JAMES COOK UNIVERSITY
SOLAR ENERGY

SOLAR PHOTOVOLTAIC AND STORAGE FOR DOMESTIC USE

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When Alternative energy is no longer an alternative.
-Anonymous

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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 down to parity 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 advantages of a long system life time, generally 25 years with minimal maintenance. A solar system is modular, silent, has an infinite fuel source and with no 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 optimizing three selectable options for the user. This has the benefit at a household domestic level with electricity savings and the complimentary grid stabilization consequences for Ergon and other electricity suppliers. This is a suitable proposition towards the government, as a margin from the budget each year is directed towards renewable technologies. This thesis is the original framework to put forward a proposal for a battery energy storage rebate scheme in Queensland and principally Townsville. The city of Townsville will be the focus of this project and is a very suitable place for solar production as it is situated with a high altitude and large levels of solar radiation.

The need for the current up-to-date estimates and appropriate calculations for the cost and feasibility for solar installations has never been greater. This proposed program hopes to bring 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 Townsville.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AEMO	Australian Energy Market Operator
ALCC	Annualized Life Cycle Cost
BES	Battery Energy Storage
CO2	Carbon Dioxide
DC	Direct Current
DER	Distributed Energy Resource
DOD	Depth of Discharge
EPS	Emergency Power Supply
EPBT	Energy Payback Time
F	Frequency
GUI	Graphical User Interface
GHI	Global Horizontal Irradiance
HEV	Hybrid Electric Vehicle
IC	Integrated Circuit
IRR	Internal Rate of Return
J	Joules
KWHR	Kilowatt Hour
LV	Low Voltage
LCC	Life Cycle Cost
MATLAB	Matrix Laboratory
NEM	National Electricity Market
NPV	Net Present Value
O	Outdoor
PV	Photovoltaic
PDF	Probability Density Function
RTP	Real Time Pricing
SOC	State of Charge
SOH	State of Health
V	Volts
WAN	Wireless Area Network

LIST OF APPENDICES

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 utilized 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 Earth's population from doubled 1927 to 1974 and this occurred again in the following 25 years (to 1999). Cohen emphasized that in the last 40 years the world's population has doubled and that people had never lived through such an event, and now 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 million by 2100, the stakes have never been so high for the supply of clean, efficient and stable Electrical Energy. [4] The worlds 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 21st 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 high quality, dependable and above all ethical. Currently 10 Giga-tonnes of carbon dioxide is produced each year as fossil fuel emissions [as a byproduct of electricity production] and remains the largest single sector emitter. [7] In the wake of global warming and carbon emissions the demand for green renewable energies has grown exponentially.

The breakdown of energy from sources can be seen in the below **Figure 1-1**. The green energies wind, geothermal, wave, hydroelectricity and solar are now in their greatest demand due to their ability to produce power and the minimal to non-existent carbon footprint. Valentine 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 Photo-Voltaic (PV) have been significantly subsidized to augment and incentivize 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 7th global market for PV and introduced one of the world's first renewable energy target schemes in 2001. [10]
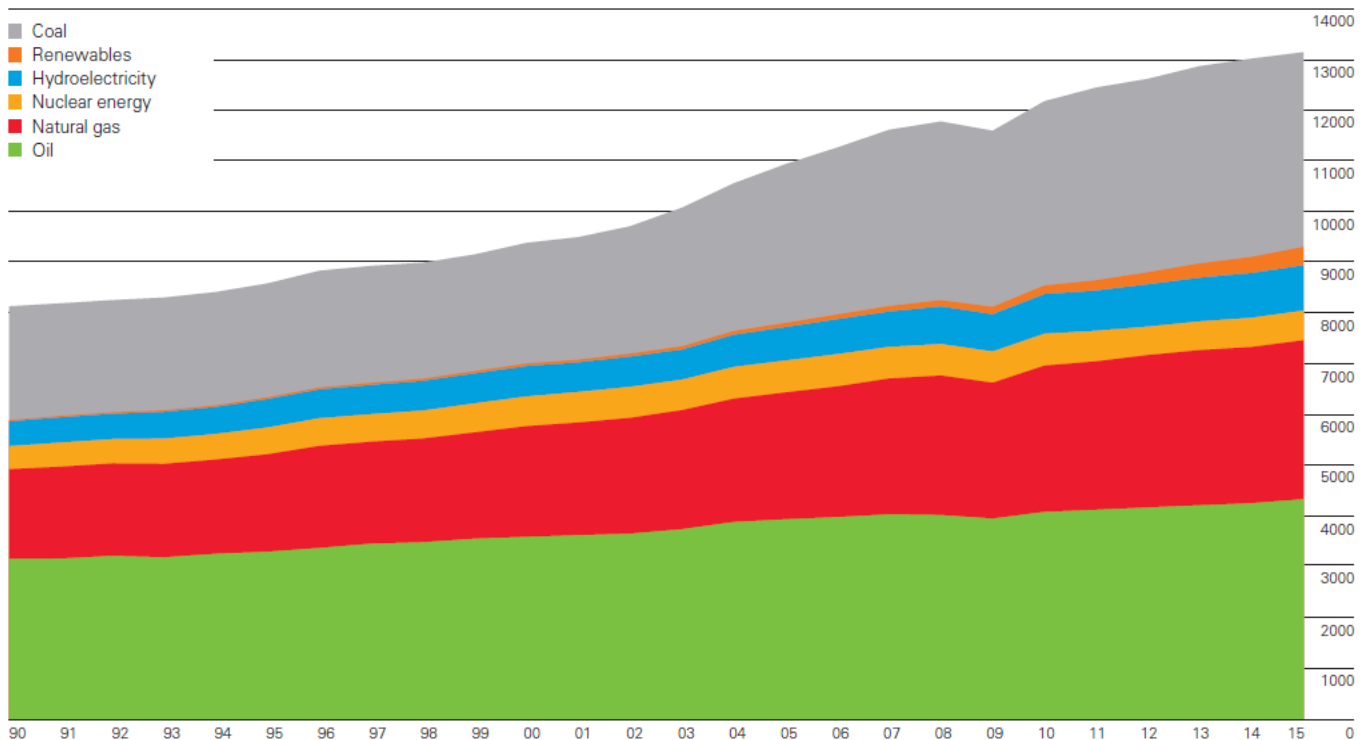
Figure 1-1 - *Worlds Energy Consumption By Source (Million Tons Vs. Year) [7]*

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, subsidized 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 utilized. [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 analyzed 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 sufficient models to size and optimize PV and BES systems for different configurations of household demand to maximize savings and disruptive outputs to the LV grid network. 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. The ability to provide a minimum optimized market buy in for potential customers will be found. This is to open up the market and show potential avenues for investment for customers. The program is to calculate the minimum requirements for a hybridized PV/BES system for less network strain. The Research will be found regarding the minimum system requirements for a standalone PV/BES system. The goal of this research is to provide a sound basis for a proposal to the government to enact a rebate scheme for BES systems in Townsville and wider Queensland.

1.3 Scope

Photovoltaic systems have been around for just over 50 years and their daily use and efficiency is increasing. Farmer & 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 with a working model extrapolating to other applications is possible. The different tariffs schemes throughout the world and indeed Australia will not be analyzed; 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 bill 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 but principally with solar photovoltaic energy production. The term solar system will refer to the entire systems incorporating solar PV panels, the DC to AC inverter and the battery bank or BES system and not other configurations. For clarification, one cell is P-N junction. Many cells make a module (generally 36 or 72) and usually 10 or 20 modules make an array. A solar system may have one or two arrays; any panel combined with an inverter is considered a solar system in this paper. 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 batters such as the Tesla Powerwall and LG Chem RESU and Zinc Bromide batteries such as ZBM 2 by Redflow. The solar irradiance for Australia and principally Townsville will only be analyzed.

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 world. The cry to slate increased energy demands has been met with unsubstantiated claims. The electrical energy sector is turning towards clean, ethical, dependable energy sources. The renewables 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 in February this year (2017), which left over 90,000 people without power. The move to justify and improve renewables energy technology has never been so evident.

In the fallout of the SA blackout the capacity 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. This respect will explore how electricity is charged to the consumer and sold to the supplier. The solar irradiance is examined and 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 endeavored 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 modern solar systems which will be 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. The Figure 2-1 below shows the operation of 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]

1 Solar Panels convert sunlight into clean green DC electicity

2 Inverter converts DC electriciy into useable AC electricity

3 Existing electrical switchboard with new bi-directional metering installed

4 **Exported electricity** when the solar system generates more electricity than your household uses the excess electricity goes back into the grid and spins your meter backwards adding credit to your electricity bill

5 During peak periods and at night electricity is imported from the grid

Supply authority power grid

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 current 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 (PV) 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 emphasized 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 photo-voltaic 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 Silicone with the P (positive) layer being doped usually with Boron or Gallim 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 photos 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*. These electrons can 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]
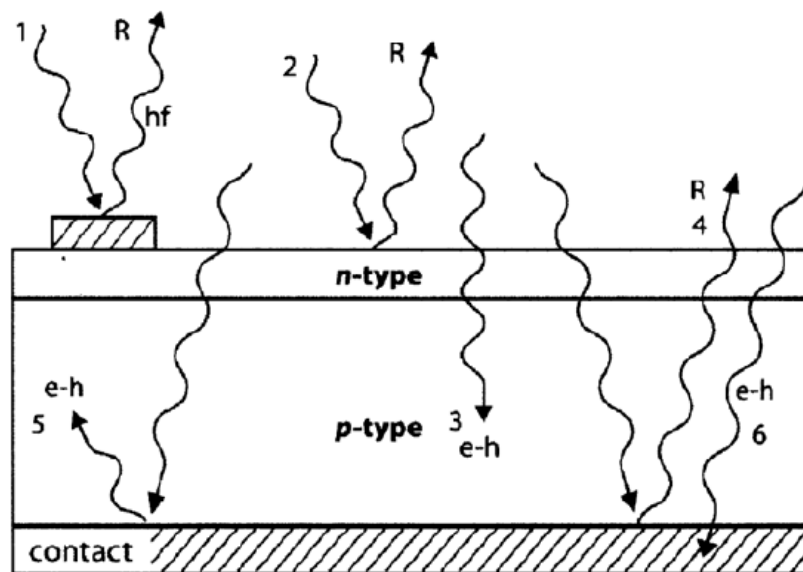
Figure 2-2 *- Behaviour of light shining on a solar cell. 1/2/4/5.) Reflection 3/6.) Absorption [21]*

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]

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

Where:

- $P_{PV,STC}$ – is the solar output under standard test conditions
- GHI – Global Horizontal Irradiance
- γ – is the temperature coefficient
- T_C -is the cell temperature
- $N_{PV,S}$ & $N_{PV,P}$- are determined by the system design.

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:

i.	Amorphous Silicon solar cell (a-Si)	vi.	Perovskite solar cell
ii.	Concentrated PV cell (CVP and HCVP)	vii.	Photoelectrochemical cell (PEC)
		viii.	Plasmonic solar cell
iii.	Crystalline silicon solar cell (c-Si)	ix.	Polycrystalline solar cell (multi-Si)
iv.	Multi-junction solar cell (MJ)	x.	Thin-film solar cell (TFSC)
v.	Nanocrystal solar cell	xi.	Organic solar cell (OPV)
xii.			
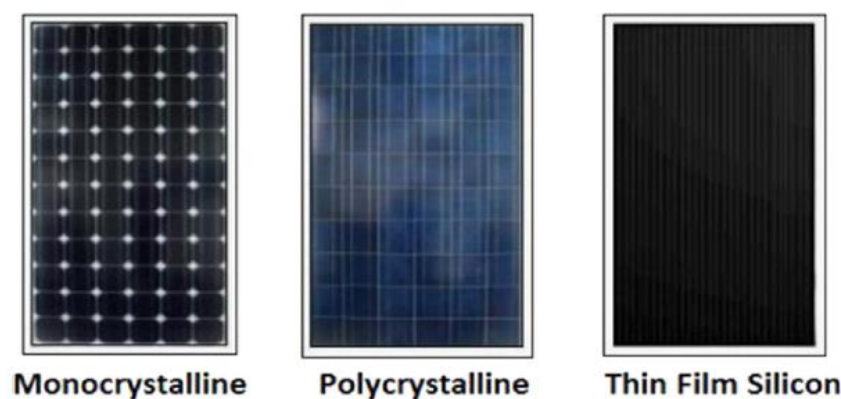
Figure 2-3 - Photovoltaic Panel Types [21]

The main types of solar panels in use in the domestic sector are shown above in ***Figure 2-3*** and are Monocrystalline, Polycrystalline and Thin Film Silicone. The classification of solar panels is shown in ***Figure 2-4*** below. 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.
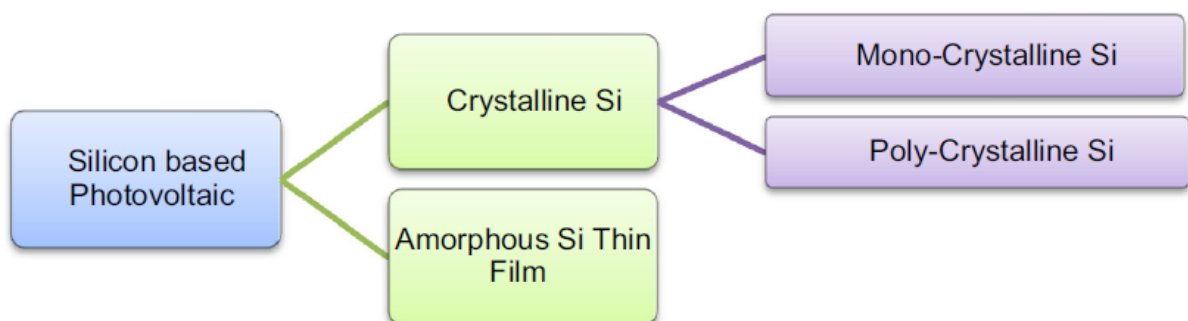
Figure 2-4 - Classification of the silicon PV panels. [21]

