

University of Southern Queensland  
Faculty of Health, Engineering and Sciences

# Using Renewable DC Energy Sources: Improving Domestic Energy Efficiency

A dissertation submitted by

Mark Thorley

0061029218

In fulfilment of the requirements of  
ENG4111 and 4112 Research Project  
towards the degree of  
Bachelor of Engineering (Honours)  
(Electrical and Electronics)

Submitted 12 October, 2016

# Abstract

For over 100 years the generation of AC electricity has occurred at central locations with distribution through the utility grids to the load. However, in recent years there has been a significant rise in the installation of residential embedded generation, primarily in the form of photovoltaics, which generate DC energy. There is also an impending revolution in the installation of distributed domestic battery storage systems which also utilise DC energy. Finally, there is an increase in the number of electronic devices operating primarily on DC in use in daily domestic applications.

The combination of these three situations raises the question of using DC energy directly from the generation or storage medium without inverting to AC first. This project seeks to answer this question through determining if an efficiency gain, both energy and financial, can be achieved.

To complete this analysis, an investigation of AC and DC energy supplies was conducted with the various advantages and disadvantages being reviewed. Average residential usage profiles were determined along with average daily consumption. Models were created to simulate their function. Once the models were developed a range of AC and DC configurations were simulated with and without photovoltaics and battery storage systems installed.

This modelling determined that converting a residential installation to DC, whilst still maintaining an AC grid connection through a central inverter/rectifier, yielded an energy saving of between 1.686% and 4.694%. However financially, the operation of an AC system with photovoltaics connected was the best option. This is a configuration that is very popular for residential installations.

Despite residential DC utilisation offering an energy efficiency gain over the accepted AC, the financial benefits are still not available and the absence of residential DC appliances makes further advancement in the area difficult. However, with the continuation of photovoltaic installations, the impending installation of battery storage systems, changing consumer load types and the positive results determined by this project, it is clear that residential DC installations could be a viable option in the not too distant future.

University of Southern Queensland  
Faculty of Health, Engineering and Sciences  
**ENG4111 & ENG4112 Research Project**

**Limitations of Use**

The Council of the University of Southern Queensland, its Faculty of Health, Engineering and Sciences, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Health, Engineering and Sciences or the staff of the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled “Research Project” is to contribute to the overall education within the student’s chosen degree program. This document, the associated hardware, software, drawings, and any other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

## Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Mark Thorley

Student Number: 0061029218

# Acknowledgements

I would like to extend my sincere thanks to Mr. Andreas Helwig for sharing his knowledge and providing guidance, support and constructive discussions during the completion of this research project.

Thanks to my employer, colleagues and supervisors for their ongoing flexibility and support during the completion of this research project and the degree as a whole.

To my family and friends, thank you for the understanding you have all shown over the last five years whilst I have been absent from many events.

Finally, the greatest thanks needs to go to my wife, Madison, and two young children, Evan and Alexis. No words can describe how appreciative I am of your support, understanding and sacrifices during the completion of my studies.

# Contents

List of Figures .....	viii
List of Tables .....	xi
Nomenclature.....	xii
Chapter 1      Introduction.....	1
1.1      Project Aim .....	2
1.2      Objectives .....	2
Chapter 2      Literature Review.....	4
2.1      History of DC power distribution .....	4
2.2      Why did AC power distribution become so dominant?.....	5
2.3      The challenges of DC protection compared to AC applications.....	8
2.4      Safety .....	12
2.5      DC Microgrids .....	14
2.6      DC Generation and Storage .....	21
2.7      DC Domestic Appliances.....	27
2.8      Residential Energy Use.....	31
2.9      Literature Review Summary .....	34
Chapter 3      Methodology .....	36
3.1      Overview.....	36
3.2      Domestic Load Profiles.....	37
3.2.1      Logging Information.....	37
3.2.2      Distribution Monitoring System .....	43
3.3      Model Development and Analysis.....	47
3.3.1      House 1 Model.....	59
3.3.2      Configuration 1 - AC house with DC-internal appliances .....	63
3.3.3      Configuration 2 - Removal of appliance AC/DC rectifiers.....	65
3.3.4      Configuration 3 – Removal of appliance AC/DC rectifiers with reduction in baseload .....	66

