071	0.07448
	6000	3	1	0	17	6205	11	0.27071	0.07448
* No pool	6000	3	1	1	17	6205	11	0.27071	0.07448
	6000	2	0	0	14.1	5146.5	11	0.27071	0.07448
	6000	2	0	1	14.1	5146.5	11	0.27071	0.07448
	6000	2	1	0	14.1	5146.5	11	0.27071	0.07448
	6000	2	1	1	14.1	5146.5	11	0.27071	0.07448
	6000	1	0	0	11.2	4088	11	0.27071	0.07448
	6000	1	0	1	11.2	4088	11	0.27071	0.07448
	6000	1	1	0	11.2	4088	11	0.27071	0.07448
	6000	1	1	1	11.2	4088	11	0.27071	0.07448
Melbourne	3000	4	0	0	14.6	11789.5	11	0.27071	0.07448



	3000	4	0	1	13.7	5767	11	0.27071	0.07448
	3000	4	1	0	22.8	21097	11	0.27071	0.07448
	3000	4	1	1	21.9	15074.5	11	0.27071	0.07448
	3000	3	0	0	19.2	9928	11	0.27071	0.07448
	3000	3	0	1	11.1	8066.5	11	0.27071	0.07448
	3000	3	1	0	27.4	19272	11	0.27071	0.07448
	3000	3	1	1	19.4	17410.5	11	0.27071	0.07448
	3000	2	0	0	15.3	8541	11	0.27071	0.07448
	3000	2	0	1	10.6	3869	11	0.27071	0.07448
	3000	2	1	0	23.5	17885	11	0.27071	0.07448
	3000	2	1	1	18.8	13176.5	11	0.27071	0.07448
	3000	1	0	0	11.6	6168.5	11	0.27071	0.07448
	3000	1	0	1	7.4	1861.5	11	0.27071	0.07448
	3000	1	1	0	19.8	15512.5	11	0.27071	0.07448
	3000	1	1	1	15.6	11169	11	0.27071	0.07448
Hobart	7000	4	0	0	32.3	7336.5	11	0.27071	0.07448
	7000	4	0	1	15.8	5329	11	0.27071	0.07448
	7000	4	1	0	57.8	10001	11	0.27071	0.07448
	7000	4	1	1	41.3	7993.5	11	0.27071	0.07448
	7000	3	0	0	27.2	6935	11	0.27071	0.07448
	7000	3	0	1	22.1	5037	11	0.27071	0.07448
	7000	3	1	0	52.8	9599.5	11	0.27071	0.07448
	7000	3	1	1	47.7	7701.5	11	0.27071	0.07448
	7000	2	0	0	23.4	5621	11	0.27071	0.07448
	7000	2	0	1	10.6	4161	11	0.27071	0.07448
	7000	2	1	0	49	8285.5	11	0.27071	0.07448
	7000	2	1	1	36.1	6862	11	0.27071	0.07448
	7000	1	0	0	16.9	3285	11	0.27071	0.07448
	7000	1	0	1	5.1	2993	11	0.27071	0.07448
	7000	1	1	0	42.5	5949.5	11	0.27071	0.07448
	7000	1	1	1	30.6	5694	11	0.27071	0.07448
Sydney	2000	4	0	0	20.1	7336.5	11	0.27071	0.07448
	2000	4	0	1	14.6	5329	11	0.27071	0.07448
	2000	4	1	0	27.4	10001	11	0.27071	0.07448



	2000	4	1	1	21.9	7993.5	11	0.27071	0.07448
	2000	3	0	0	19	6935	11	0.27071	0.07448
	2000	3	0	1	13.8	5037	11	0.27071	0.07448
	2000	3	1	0	26.3	9599.5	11	0.27071	0.07448
	2000	3	1	1	21.1	7701.5	11	0.27071	0.07448
	2000	2	0	0	15.4	5621	11	0.27071	0.07448
	2000	2	0	1	11.4	4161	11	0.27071	0.07448
	2000	2	1	0	22.7	8285.5	11	0.27071	0.07448
	2000	2	1	1	18.8	6862	11	0.27071	0.07448
	2000	1	0	0	9	3285	11	0.27071	0.07448
	2000	1	0	1	8.2	5694	11	0.27071	0.07448
	2000	1	1	0	16.3	5949.5	11	0.27071	0.07448
	2000	1	1	1	15.6	5694	11	0.27071	0.07448
Brisbane	4000	4	0	0	19.1	6971.5	11	0.27071	0.07448
	4000	4	0	1	19.8	7227	11	0.27071	0.07448
	4000	4	1	0	25	9125	11	0.27071	0.07448
	4000	4	1	1	25.7	9380.5	11	0.27071	0.07448
	4000	3	0	0	15.1	5511.5	11	0.27071	0.07448
	4000	3	0	1	14	5110	11	0.27071	0.07448
	4000	3	1	0	21	7665	11	0.27071	0.07448
	4000	3	1	1	19.9	7263.5	11	0.27071	0.07448
	4000	2	0	0	13.5	4927.5	11	0.27071	0.07448
	4000	2	0	1	10.4	3796	11	0.27071	0.07448
	4000	2	1	0	19.4	7081	11	0.27071	0.07448
	4000	2	1	1	16.3	5949.5	11	0.27071	0.07448
	4000	1	0	0	8.7	3175.5	11	0.27071	0.07448
	4000	1	0	1	5.4	1971	11	0.27071	0.07448
	4000	1	1	0	14.6	5329	11	0.27071	0.07448
	4000	1	1	1	11.4	4161	11	0.27071	0.07448



## APPENDIX I – MATLAB SOURCE CODE



This page intentionally left blank