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. [23] The below *Figure 2-5* trends the decrease in PV modules. From the **Figure 2-5** it shows that the cost in 1976 was approximately 100.00$/W and in 2014 it is approximately 0.80$/W.
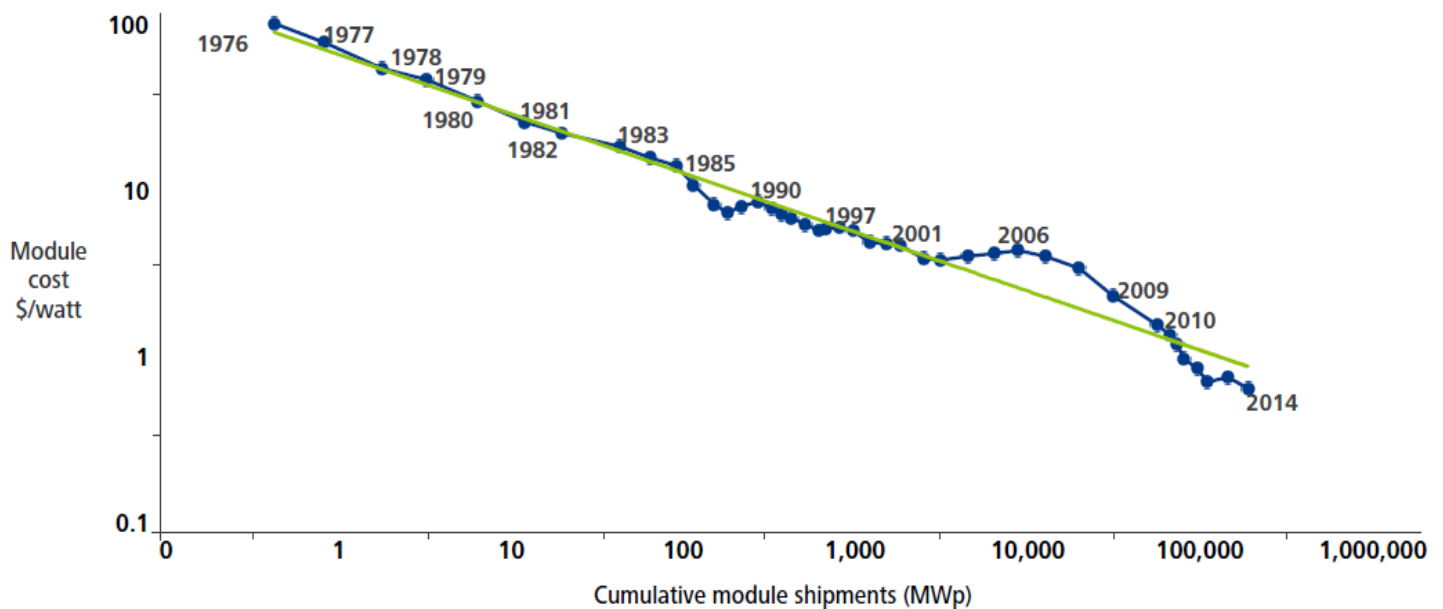
Figure 2-5 *- Swanson's Law: Module costs decline as shipments increase [23]*

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 on the below Figure 2-6 which compares renewables to other sources of energy. [24]
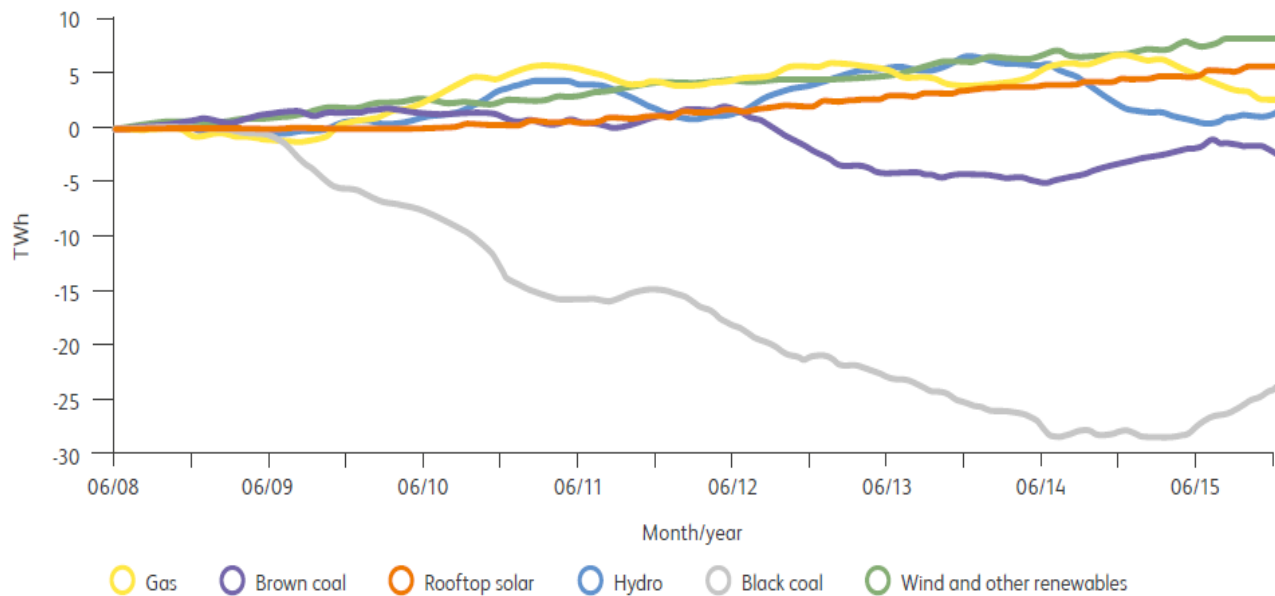
Figure 2-6- Changes in Electricity Generation by Fuel type [24]

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. In the below **Figure 2-7**, which trends the last decade of growth for PV production from 5.1GW to 227 GW in 2015. This clearly demonstrates the growth of PV technologies all over the world. [25]
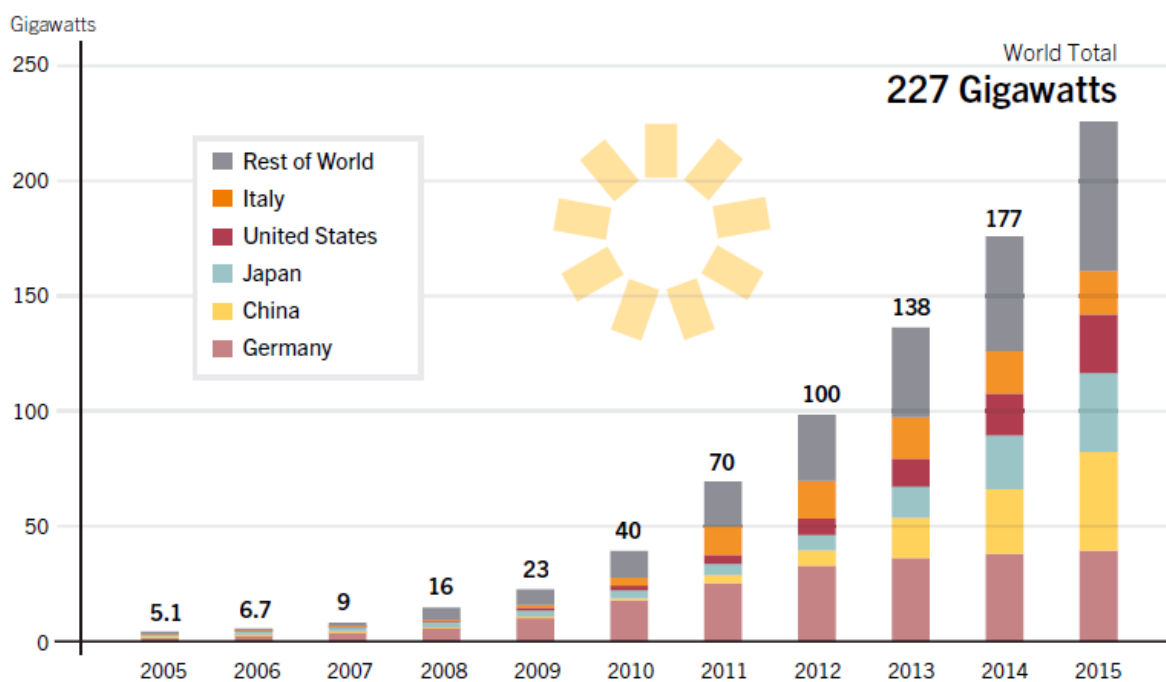
Figure 2-7- Solar PV Global Capacity, by Country/Region, 2005-2015 [25]

The growth in solar PV is occurring all over the world and Australia has seen huge increases in the amount of solar installations. The Figure 2-8 below shows the amount of installations per year in Australia. The peak noted in the years 2011 and 2012 were due to the rebate programs. [24]
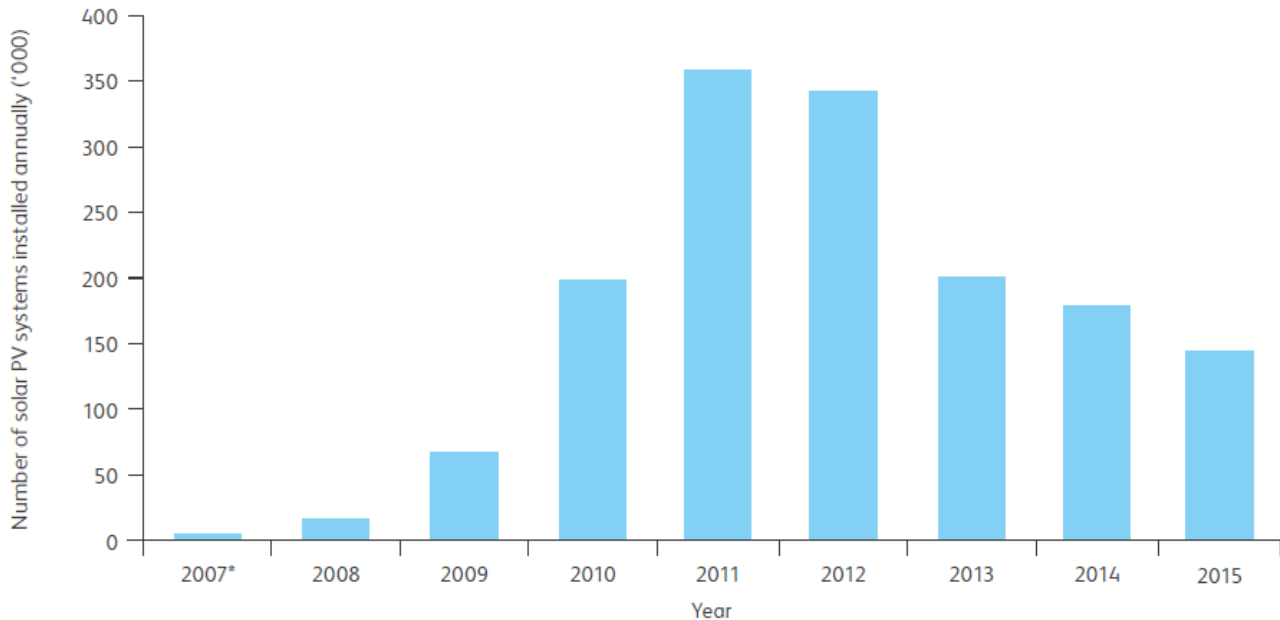
Figure 2-8- Annual Solar PV Installations in Australia [24]

While the amount of installations has started to decrease, the size of the installation has increased. The **Figure 2-9** below shows that the average kW capacity of the systems installed has increased and is due to price decreases and better technology. [24]
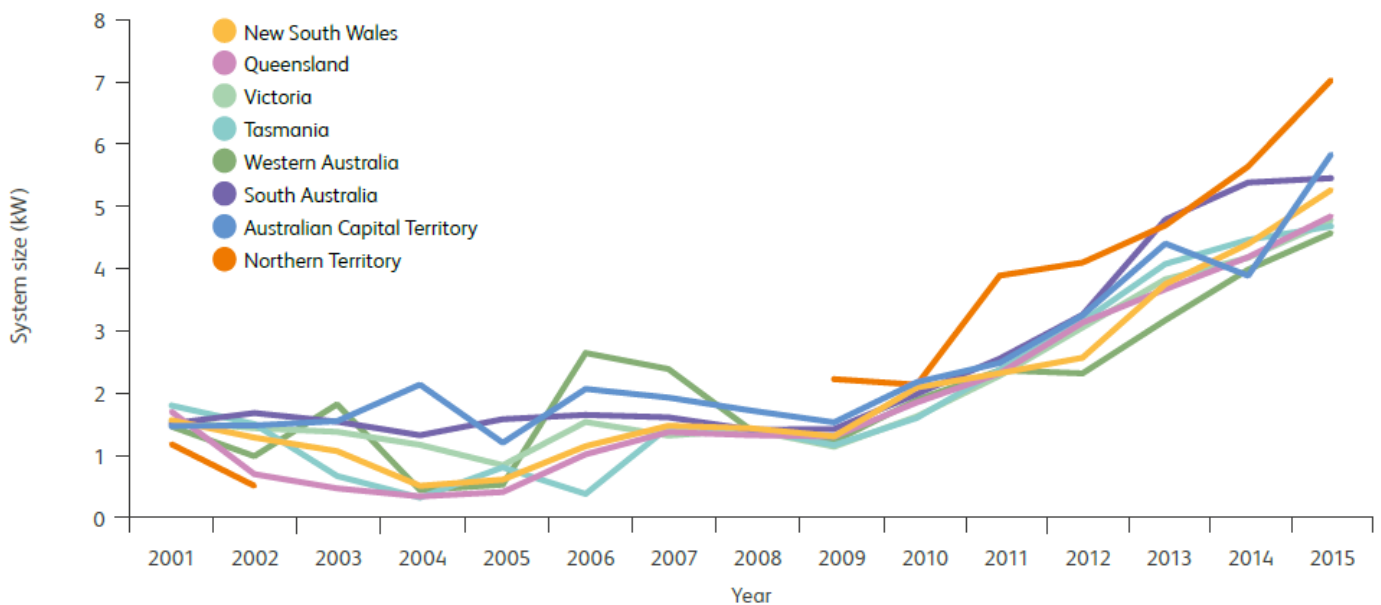
Figure 2-9- State Average Solar PV System Size (kW) [24]

The renewable energy trend has allowed Queensland to generate 4% of its electricity from renewables, with two wind farms and 466,966 domestic solar systems. [24]

Onat has highlighted in **Table 1** below the advantages and disadvantages of PV systems. [26]

Table 1- Advantages and Disadvantages of PV Systems [26]