3.3.5	Configuration 4 - Utilising a common DC bus with central AC/DC rectifier .....	67
3.3.6	Configuration 5 – Two DC buses supplied by AC grid through a central rectifier .....	68
3.3.7	Configuration 6 – AC house with total daily solar contribution .....	69
3.3.8	Configuration 7 – AC house with PV installed, following generation profile .....	70
3.3.9	Configuration 8 – Two DC buses supplied by AC grid through a central rectifier with PV connected to higher DC voltage.....	71
3.3.10	Configuration 9 – AC house with PV and batteries installed .....	72
3.3.11	Configuration 10 – Two DC buses supplied by AC grid through a central rectifier with PV and batteries connected to higher DC voltage.....	75
3.3.12	Configuration 11 - Two DC buses supplied by AC grid through a central rectifier with PV and batteries connected to lower DC voltage .....	76
3.4	Methodology Summary.....	77
Chapter 4	Results.....	78
4.1	MATLAB vs HOMER Pro .....	78
4.2	Configuration Comparison.....	79
4.2.1	Configuration 1 to Configuration 2.....	82
4.2.2	Configuration 1 to Configuration 3.....	83
4.2.3	Configuration 1 to Configuration 4.....	83
4.2.4	Configuration 1 to Configuration 5.....	83
4.2.5	Configuration 7 to Configuration 8.....	84
4.2.6	Configuration 9 to Configuration 10.....	87
4.2.7	Configuration 9 to Configuration 11 .....	87
4.2.8	Configuration Losses .....	88
4.2.9	Remote Area Power Supplies .....	93
4.2.9.1	AC configuration.....	94
4.2.9.2	DC configuration.....	94
4.2.9.3	RAPS Results.....	95

4.3	Cost Comparison.....	96
4.4	Results Summary .....	99
Chapter 5	Consequential Effects .....	101
5.1	Sustainability.....	101
5.2	Safety .....	102
5.2.1	Risk Assessment for completion of research project .....	105
5.3	Ethics.....	107
Chapter 6	Conclusion .....	108
Chapter 7	Future Work .....	110
7.1	Residential DC microgrid .....	110
7.2	Smart Switchboard.....	111
	References.....	113
Appendix A	Project Specification .....	117
Appendix B	Timeline .....	118
Appendix C	Resource Requirements.....	120
Appendix D	Supporting Tables .....	121
Appendix E	Results and Comparisons .....	122
Appendix F	HOMER Pro screenshots .....	132
Appendix G	MATLAB code .....	135
G.1	Code for determining house models from logging .....	135
G.2	Code for analysing distribution substation data .....	140
G.3	Code for House 1 model .....	152
G.4	Code for Project model .....	160
Appendix H	CD with model files .....	219



# List of Figures

Figure 2.1 – Time/current zones for AC 15Hz to 100Hz for hand to feet pathway (Australia 2010, p. 15).....	13
Figure 2.2 – Conventional time/current zones of effects of AC currents (15Hz to 100Hz) on a persons for a current path corresponding to left hand to feet (Australia 2010, p. 35).....	13
Figure 2.3 – Time/current zones for DC for hand to feet pathway (Australia 2010, p. 18).....	14
Figure 2.4 – Conventional time/current zones of effects of DC currents on persons for a longitudinal upward current path (Australia 2010, p. 36).....	14
Figure 2.5 – Simple DC microgrid arrangement (Lotfi & Khodaei 2015, p. 2) .....	18
Figure 2.6 – Simple AC microgrid arrangement (Lotfi & Khodaei 2015, p. 2) .....	18
Figure 2.7 – Impact of Solar PV (Stewart 2016) .....	22
Figure 2.8 – Monthly solar installation volume and overall average size (2016).....	22
Figure 2.9 – Annual and cumulative solar installations and capacity (Mountain 2016).....	23
Figure 2.10 – Australian residential energy by end use (EnergyConsult 2015) .....	31
Figure 2.11 – Residential consumption by fuel type (EnergyConsult 2015).....	32
Figure 2.12 – U.S. average residential electricity consumption by end-use in 2009 (Garbesi et al. 2012).....	33
Figure 3.1 – PQ-Box 100 installed in main switch board.....	38
Figure 3.2 – Close up of PQ-Box 100.....	39
Figure 3.3 – CT’s connected to each of the three phases exiting the service fuses .....	39
Figure 3.4 – Average daily profile for each of the four houses logged.....	42
Figure 3.5 – Combined Average Daily Profile for All Four Houses .....	43
Figure 3.6 – Seasonal daily average energy usage per installation.....	46
Figure 3.7 – Model location.....	48
Figure 3.8 – Reading from house fridge using CABAC Power-Mate Lite.....	60
Figure 3.9 – House 1 modelled profile .....	62
Figure 3.10 – Configuration 1 arrangement.....	63
Figure 3.11 – Configuration 1 – AC house with DC internal appliances daily profile.....	64
Figure 3.12 – Residential end use per day from MATLAB model.....	64

Figure 3.13 – HOMER Pro Configuration 1 .....	65
Figure 3.14 – Configuration 2 arrangement.....	65
Figure 3.15 – HOMER Pro Configuration 2.....	66
Figure 3.16 – Configuration 4 arrangement.....	67
Figure 3.17 – HOMER Pro Configuration 4.....	67
Figure 3.18 – Configuration 5 arrangement.....	68
Figure 3.19 – HOMER Pro Configuration 5.....	69
Figure 3.20 – Configuration 7 arrangement.....	71
Figure 3.21 – HOMER Pro Configuration 7.....	71
Figure 3.22 – Configuration 8 arrangement.....	72
Figure 3.23 – HOMER Pro Configuration 8.....	72
Figure 3.24 – Configuration 9 arrangement.....	74
Figure 3.25 – HOMER Pro Configuration 9.....	74
Figure 3.26 – Configuration 10 arrangement.....	75
Figure 3.27 – HOMER Pro Configuration 10.....	76
Figure 3.28 – Configuration 11 arrangement.....	76
Figure 4.1 – Comparison of MATLAB and HOMER Pro total annual consumption .....	79
Figure 4.2 – Difference in consumption between AC configuration and equivalent DC configuration.....	81
Figure 4.3 – Annual daily solar generation and installation usage. ....	85
Figure 4.4 – Daily energy loss per model .....	89
Figure 4.5 – Model 9 loss breakup.....	91
Figure 4.6 – Model 10 loss breakup.....	91
Figure 4.7 – Annual Total Consumption vs Annual Grid Consumption .....	92
Figure 4.8 – AC RAPS.....	94
Figure 4.9 – DC RAPS.....	95
Figure 4.10 – RAPS Annual installation consumption .....	96
Figure 4.11 – Comparison of NPC values .....	98

Figure 4.12 – RAPS annual installation consumption vs NPC.....99

Figure 5.1 – Risk Matrix (Ausgrid 2016b) .....103

Figure 5.2 – Hierarchy of Controls (Ausgrid 2016b).....104

Figure B.1 – Project Plan.....119

Figure F.1 – AC load in HOMER Pro. Used for all AC models.....132

Figure F.2 – Imported solar GHI information from Wagga weather station into HOMER Pro 133