Advantages of PV	Disadvantages of PV
Fuel source is vast and essentially infinite	Fuel source is diffuse (sunlight is relatively low density energy)
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	
Low operating costs (no fuel)	Low conversion efficiency <40%
No moving parts	
Ambient temperature operation	
High reliability in modules (>20 years)	Poorer reliability of auxiliary (BOS) elements including storage
Modular (small or large increments)	
Quick installation	
Can be integrated into new or existing building structures	Initial investment sum
Can be installed at nearly any point of use	
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 photovoltaic cell is the 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. [27] Currently Si crystalline has 25.6% efficiency while the best solar cell is InGaP/GaAs/InGaAs with 37.9% efficiency. [28] The below Figure 2-10 shows the trending increase in efficiency for solar panels.
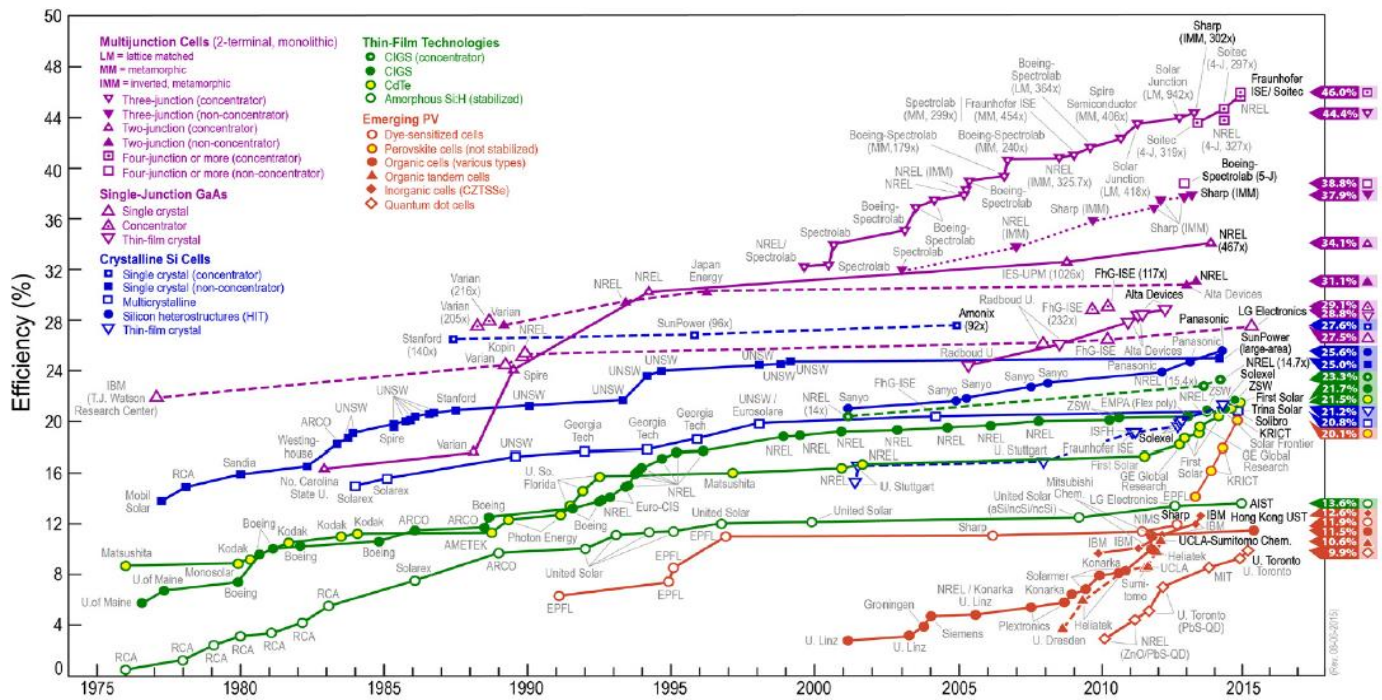
Figure 2-10 - Best Research-Cell Efficiencies, 1976-2015 [28]

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 below was produced. [19]
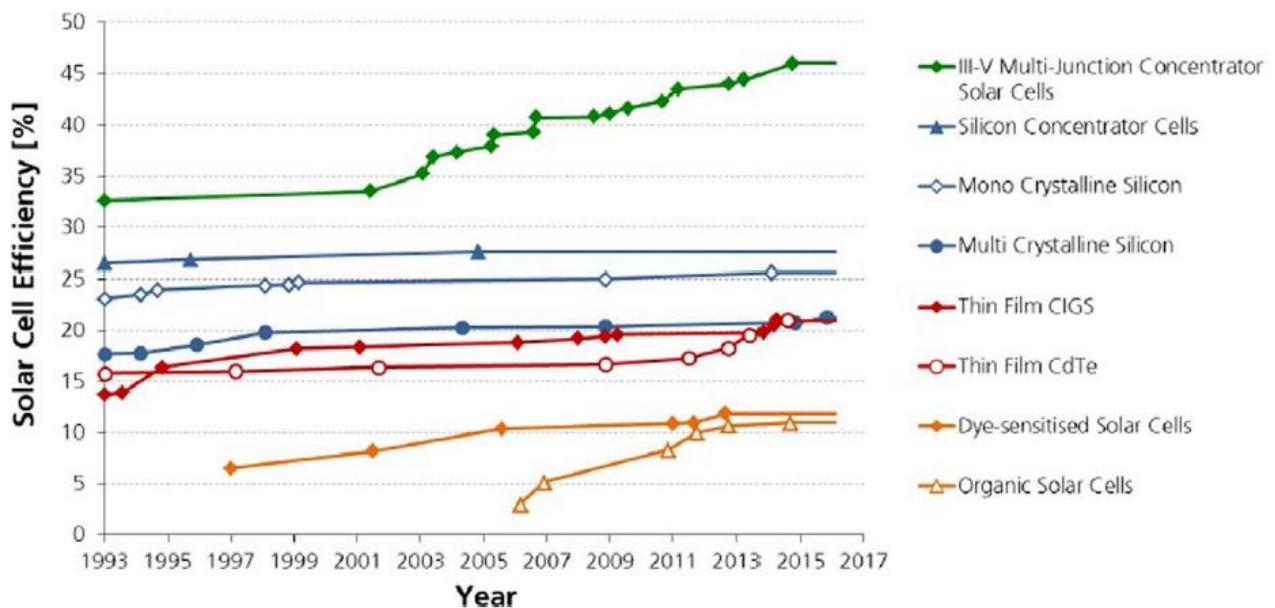
Figure 2-11 - Solar Cell efficiency [19]

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 below Figure 2-12. The voltage drop over the diode depends on the type of material which is used to construct the solar cell. Silicone Crystalline cells have 0.74 V, Thin Film (GaAs) have 1.122 V and Silicone Amorphous have 0.896 V forward biasing drop. [28]
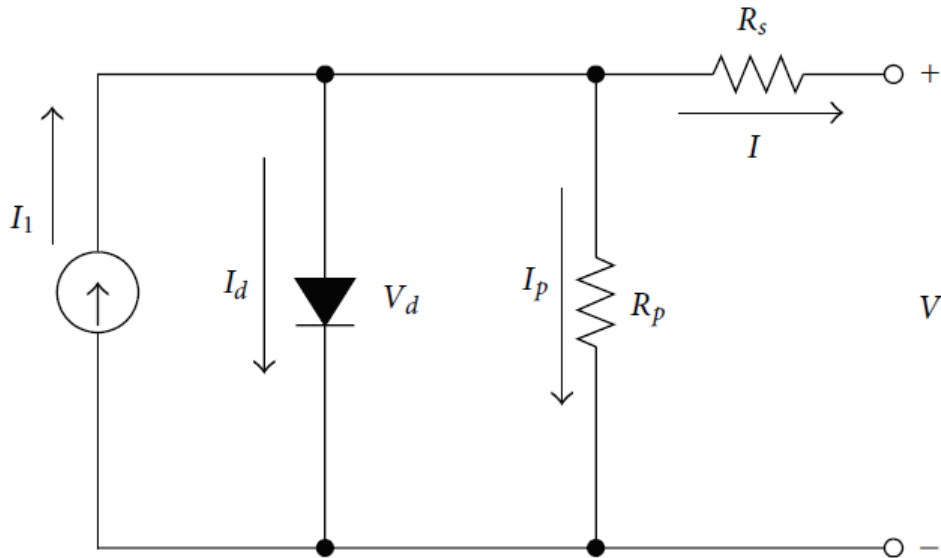
Figure 2-12- Equivalent Circuit of a solar cell [28]

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 photos and "jump" up to the conduction band producing a current. [29] [30]

The total current which flows out of the solar cell can be calculated by Kirchhoff's Current law at the top node: [31]

$$I_{cell} = I_l - I_d - I_p \qquad \text{(2-2)}$$

Where:

- I_{cell} - is the current flowing out of the cell
- I_l - is the photocurrent source
- I_d - the diode current
- I_p - the current flowing through a parallel resistor caused by a flowed P-N junction

The current produced by the photocurrent source is given by the equation:

$$I_l = [I_{SC} + k_i(T_s - T)]\frac{S_i}{1000} \qquad (2\text{-}3)$$

Where:

- I_l - is the photocurrent source
- I_{SC} - is the short circuit current at 1,000W/m^2 and 25 degrees Celsius
- T_s - is the surface temperature of the solar cell
- S_i - is the irradiation incident on the solar cell
- k_i - is the temperature modification coefficient for the short circuit current

In Baetens studies he utilized the formula below derived from Figure 2-12 for the instantaneous power produced by PV: [29] [30] [31]

$$P_{PV,ins} = I_{cell}V \qquad (2\text{-}4)$$

And:

$$I_{cell} = I_L - I_0\left[exp\left(\frac{V + I_{PV}R_S}{a_{ref}}\right) - 1\right] - \frac{V - I_{PV}R_S}{R_{sh}} \qquad (2\text{-}5)$$

Where:

- P_{PV} - is the instantaneous power produced by the cell
- I_{cell} - is the current produced by the cell
- V - is the voltage of the cell
- I_L - is the light generated current
- I_0 - is the reverse saturation current of the diode
- R$_s$ - is the series resistance of the cells
- R$_{sh}$ - is the shunt resistance of the cells
- a$_{ref}$ - is the modified ideality factor for compensation of second-order effects depending on the cell

The above formula 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. [32] Instead Borowy in his calculations for average power used the Beta and Weibull functions with the formula: [33]

$$P_{PV,avg} = \int P(S) * f(S).dS \qquad (2\text{-}6)$$

Where:

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

While Borowy used the probability function to calculate the average power produced per period. Zahedi used the formula below to calculate the production of kilowatt hours of energy produced for a solar system. This formula uses the calculated solar irradiance for a given region. [34] 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. [26]

$$P_{PV,avg}(kW) = size(kW) * PSH * PR \qquad (2\text{-}7)$$

Where:

- P_{PV} - is the average power produced in kWhr
- $size$ - is the size of the system in kW
- PSH - is the peak sun hours
- PR - is the 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. [29] [30] [31]

When a solar cell becomes shaded it stops being forward biased, stops producing current, it "turns off" and current stops flowing. 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. [35]

$$I_{substring} = I_{cell} \tag{2-8}$$
$$V_{substring} = N_s * V_{cell} \tag{2-9}$$

Where:

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

Therefore, if we have a module comprised of 60 Silicone polycrystalline cells with an open circuit voltage of 0.6626 connected serially we would expect: [36] [28]

$$V_{substring} = N_s * V_{cell}$$
$$V_{substring} = 60 * 0.6626$$
$$V_{substring} = 39.75$$

Referencing the datasheet for a standard 250W GEM Series Solar Module from Sapphire Solar with 60 cells of Polycrystalline Silicone the Open circuit voltage is 37.1 volts. [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 silicone cell is shown for 33 samples in the below **Figure 2-13**. 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. [37]
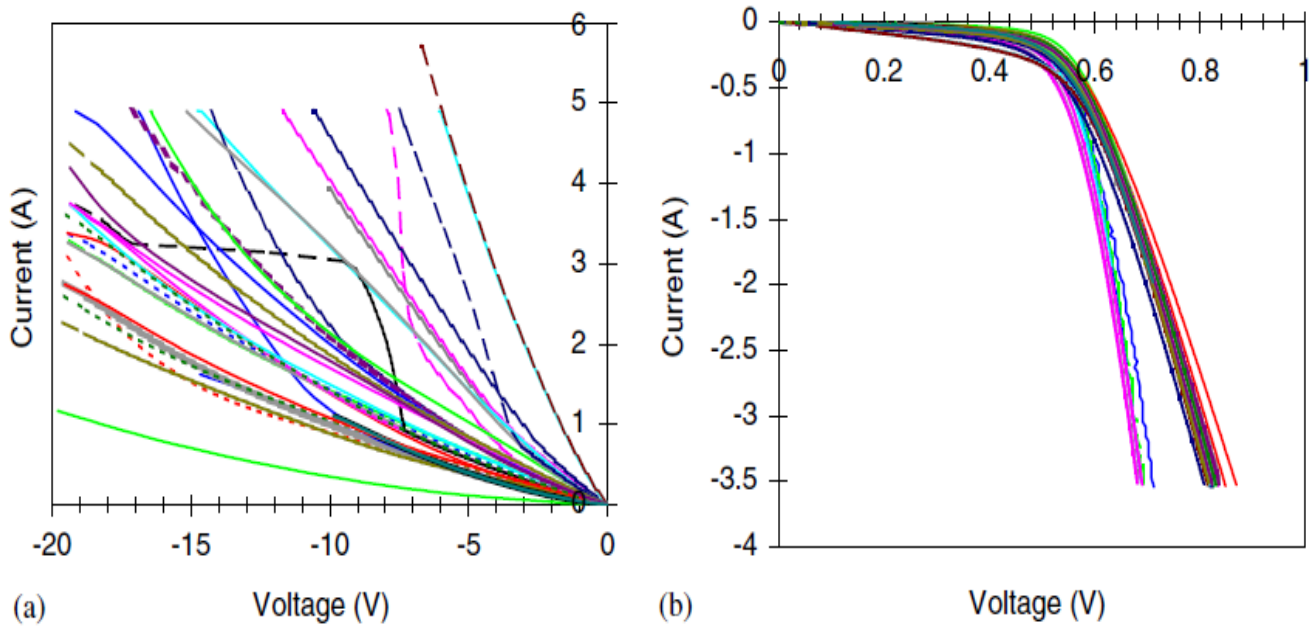
Figure 2-13 – *I-V Characteristic for Silicone 33 cells tested without Irradiance (a) reverse bias and (b) forward bias, at 22 degrees Celsius [37]*

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. Mohammod 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
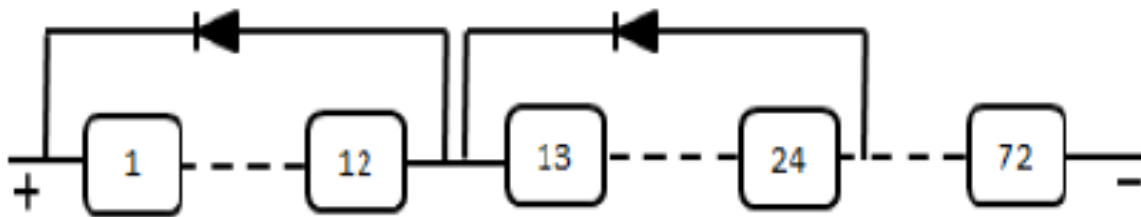
Figure 2-14 - Adding No-Overlapped bypass diodes [30]
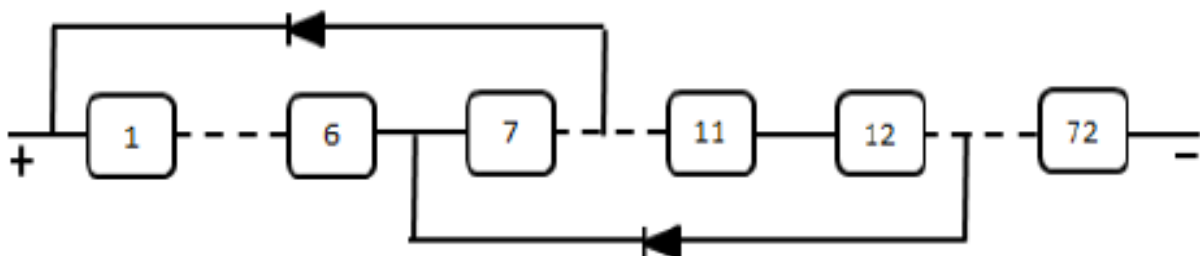
Figure 2-15 - Adding Overlapped bypass diodes [30]

will form. This open circuit in the series connected system stops all flow of current and the PV system will no longer function. [38] [39] [30] [35]

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. [38] [39] [30] Duong continues by saying that the configuration of the bypass diodes have an important influence on the possibility of a hot spot forming. Two common configurations are shown above in Figure 2-14 & Figure 2-15.
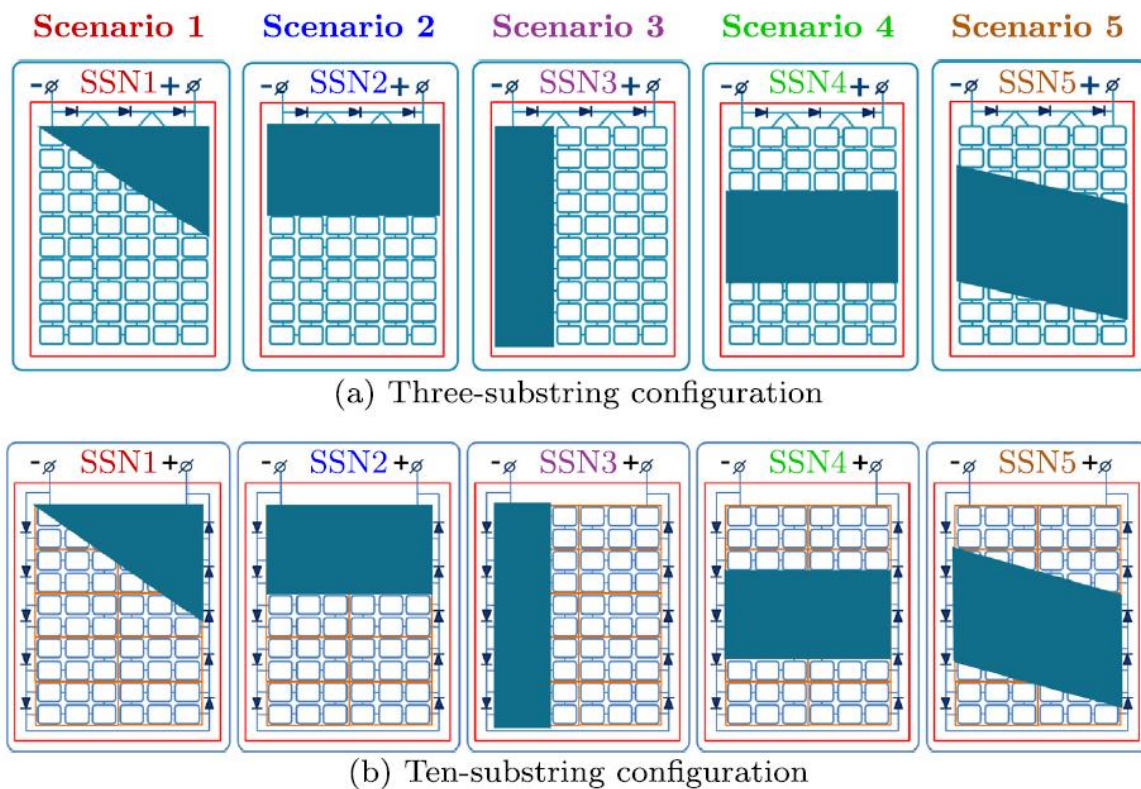
Figure 2-16 - Shading Scenarios used by Mai [38]

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. 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 account.

The interesting finding was that for a tropical climate the not-overlapped diode configuration was optimal. [39] 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 the Figure 2-17 below. [40] [38] [41]
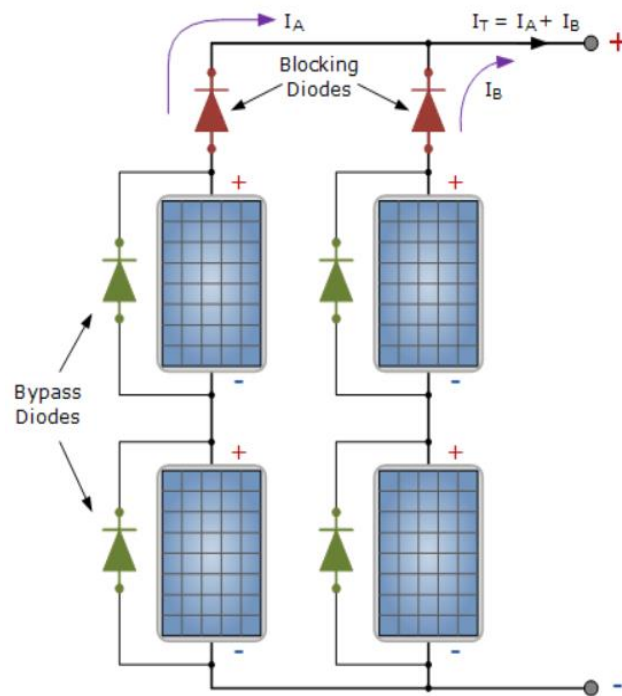
Figure 2-17 - Diagram of Bypass and Blocking diode functions [40]

2.3.7 Cost of Installation for PV

The cost of a solar panel installation varies due to three primary factors: [42]

- System Size
  - Generally, a 1.5kW system will produce a third of a households 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 special frames have to be installed they 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* below:

Table 2 - Approximate Cost of Solar Systems After Rebate in QLD [42]

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 1.5kW system will generate approximately 6.3kW of electricity per day. The Australian Government uses the number 18kW for the average household although later in this paper it is re-establish 20kW. Using this number we arrive at a 1/3 reduction in electricity price for a household with irradiance equivalent to Brisbane, Australia. [42]

2.3.8 Payback of PV

The advent of PV technology gives hope to sever the worlds dependence for its energy from fossil fuels. The obligations are outlined in the Kyoto protocol for the decrease of carbon dioxide and other gas emissions. While commenting on the lure of renewable technologies Rajoria raised the important factor of energy payback as a main criterion for comparison of energies. [43]

Knapp agrees with Rajoria and notes that the query translates into one key sense, 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. [44] The EPBT is an equivalent for a 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. [45] [46]

$$EPBT = \frac{(production\ energy\ requirements)}{(power\ rating)(insolation)}$$

(2-10)

Where:

- $production\ energy\ requirements$ – the gross energy required to produce the product ie.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 stand alone 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 silicone PV rooftop system in 2005 the EPBT was calculated by Peharz at 3 years. [47] [44] Sampiao has validated the figures of 0.7 to 2 years for EPBT of PV subject to technology and location. Sampio provided the below **Figure 2-18** for EPBT decrease.
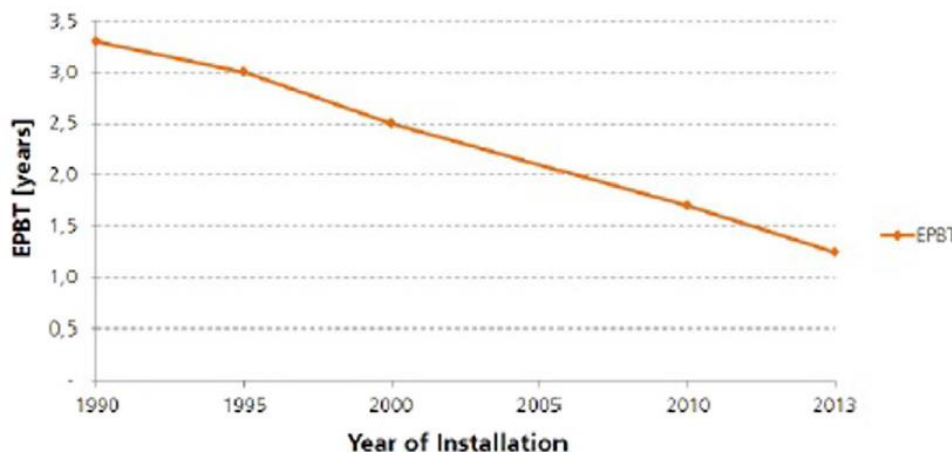

Figure 2-18 *-Historical trend in times of Energy Return (EPBT) of photovoltaic modules of crystalline silicon [44]*

2.4 Inverter System Technologies

An Inverter, Converter, Solar Inverter, or PV Inverter is an electrical device which converts 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. [48]

The inverter system in its most basic form can be organized 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: [49]

- 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 suppliers 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 suppliers 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) – is 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". [48]
- Anti-Islanding – is 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 MMPT algorithms and realizations, multilevel topologies, soft switching, output filter optimization and silicon carbide semiconductors. [50]

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 the 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. [1] This protection is in the form of undervoltage, overvoltage, under-frequency and over-frequency is outlined in the **Table 3** below. [51]

Table 3 - *Passive Anti-Islanding Set-point values [51]*

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

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[1] The typical installation wiring for a grid tie inverter system as described in AS4777 is given in the appendices.

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. [52]

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 whence it is created to when it is utilized as shown in the below Figure 2-19. [53]
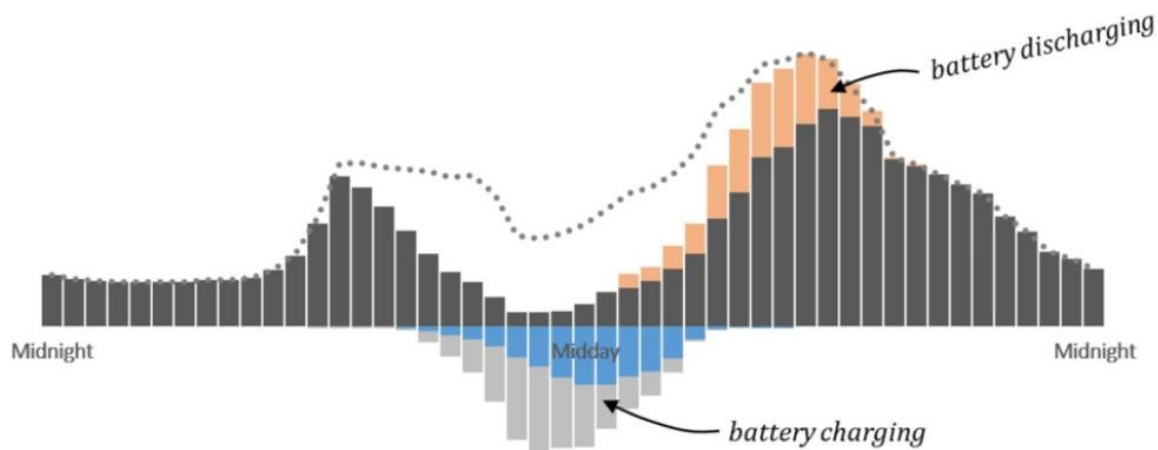
Figure 2-19 - Graphical view of potential offset with BES [53]

The two 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 4-13.2kWhr 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 lapse in time it seems reasonable. [54] The retail price for a 10kWhr LG RESU is $9,700.00AUD, a 10kWhr ZBM2 is $10,600AUD and a 13.5kWhr Tesla Powerwall 2 is $8,750AUD.

Battery Energy storage systems are costly, but with a government subsidy or rebate they become readily and economically viable. This is an acceptable proposition as the following 1st

July 2016, Adelaide in South Australia have in effect the 50% of the installed system cost up to a maximum of \$5,000 for battery energy storage systems. [55]

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 during 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. [56]

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. [33] Optimal charging and discharging of a battery is dependent on the batteries characteristics and condition. The following is an explanation of battery nomenclature which affect its production and storage. [57]

A PV system is not charging constantly but changes with solar irradiance and temperature. Shen summarized 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. [57] The energy stored on any day is given by the equation:

$$E_B(n) = E_B(n-1) * (1 - \eta_s) + \left(E_{pv}(n) - \frac{E_L(n)}{\eta_{inv}} \right) * \eta_{batt} \qquad \text{(2-11)}$$

Where:

- $E_B(n)$ – is the energy stored in the battery on nth day (present day)
- $E_B(n-1)$ – is the energy stored in the battery on nth-1 day (day before)
- η_s – is the daily battery self-discharge rate
- E_{pv} – is the energy generatred by the solar arry on the nth day
- η_{inv} – is the efficiency of the inverter
- η_{batt} – is the efficincy of the battery

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

$$E_{B(min)} \le E_B(n) \le E_{B(max)} \qquad \text{(2-12)}$$

Where:

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

The $E_{B(\text{min})}$ 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. [57]

$$E_{B(min)} = (1 - DOD_{max}) * C_{batt} \qquad (2\text{-}13)$$

$$1 - DOD_{max} = SOC_{min} \qquad (2\text{-}14)$$

Therefore,

$$E_{B(min)} = SOC_{min} * C_{batt} \qquad (2\text{-}15)$$

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

The 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 formula: [57] [58]

$$SOC(n)\% = \frac{E_B(n)}{C_{batt} * V_{rated}} * 100 \qquad (2\text{-}16)$$

The 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. [59] Batteries can suffer by 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: [58]

$$SOH\% = \frac{E_B(n)}{E_{rated}} * 100 \qquad (2\text{-}17)$$

Where:

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

2.6 North Queensland 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. [60]

Australia is situated approximately in the middle of the tropic of Capricorn at 23.5 degrees 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 below in Figure 2-20 and was taken from the Bureau of Meteorology website. [61]
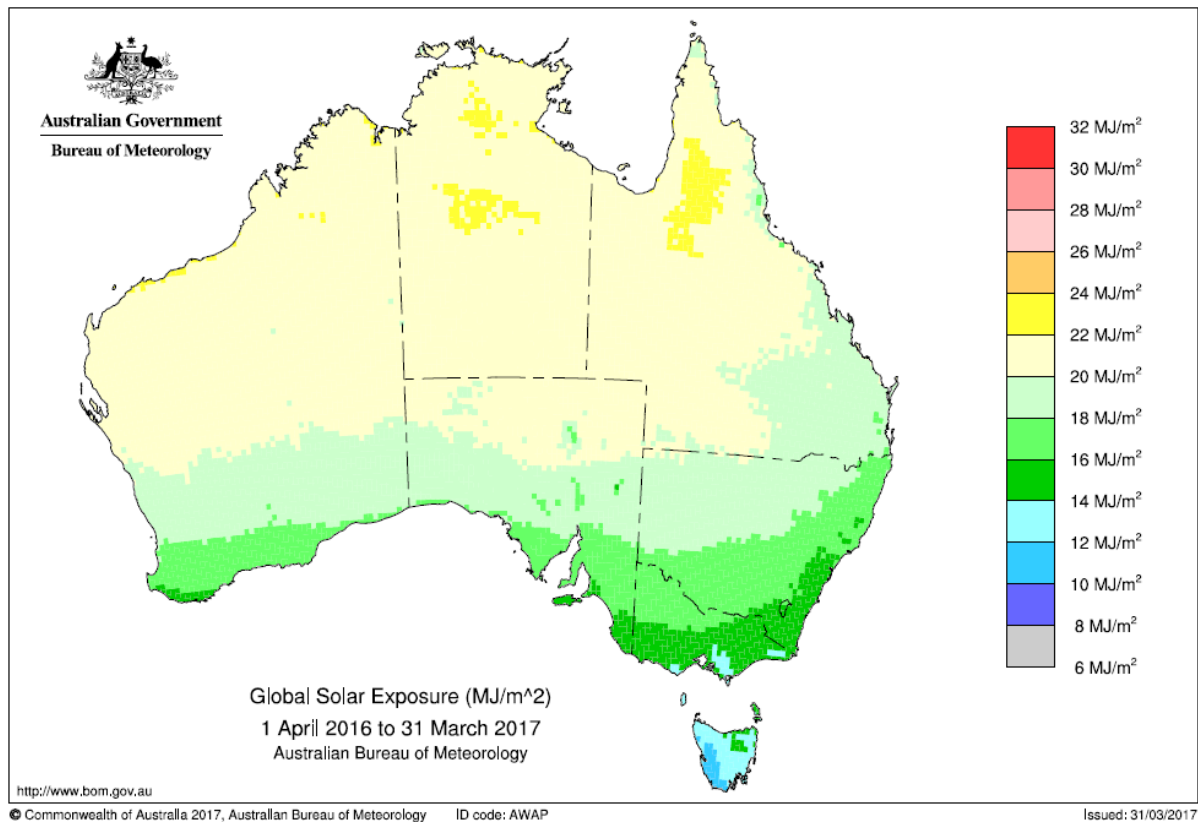
Figure 2-20 - Australian Solar Irradiance [61]

The Figure 2-20 above shows that Townsville experiences approximately 22MJ/m^2 of solar energy each year with approximately 300 days of sunlight. [62] Townsville experiences high levels of solar radiation throughout the year due to its high solar elevations and low total ozone columns. [63] This 22MJ/m^2 is a yearly figure and consequently from the tilt of the Earth's axis it varies as shown in the *Figure 2-21* below. 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.
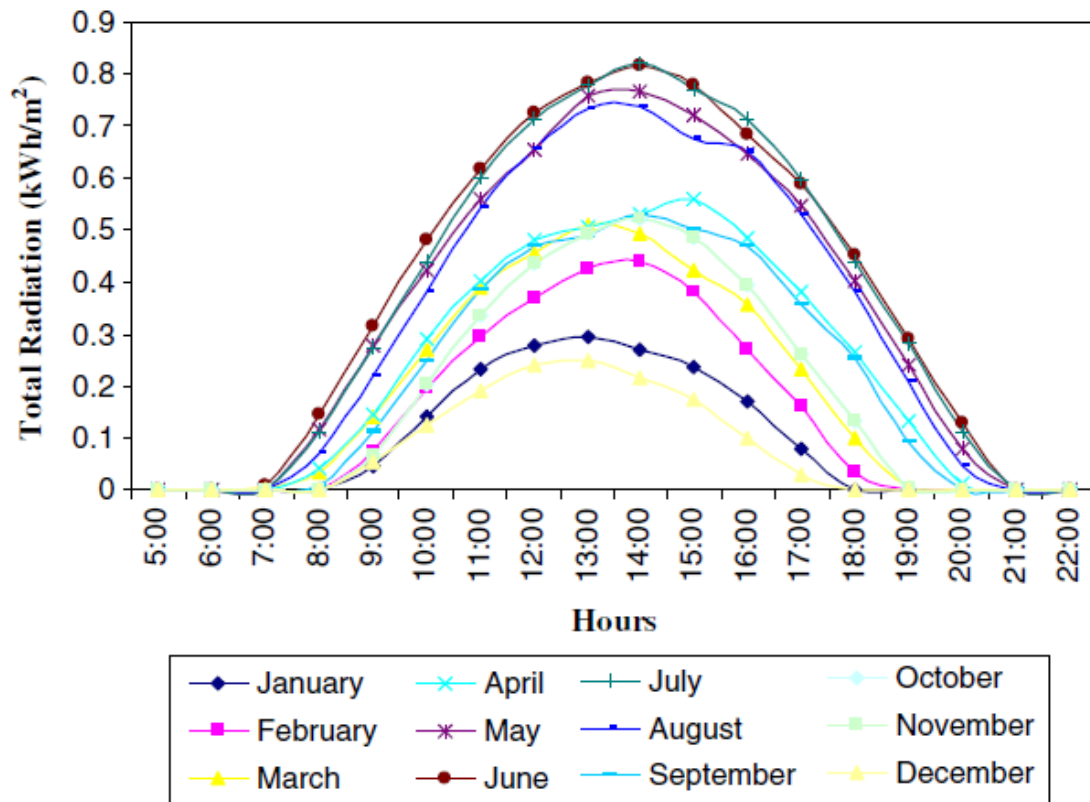
Figure 2-21- Average hourly total solar radiation on horizontal surface (measured) [63]

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 **Figure 2-22** show higher amounts of solar radiation due to pitch and orientation.
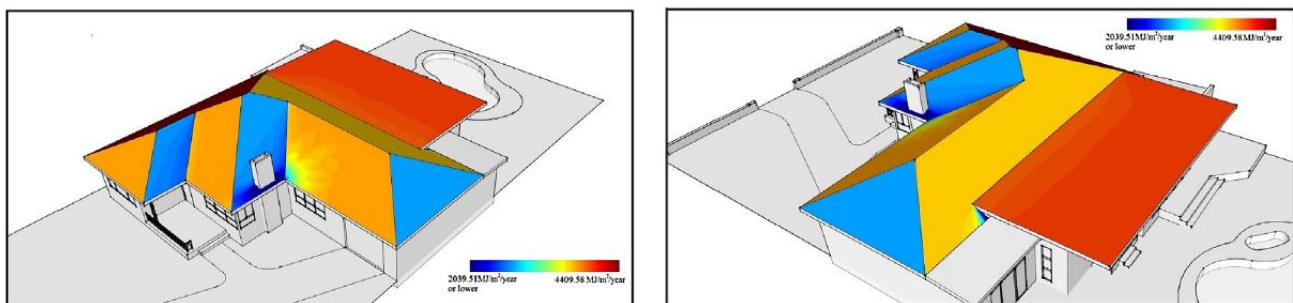
***Figure 2-22** - 3D annual radiation map of pitched roof from south-eastern view (left) and north-eastern view (right) [9]*

2.7 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 though transmission lines. [24] 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 Queensland, 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 stake holders. [64]

The NEM supplies energy to Ergon Energy who are both a retailer and a distributor and play a relatively minor role in generation. Ergon Energy supplies electricity to Queensland with a service area of 97% including Townsville as shown in the Figure 2-23 right. [65]
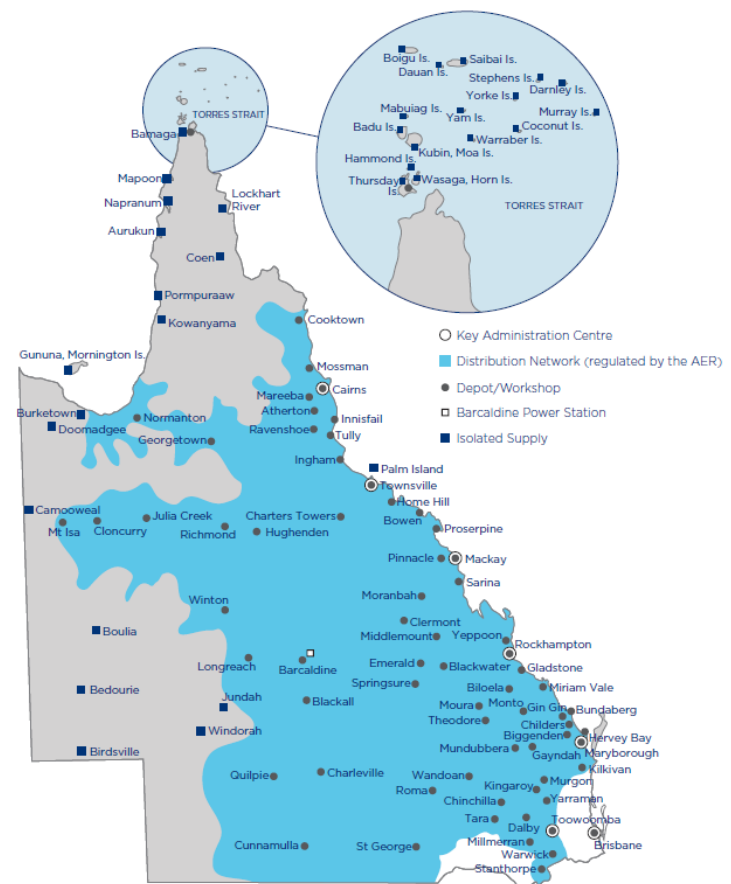
Figure 2-23- Ergon Energy Service Area [65]

2.8 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 after returning home from work and are preparing dinner, cleaning and using the lighting and air-conditioning the load increases again. This spike at the end of the day reduces as they go to bed and this profile repeats daily.

There are many variables which can affect this general load profile such as temperature, living arrangement, holiday seasons and PV. [66] 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.
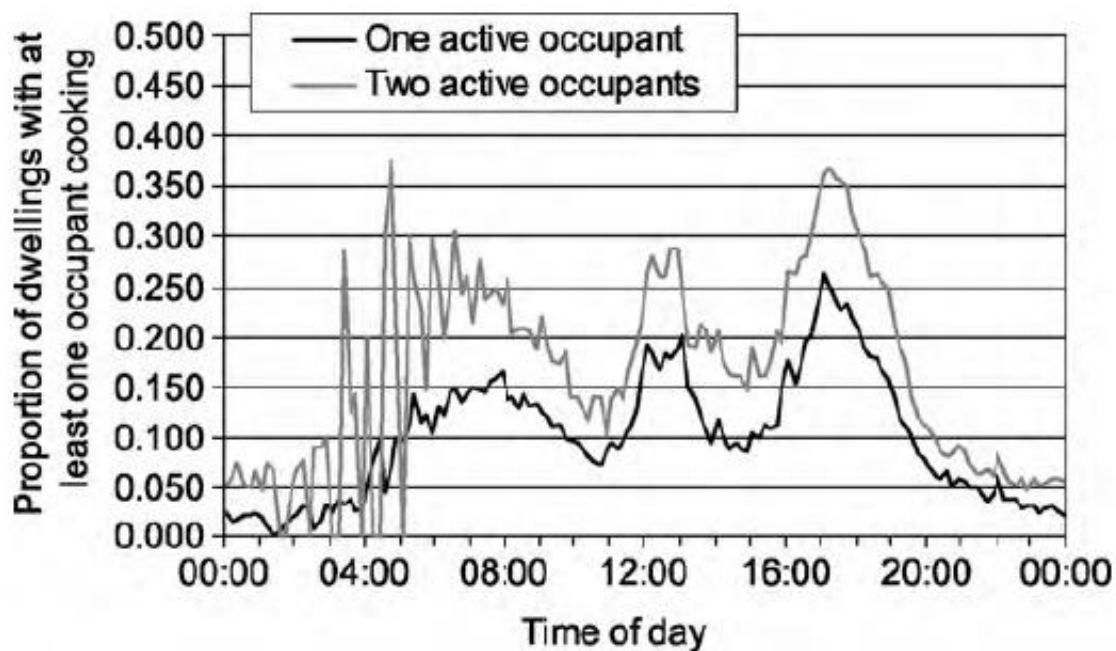
Figure 2-24 - Activity profiles for 'cooking'', for one or two active occupants on a week day [66]

From the above **Figure 2-24** 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 fed-ins produce a greater degree of volatility. Hoffmann noted that fed-in energy from PV systems

have the potential to disrupt the network and the networks ability to stabilize itself. The below Figure 2-25 is the typical load profile during the course of the day for an office building. [67]
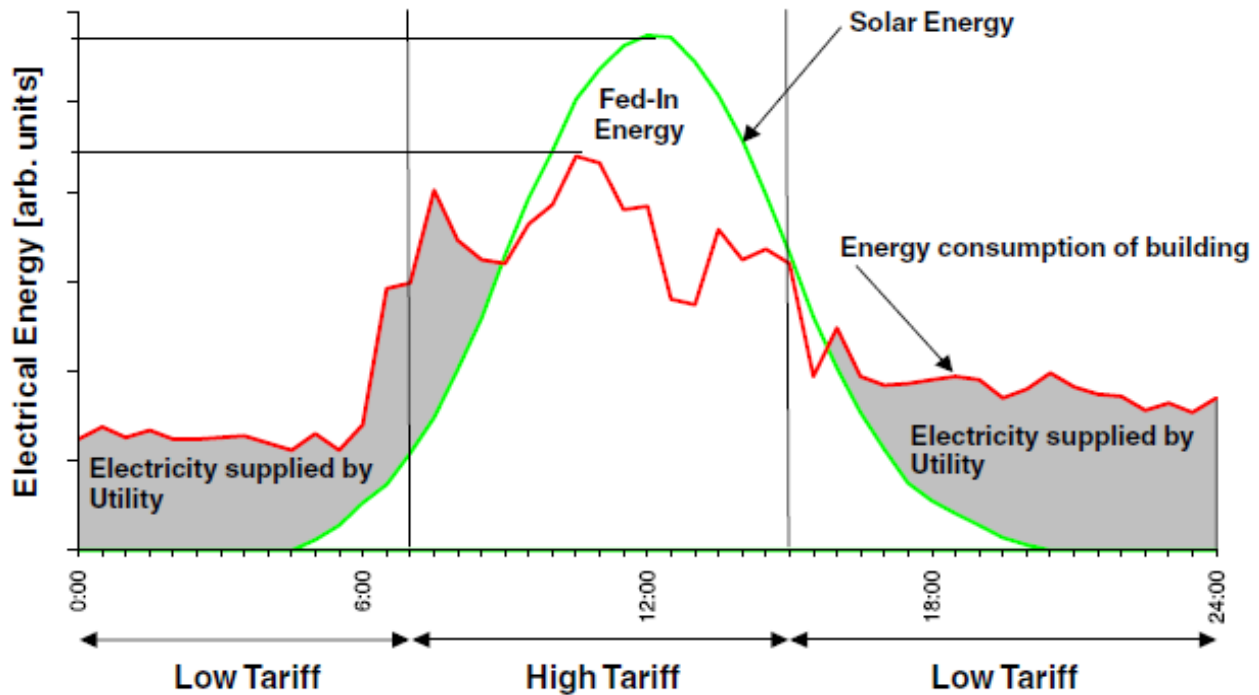
Figure 2-25 - 24hr Energy Profile [67]

The above figure 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. The below Figure 2-26 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. [68]
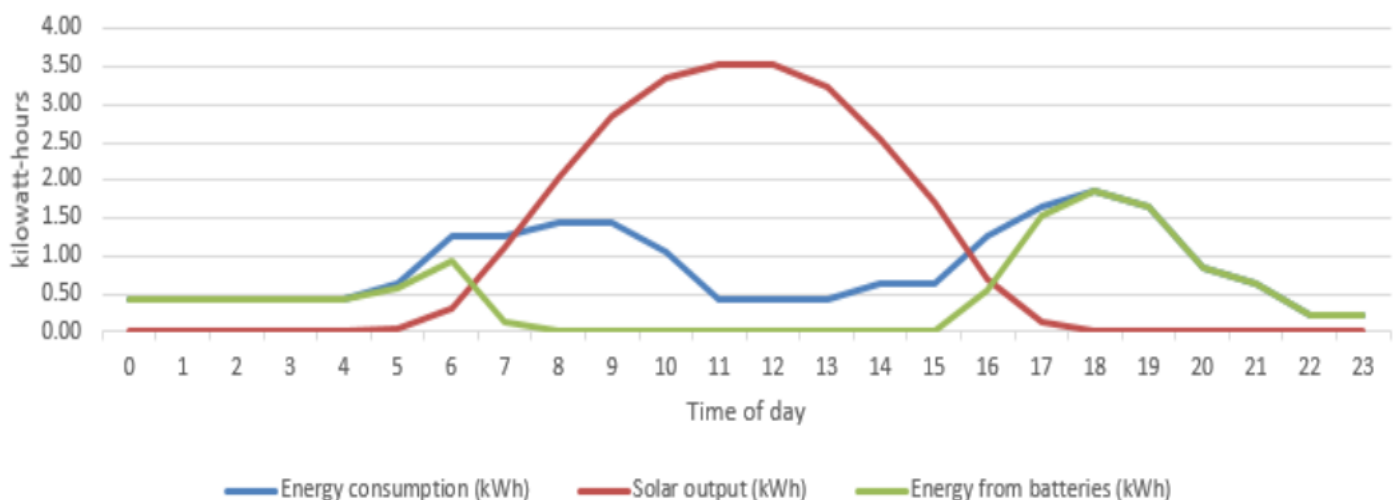
Figure 2-26 - Standalone Household Consumption Load Profile [68]

2.9 Network Demand Challenges

Ergon Energy is constantly monitoring this 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 below Figure 2-27 is from Ergon Energy at the Dundowran Feeder in Hervey Bay (Qld) and illustrates how PV has affected the load profile. [69] It shows a reverse flow during the middle of the day at approximately 12:30pm in 2015.
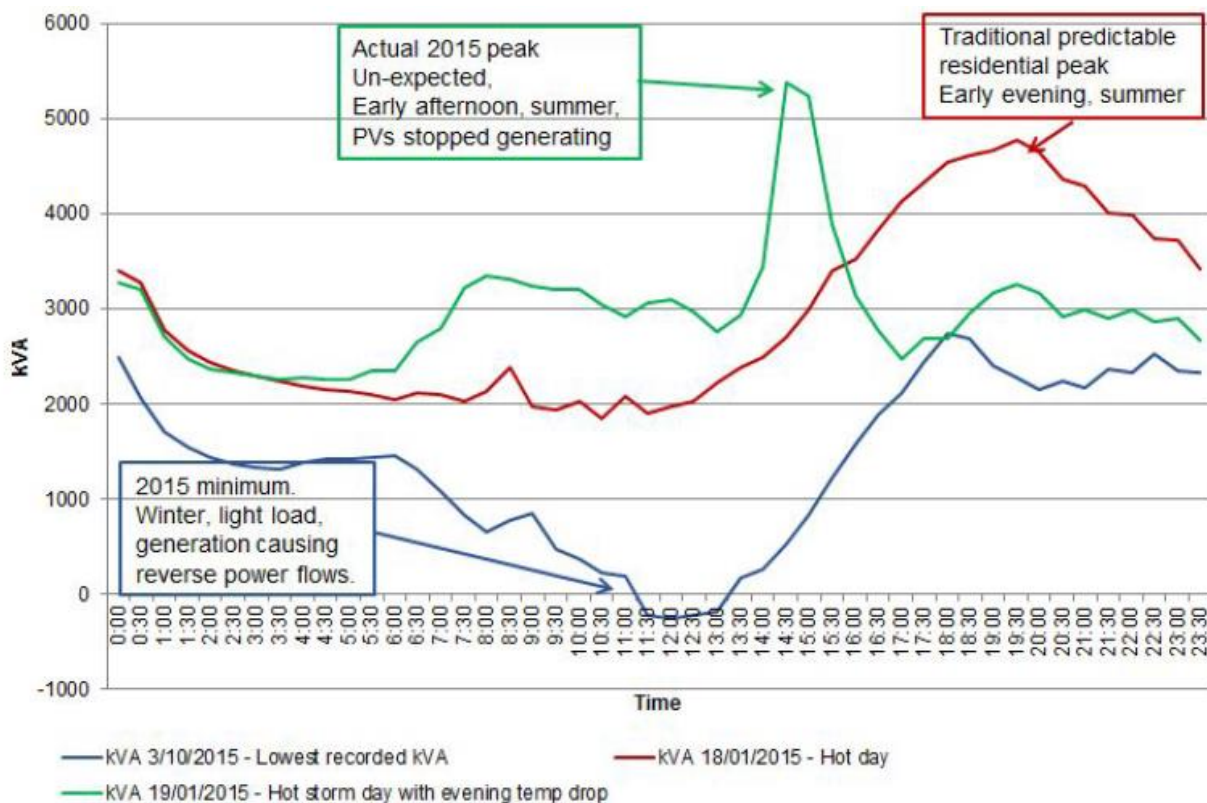
Figure 2-27 - Dundowran Feeder Load Profile [69]

The Planners at Ergon Energy need to identify issues with feeders and disruption which may occur with the grid. In the above Figure 2-27 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. [69]

2.10 Tariffs and Rebate Change

An electricity meter is a device used by the 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 of usage. The below **Table 4** lists the different residential tariffs; tariff 11, tariff 31, tariff 33 and the solar fed-in tariff. [70]

Table 4 - Electricity Pricing Information [70]

Tariff 11 Residential - 1 Jul to 30 Jun All usage. Anytime.	Price (exc. GST)	Price (inc. GST)
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
Controlled load **Tariff 31 Night rate (super economy)**	Price (exc. GST)	Price (inc. GST)
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
Tariff 33 Controlled supply (economy)		
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
Solar feed-in tariff options		
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 Queensland Solar Rebate Scheme was an incentive introduced in 2008 for customers who applied before the 9th July 2012, and allowed a feed-in tariff rate of 44 cents per kilowatt hour. [71] The scheme expired on the 1st July 2012 and for persons still receiving the tariff it is substantially higher than the current 7.448 cents/kWhr. The current feed in rate is less than one third for what is paid for the general usage Tariff 11 of 27.071 cents/kWhr. The low feed in tariff rate is beneficial to Ergon the electricity supplier as they are effectively purchasing the power at 7 cents and kilowatt hour and selling it to the person next door for 27 cents per kilowatt hour. This is creating them 20 cents per kilowatt hour 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 electricty is consumed or delivered. [71]

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, 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. [72] [31]

Ergon Energy, Queensland'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. [73] They further reinforced this by saying many Northern Districts have up to 73 per cent more electricity consumption in Summer compared to Winter and Autumn seasons. The Figure 2-28 below highlights the stark contrast in consumption between Winter and Summer months.
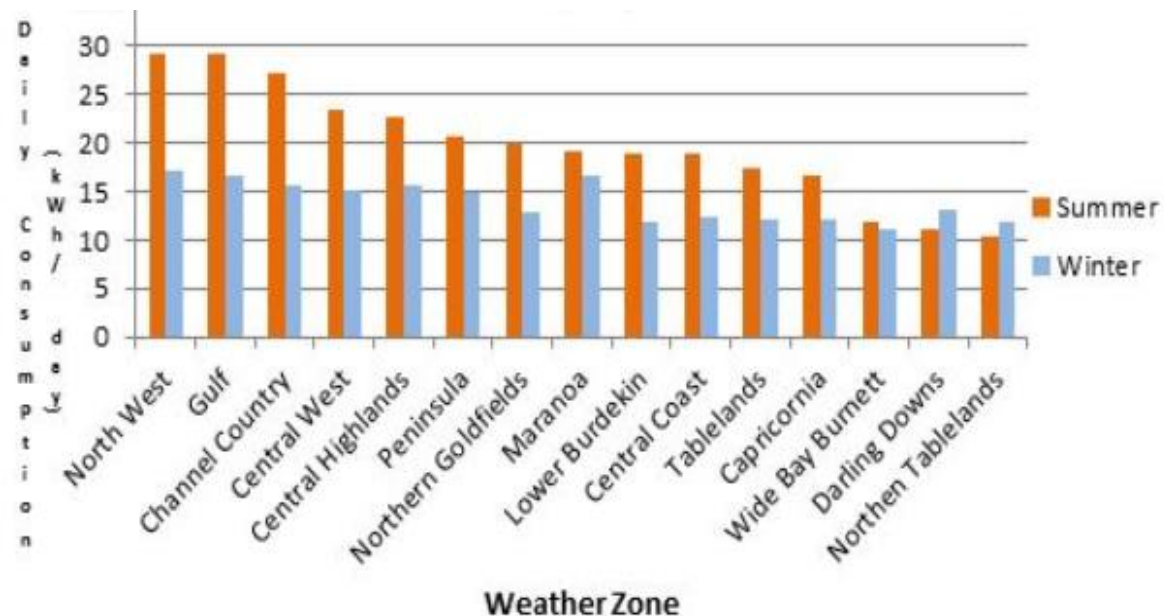
Figure 2-28- Tariff 11 kWh/day - Summer Vs Winter [73]

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 15th of August 2015 to the 16th of August 2016 with Tariff 11 and 33 was averaged to a 21.01 kWhr per day with 2216kWhrs from February to May. This was in accordance with the Australian Government website "Energy Made Easy" that estimated 20 kWhr per day and 1804kWhr total in Summer for a household under those conditions with that postcode. [74]

2.11 Economics of PV & BES System

Solar PV and BES technologies give consumers the ability to mitigate the cost of their electricity bills. Although the economics behind a PV/BES installations are broad with many underlining variables which may affect the feasibility and returns. There are several models which are available to access and evaluate the performance of PV and BES systems. [75] [76] [26] 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 and 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 below and illustrated in Figure 2-29:

- Solar Panels
- Inverter
- Battery
- Electricity tariff structure
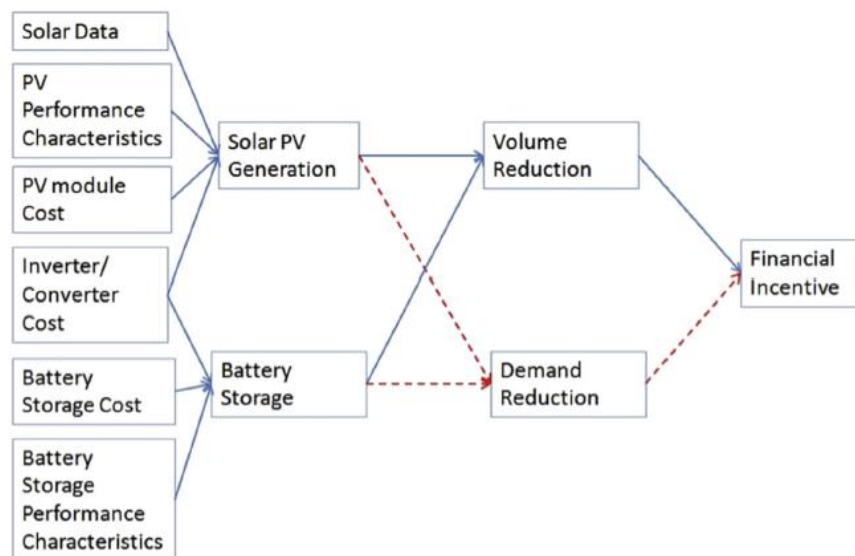
Figure 2-29 - System Variables and Saving Mechanisms [22]

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 periods. If the government offers a rebate scheme for the installation of solar impacts payback periods. The time value of money must be mentioned as a cash lump sum payment against a financed scheme must be assessed for returns.

2.12 Market Software Competitors

There are software programs currently on the market which utilize 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. There are currently several free programs which are available on the internet. They can be used to give indication to a potential customer the metrics for their installation and prospective returns.

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, operational pool or spa, if there are gas mains and when most of the electricity is consumed. Three of these programs will be analyzed below and commented upon for user navigability, accessibility and aesthetic appeal:

2.12.1 Solar Power Calculator

https://solarcalculator.com.au/
This is the best of the three options. Offering a visually appealing graphical user interface with simple inputs. It gives the customer a graph and return on investment.
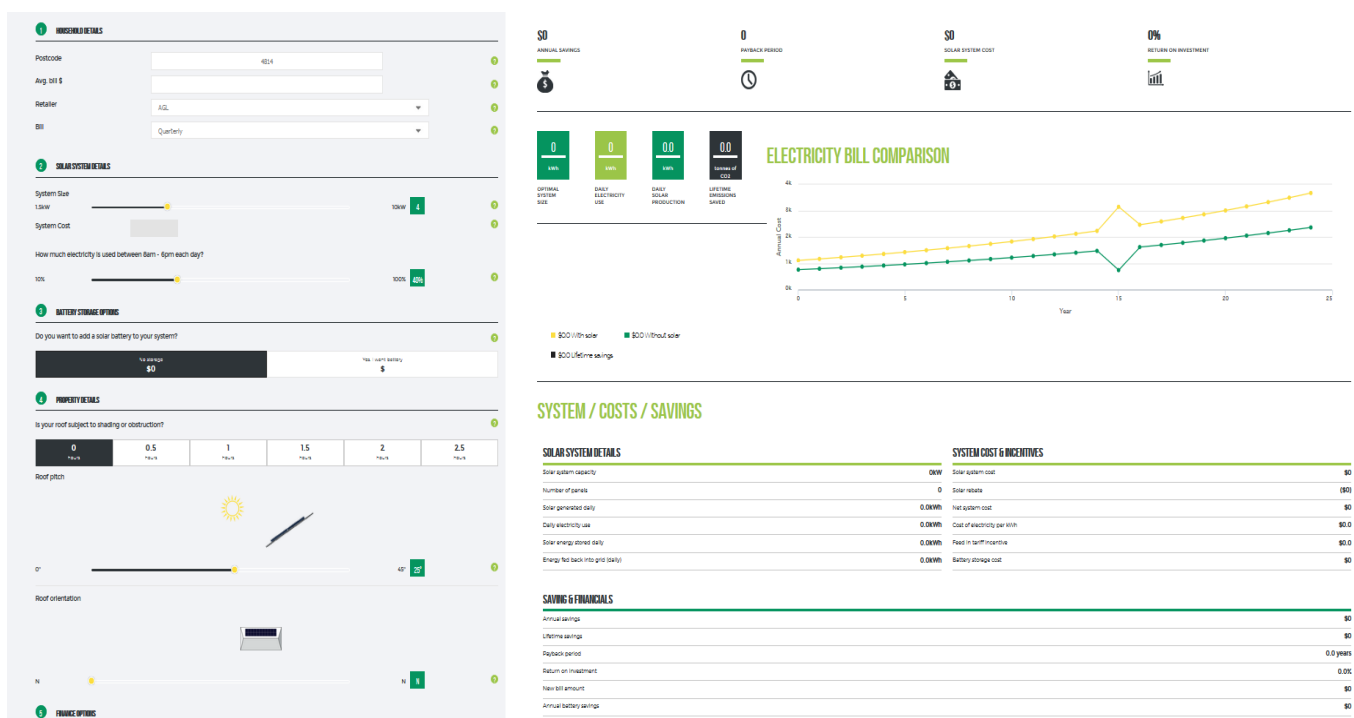
Figure 2-30 - Solar Power Calculate GUI

2.12.2 Solar Choice Solar & Battery Storage Sizing & Payback Calculator

https://www.solarchoice.net.au/blog/solar-pv-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 visualize the impacts of battery impacts.

Figure 2-31- Solar Choice GUI

2.12.3 Solar Savings Calculator

https://www.solarmarket.com.au/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 analyzed programs and has a good GUI.

Figure 2-32 – Solar Savings GUI

2.12.4 Hybrid Optimization Model for Multiple Energy Resources

The current market leader for modelling of renewable technology systems is a design tool called the Hybrid Optimization Model for Multiple Energy Resources (HOMER) [77]. HOMER is a microgrid software developed by HOMER Energy and is currently the global standard for optimizing microgrids. HOMER has been successfully implemented in the design and optimization of military bases, grid connected campuses island communities and village power.

HOMER allows the comparison of thousands of possibilities to compare and access impacts of multiple variables such as wind speeds, fuel costs, solar irradiance and demand changes. There are heuristic techniques and algorithms embedded into the system which aids analysis. HOMER is a bulk processing tools which allows the simulation of a microgrid from time intervals of one minute for an entire year. [78] The interface for HOMER is shown below in Figure 2-33.

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

- Biomass
- Hyrdo
- Combined Heat & Power
- Advanced Load
- Advanced Grid
-

- Hydrogen
- Advanced Storage
- Multi-Year
- MATLAB Link

Figure 2-33- HOMER GUI [77]

2.13 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 keys 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 minimize strain and stabilize demand peaks has enormous potential. The next question is what is the optimal size for reasonable stability with a positive maximized 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. [63] [9] While Jardini, Tonkoski, and Paatero have each conducted studies for the load profiles of domestic residential households and annual daily power consumptions. [79] [80] [81] Individually Faxas and Riahi made models for priority load control algorithms optimizing energy management systems. [75] [82] The efficiencies of different types of solar cells were explored by Edalati. [83]

The efficiencies of both inverters systems and BES systems have been modelled by Kandatsu. [84] Zahedi submitted an interesting paper on the differing effects of different tariff schemes in Australia. [85] There has been extensive work with the life cycle assessment and economic analysis of low concentrating PV systems by De Feo and Petitio respectively. [86]

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 optimized 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 optimized 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 was 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 hybridized system which helped reduce peak demand and stabilized 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.

Despite the limited literature and access to programs for optimization and upgrades this thesis will investigate the optimization and deployment of sufficient models to size and optimize PV and BES systems. These models and program will be suitable for different residential households to provide maximum return on investments and minimize disruptive outputs to the grid. Three models will be created in a GUI for a MATLAB program each with 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 Ergon reduce peak demand to create a more stabilized and reliable electricity network for Australia. [22]

3 METHODOLOGY

The aim of this chapter is to discuss the methodology and techniques which will be employed to address the issues raised in the Literature Review. There has been extensive research into the field of PV and BES technologies in the Literature Review, in order to find the gaps in the existing body of knowledge, and where improvements and further research was necessary. This thesis will design and implement a commercially acceptable PV installation modelling program with a GUI in MATLAB. This methodology will develop criterion for the programs testability and was selected from several proposed methods. The layout will be split into several different
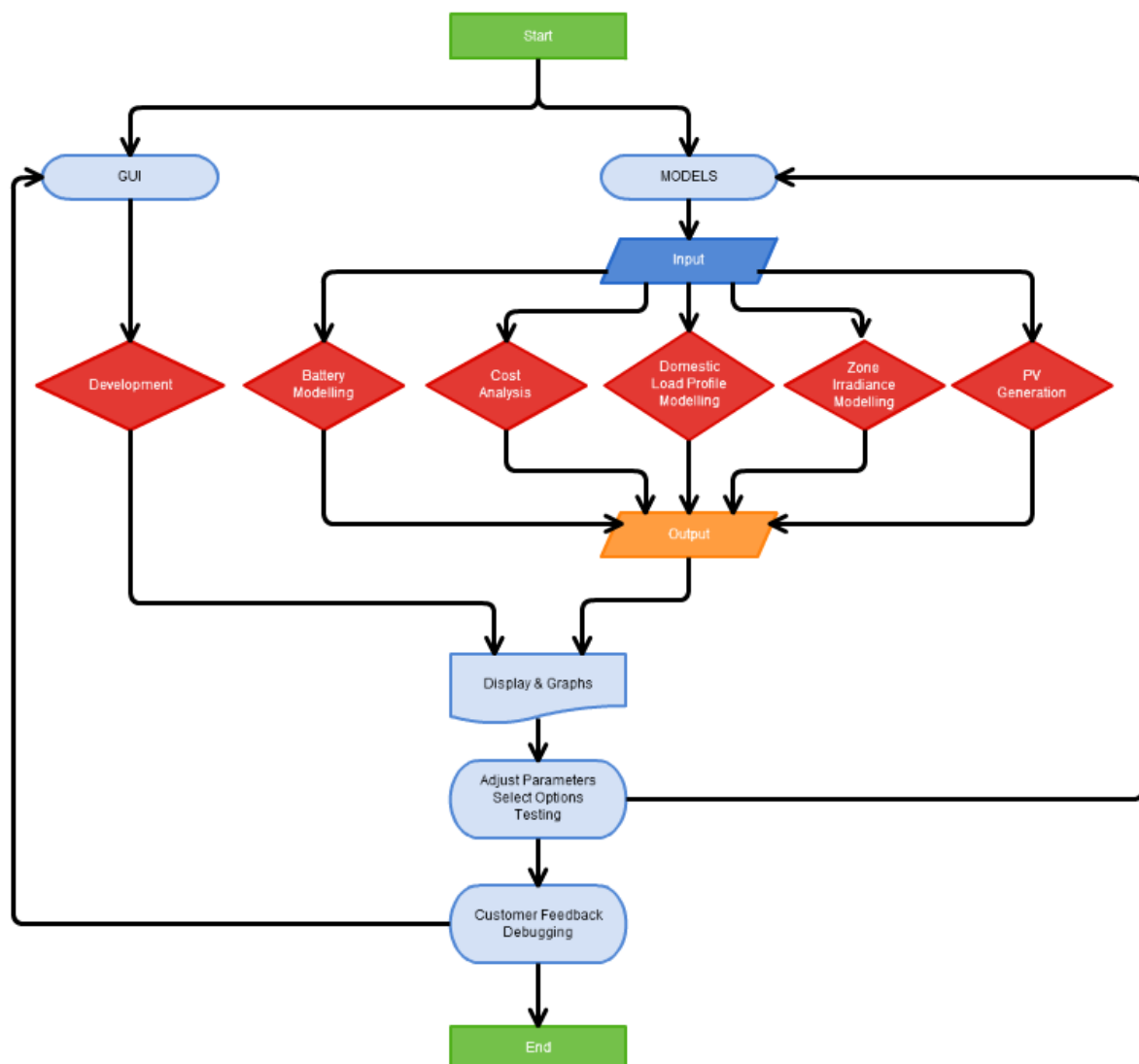
Figure 3-1 - Illustrated Scope of Works for Program Design

phases for ease of explanation and measurable progress milestones. The program is to host varying inputs for subsequent outputs while creating three conditions which will be addressed

in greater detail in the proceeding chapter. One of the outputs for the program will be an economic assessment of the conditions with the corresponding economic climate.

The project will be 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 will be recommended in further research but is beyond the scope of this thesis. The substitution for simulations and comparative analysis was a reasonable trade off as there is minimal loss of accuracy and this technique has been utilized often and reduces external errors. The development of the program is illustrated in the above Figure 3-1. The illustrated Figure 3-1 shows how each section can be developed individually and incorporated into the finished working program.

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 as which to conduct this thesis. Matlab will be used to realize the different phases of this paper and host the GUI for operation.

3.2 Description of Functionality

The aim of this thesis is to develop a program to size and optimize PV and BES systems for different configurations of household demand, to maximize savings and 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.

Three models will be created in a GUI for a MATLAB program 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 stabilized and reliable electricity network for Australia.

There are three models which will be discussed in greater detail in each of their respective headings. The first is effectively an enticer or market entry for persons whose sole incentive is an investment with maximized returns. A flow chart of the systems overview can be seen in the below Figure 3-2. The flow chart shows the customer inputs, the models and algorithms, the output options and the output parameters. There is also an advanced input parameter tab for a more detailed assessment.

The second model is the grid stabilization scheme which will be proposed to Ergon and at a governmental level for prospective budget or backing. The grid stabilization scheme will develop a model for the optimized battery-to-panel ratio. This model will smooth the energy taken from the grid.

The third model will be the optimal sizing for a standalone PV system. This is dependent on the demand requirements of the household the optimal number of solar panels and battery size will be selected.
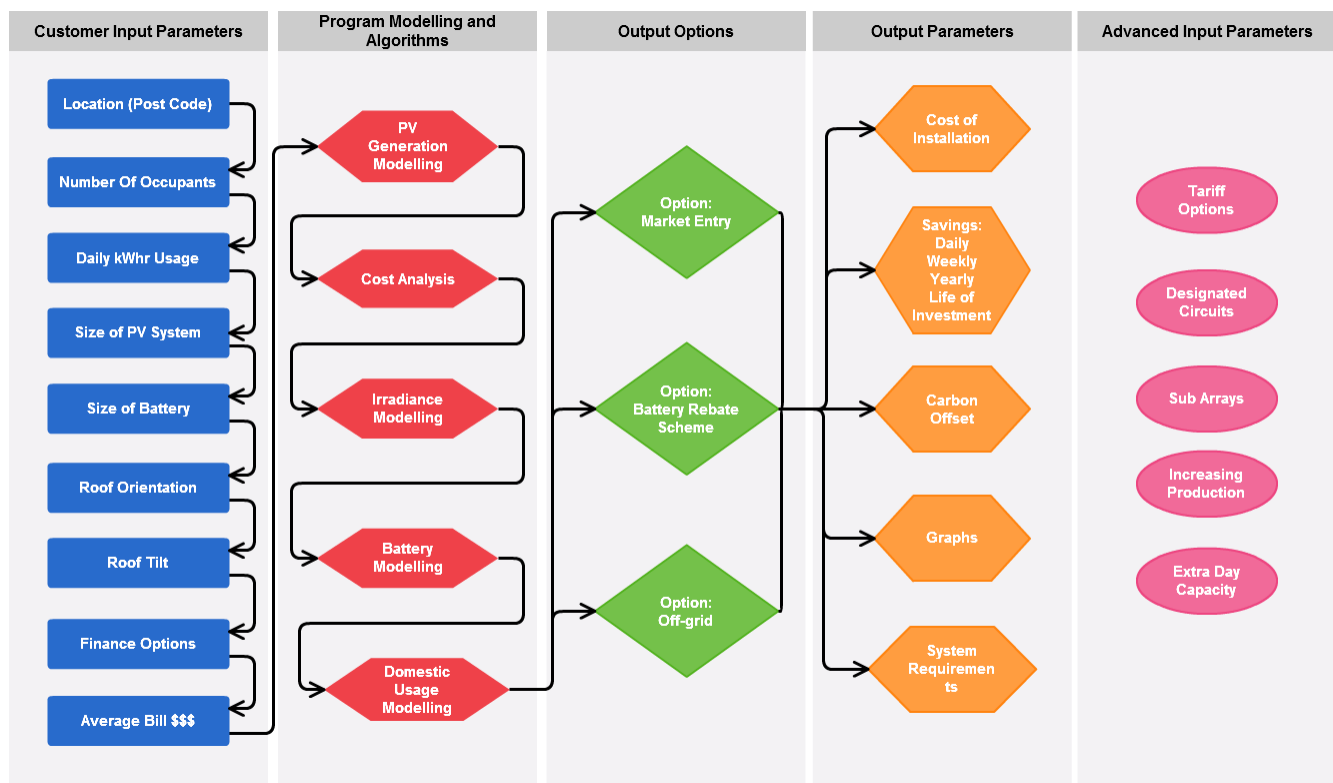
Figure 3-2 - Program Overview

3.2.1 Market Entry – Maximum Return

The Market Entry option is effectively an enticer or market entry for persons whose sole incentive is an investment with maximized returns. This will evaluate the cheapest installation costs and equipment. Depending on the value of daily demand and system sizes, will produce the optimized level of panels to battery ratio for the best return.

3.2.2 Incentivised Grid Stabilization Scheme

The second option is the grid stabilization scheme which will be proposed to Ergon and at a governmental level for prospective budget or backing. The underlying goal of this research is to provide a sound basis for a proposal to the government and Ergon for funding. This is an acceptable proposition as of the 1st July 2016, Adelaide in South Australia already have in effect a rebate of 50% of the installed system cost up to a maximum of $5,000 for battery energy storage systems. [55]

3.2.3 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 or remote small low power operations which are entirely run on renewable energy.

3.3 User Parameters

3.3.1 Input Parameters

The input parameters are values which are entered into the program via the GUI. This allows an individualized assessment of every system to allow for unique differences. The input parameters will be 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.

3.3.1.1 Basic Input Parameters

The value which will be input first is the area post code. This allows for the program 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 kW or instead a quarterly bill kW/dollar can be input. This average would have been checked and if it is out of a certain tolerance an alarm will be displayed 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 there any shading during the day and for how long. The next input is if battery storage is wanted; what size and cost.

3.3.1.2 Advanced Input Parameters

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 stabilization for a battery rebate and for a standalone system.

3.3.2 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.

3.4 Graphical User Interface

The Graphical User Interface (GUI) will have an initial screen which will be visually appealing to entice users though aesthetics. The inputs will prompt the user to the next step and will be easily navigable. There will be drop down boxes for options where available and auto corrects. If a value falls outside an allowable range then warnings will appear. Where possible there will be scaling options. For the roof pitch, there will be variable angle and for the orientation there will be a moveable model house to rotate. This will be double for a double array orientation. The three options for the desired system will be colour coordinated with a corresponding diagram to indicate to the user which system they have selected.

3.5 Economic Analysis

This section will focus on the methods to predict the financial outcomes associated with each installation. The methods which will be used are the most common indicators to determine profitability and are: Net Present Value (NPV), Life Cycle Cost (LCC), Annualized Life Cycle Cost (ALCC), Internal Rate of Return (IRR), Annual Payment (ANN-PMT), Electricity Price (EP) and Benefit to Cost Ratio (B/C). [87] [76] Abdul summarized the merits and limitations of the economic tools below in **Table 1**.

Table 5 - Merits and Limitations of main economic tools for calculation of LCC [76]

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 [24, 25].	Not usable when the comparing alternatives have different life length. Not easy to interpret [23].	Most LCC models utilize the NPV method [23]. Not usable if the alternatives have different life length [24].
Simple Payback (SPB)	Easily calculated and interpreted [24].	Does not take inflation interest or cash flow into account.	Rough estimation if the investment is profitable [24].
Discount Payback Method (DPB)	Taking the time value of money [24].	Ignores all cash flow outside the payback period [24].	Only useful for screening but not decision making [24].
Equivalent Annual Cost (ECA)	Different alternatives with different life length can be compared [26].	Gives a mean value & doesn't specify the actual cost during each year of the LCC [26].	Comparing different alternatives with different life's length [26].
Internal Rate Of Return (IRR)	Results are presented in percent which gives an obvious interpretation [24].	Calculations need a trial and error procedure. Determined when the investments will generate an income [24].	Can only be used if the investments will generate an income [23].
Net Savings (NS)	Investment can be easily decided and [23].	Can be used if the investment generates an income [23].	Can be used to compare investment options, if the investment generates an income [23, 26].

3.5.1 Life Cycle Costing

The life cycle cost (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 a the sum of all the net present worth. [88] [89] [26] 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 (C) 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.

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

Where:

- I_{pc} – is initial purchasing cost of equipment's
- I_c – is installation cost
- M_c – is operation and maintenance cost
- R_c – is replacement of system components cost
- P_c – is environment pollution mitigation and disposal cost of residues
- R_v – is salvage value of remaining materials
- E – is the 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 takes into account 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 projects lifetime can be converted into a present worth value and evaluated. Using the below present worth factor: [34]

$$x = \frac{1+i}{1+d} \tag{3-2}$$

Where:

- x – is the present worth factor and is a dimensionless quantity
- i – is the inflation rate
- d – is the discount rate

We can now calculate the present worth for costs at the beginning of the year and a subsequent for costs 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 below: [34]

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

$$P_{a1} = XP_a \qquad \text{(3-4)}$$

Where:

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

Using the two factors for present worth we can calculate the entire Life Cycle Cost (LCC) for the project: [34]

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

Where:

- C_n – is the expense occurred at the begginning of the year
- C_o – is the expense occurred at the end of the year

The Anualized Life Cycle Cost (ALCC) is useful for comparing two projects that do not have the same life span, making the LCC's uncomparable; so a comparison on an anualized basis is necessary. The ALCC would be assumed to be simply divided by the amount of years of the project. This is assumming an unchanging cost per year, which is not the case due to inflation and discount rates. Instead the ALCC is determined by:

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

If the money for a project is borrowed then the mortgate 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 Annual Payment for a project the following formula will be used: [34] [90]

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

Where:

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

The electricity price can be calculated from the ANNPMT 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 formulas will be use: [34]

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

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

Where:

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

3.5.2 Net Present Value

The Net Present Value (NPV) takes the present value of the money into consideration and is most accepted standard of assessment for financial investment. [87]

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

Where:

- n – number of years
- P_v – Present value
- d – Discount rate
- F_n – is constant dollar cash flow

3.6 Statistical Methods & Limitations

The project is large and multidimensional, and deals with complex modelling and various variables. The limitation from the project start is the time constraint. Six months to completely design, test and verify a working program model is a difficult task. The scaling of the testing from compiling the data to comparing the data is a trade-off which will be made. Access to the most recent data for irradiance, prices, efficiencies and sizes may be an issue and will affect the outcomes associated with the program. The most recent information will be sourced, but finding data which is verified and within the last two years is difficult.

The creation of the GUI in the Matlab tool box is an advantage due to the add-ons and all the online sources and information available. The limitation is the user's ability to utilise all the features and implement Matlab to its optimized ability.

There are no ethical considerations while conducting the project which need to be addressed. There is a conscious bonus as this project is promoting the usage of green renewable energy which may help stimulate the market within the Townsville and the wider Queensland region.

3.7 Expected Results

The project to create a program to adequately size and optimise the PV system for three options is a large undertaking. The models and algorithms which will be utilized have been created and validated. Therefore, the expected results from using these models and algorithms will be exactly as expected. The uncertainty in the results arise from not having a model which combines all the models together. For example, the program will use the modelling of recent battery models, inverter models, PV models, irradiance models, current inflation and mortgage rates and in use tariff schemes. The combination of these models with many variables is where the results may not be as expected.

4 PROJECT MANAGEMENT PLAN

The following is the project management plan which was created for this thesis. This project overview was to ensure the project was completed on time, safely and under budget.

4.1 Project Timeline

The project proposal is due 5th May of Semester 1. The Draft has been completed and amendments are currently being made. This is on track for the project timeline. The completion hand in date is Friday Week 10 of Semester 2.

4.2 Gantt Chart

The Gantt chart was created to give overview and scope for the works. Milestones were marked to ensure adequate progress was being achieved. The Gantt chart is attached in Appendix 1 and is currently under review.

4.3 Risk Assessment

The risk assessment was completed as per the JCU procedure on the website. It is attached and all possible risks associated with the project we considered.

4.4 Project Funding

The project is limited in its allowable budget and scope for the works of testing and were downgraded to comply with budget availabilities. The primary costs of the project are with licenses for the computer software.

Matlab Student Version - $115 AUD

5 Appendices

APPENDIX 1 – PROGRESS GANTT CHART

	Task Name	Duration	Start
1	1 2017 Electrical Thesis	172 days	Fri 2/17/17
2	1.1 Semester 1	76 days	Fri 2/17/17
3	1.1.1 Topic Selection	7 days	Fri 2/17/17
4	1.1.2 Proposal	35 days	Tue 2/28/17
5	1.1.2.1 Research	7 days	Tue 2/28/17
6	1.1.2.2 Formatting Dcoume	7 days	Thu 3/9/17
7	1.1.2.3 Write Introduction	7 days	Mon 3/20/17
8	1.1.2.4 Write Literature Re	7 days	Wed 3/29/17
9	1.1.2.5 Write Methodology	7 days	Fri 4/7/17
10	1.1.3 Draft	12 days	Tue 4/18/17
11	1.1.4 Final Proposal Submissic	7 days	Fri 5/5/17
12	1.1.5 Proposal Presentation	14 days	Tue 5/16/17
13	1.2 Semester 2	49 days	Mon 6/26/17
14	1.2.1 Testing and Modelling	7 days	Mon 6/26/17
15	1.2.2 Thesis Writing	44 days	Wed 7/5/17
16	1.2.2.1 Results and Discussi	20 days	Wed 7/5/17
17	1.2.2.2 Draft	12 days	Wed 8/2/17
18	1.2.2.3 Final Draft	12 days	Fri 8/18/17
19	1.2.3 Abstract and Poster	11 days	Fri 8/18/17
20	1.2.4 Seminar Drafting	11 days	Tue 9/5/17
21	1.2.5 Seminar Presentaiton	12 days	Wed 9/20/17
22	1.2.6 Final Thesis Submission	7 days	Fri 10/6/17

APPENDIX 2 – 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 electricity printers 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 3 – PROGRAM OVERVIEW
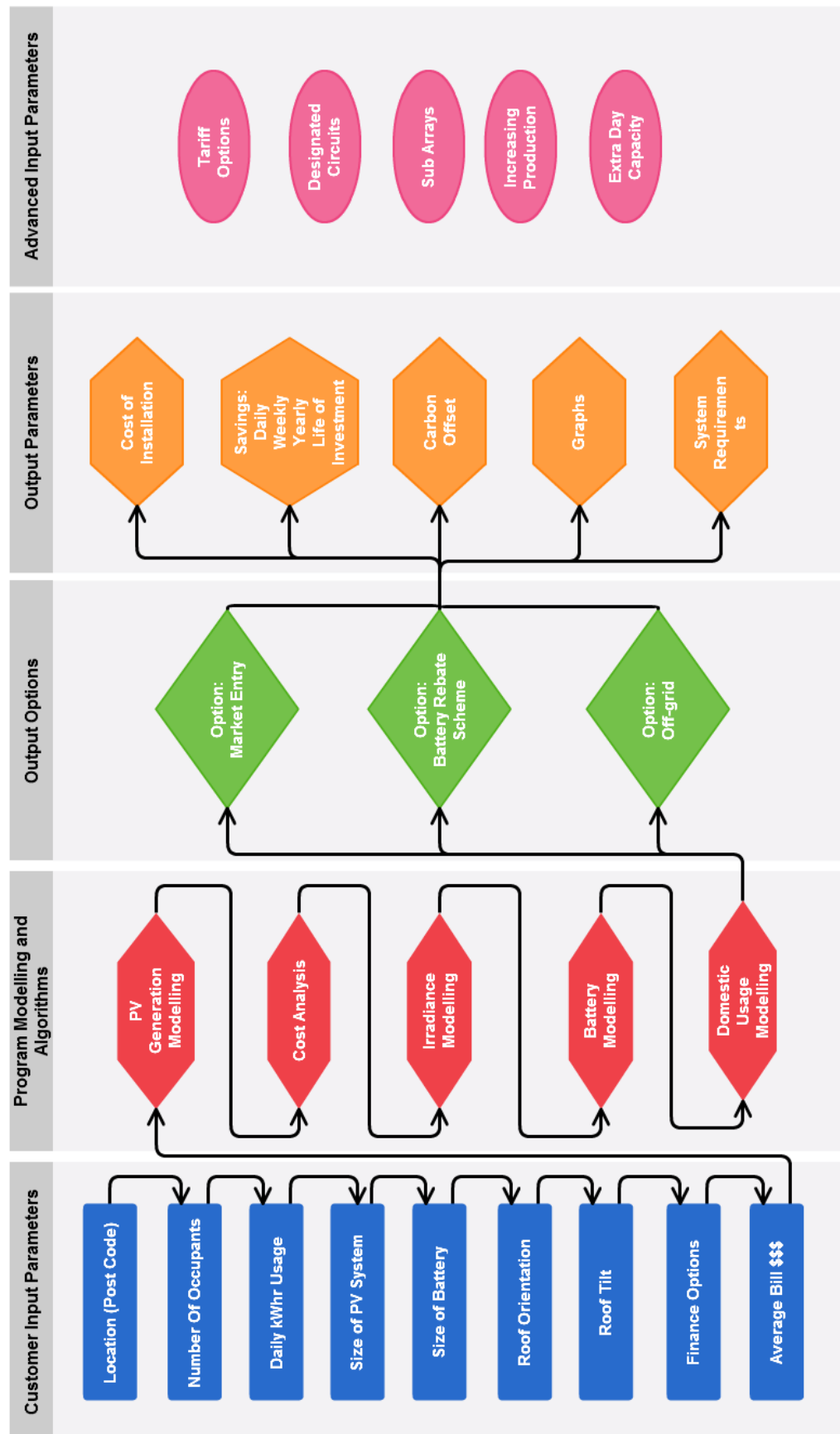
APPENDIX 4 – TYPICAL INSTALLATION WIRING OF INVERTER

AS/NZS 4777.1:2016   12
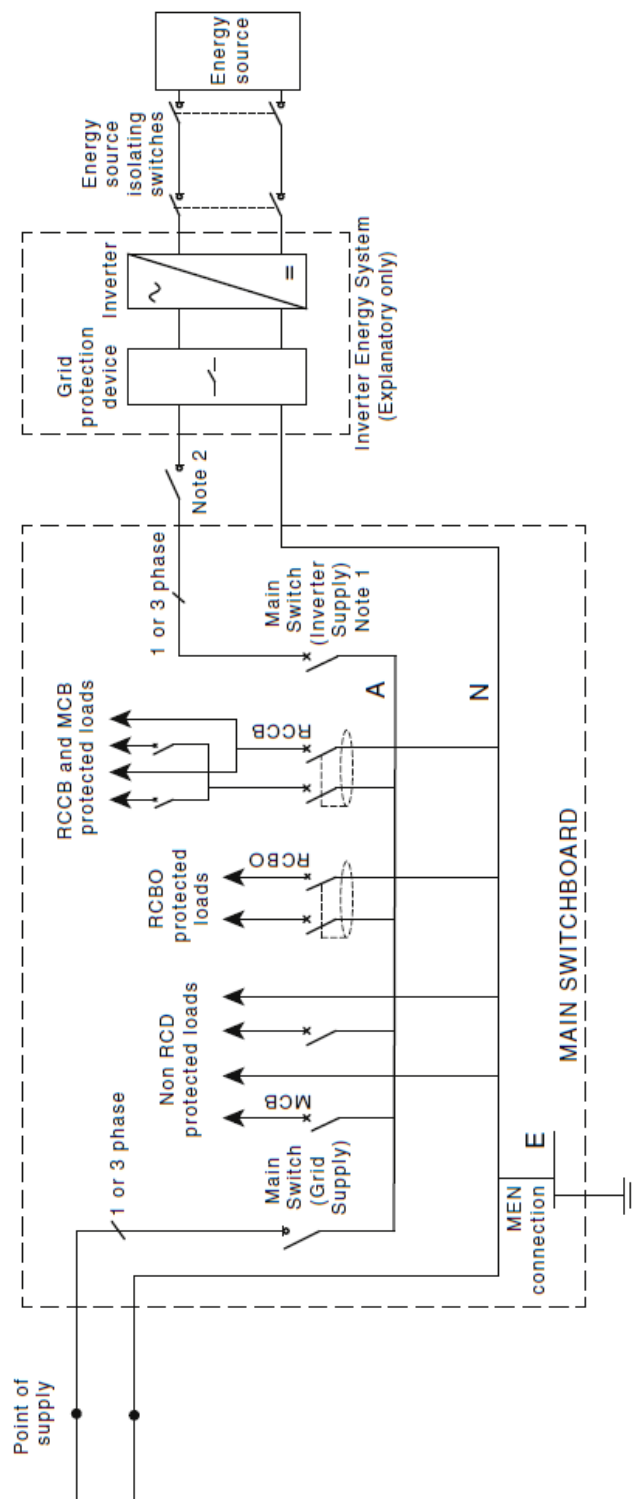
FIGURE 1   TYPICAL INSTALLATION OF AN INVERTER ENERGY SYSTEM TO A MAIN SWITCHBOARD

Notes

1 For the main switch (inverter supply) and cable protection requirements refer Clause 3.4.

2 For isolating switch requirements refer Clause 3.4.3.

3 Earth connections other than the main earth conductor and earth electrode are not shown.

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APPENDIX 5 – 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.

6 REFERENCES

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