Figure F.3 – BSS input into HOMER Pro .....133

Figure F.4 – Time of Use tariff structure.....134

# List of Tables

Table 2.1 – Power system full-load conversion efficiencies.....	29
Table 2.2 – Season household electricity usage (AER 2015) .....	33
Table 2.3 – Regional NSW average household size .....	34
Table 3.1 – Individual house information.....	41
Table 3.2 – Distribution substation usage.....	45
Table 3.3 – Distribution substation seasonal average .....	45
Table 3.4 – Voltage drop per ampere-meter for domestic cables .....	50
Table 3.5 – Appliance ratings and operating times for use in models .....	52
Table 3.6 – Component efficiencies used in models.....	55
Table 3.7 – Electricity Tariffs used in HOMER Pro.....	58
Table 3.8 – House 1 model appliance ratings and operating times.....	61
Table 3.9 – Appliance split between two DC voltage levels .....	69
Table 4.1 – RAPS configuration summary .....	95
Table 5.1 – Risk assessment for completion of research project .....	105
Table C.1 – Resources required for research project completion .....	120
Table D.1 – Daily solar exposure.....	121
Table E.1 – MATLAB autumn results, average kWh/day.....	123
Table E.2 – MATLAB winter results, average kWh/day.....	124
Table E.3 – MATLAB spring results, average kWh/day.....	125
Table E.4 – MATLAB summer results, average kWh/day.....	126
Table E.5 – MATLAB average kWh/day .....	127
Table E.6 – MATLAB average kWh/year.....	128
Table E.7 – HOMER Pro results models 1, 2, 3, 4 and 5 .....	129
Table E.8 – HOMER Pro results -models 7, 8, 9, 10 and 11 .....	130
Table E.9 – HOMER Pro RAPS results.....	131

# Nomenclature

ABS	Australian Bureau of Statistics
AC	Alternating Current
A/C	Air Conditioning
AEMO	Australian Energy Market Operator
AGM	Advance Glass Mat
ALARP	As Low As Reasonably Possible
BSS	Battery Storage System
DC	Direct Current
DVD	Digital Video Disc
ESS	Energy Storage System
GHI	Global Horizontal Irradiance
GPO	General Purpose Outlet
HOMER	Hybrid Optimisation Model for Multiple Energy Resources
HV	High Voltage
Hz	Hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
kW	Kilowatt
kWh	Kilowatt hours
LED	Light Emitting Diode
Li-Ion	Lithium Ion
LPG	Liquefied Petroleum Gas
LV	Low Voltage
MCCB	Moulded Case Circuit Breaker
NASA	National Aeronautics and Space Administration
NEM	National Electricity Market
NiCad	Nickel Cadmium
NiFe	Nickel Iron
NiMH	Nickel Metal Hydride
PPE	Personal Protective Equipment
PV	Photovoltaic
RAPS	Remote Area Power Supply
RBA	Reserve Bank of Australia
RBS	Residential Baseline Study

RMS	Root Mean Square
TV	Television
UPS	Uninterruptible Power Supply
SWER	Single Wire Earth Return

# Chapter 1 Introduction

Since the ‘War of Currents’ which took place between George Westinghouse and Thomas Edison around 1890, AC energy has been the accepted energy type for grids throughout the world. However, loads and generating types have changed significantly in recent times with a move towards renewable domestic generation and an impending revolution in the installation of distributed domestic battery storage systems. Consequently, there is an increase in the number of electronic devices all operating primarily on DC now in use in domestic daily applications.

The installation of domestic PV systems, with no energy storage system, generate DC energy that is immediately converted to AC using an inverter (Speidel & Bräunl 2016). In a net metered installation, the consumer then utilises whatever energy they require with the excess, if any, being exported back to the utility grid. If the consumer requires more energy than is being generated by the PV system, then they obtain this from the utility grid. The energy that the consumer uses supplies items such as lights, television, stereos, washing machines, driers, hot water systems, air-conditioners, computers, chargers for small appliances, etc. Some of these items, such as television, computers and electronic devices operate on DC power and hence convert from AC to DC (Amin et al. 2011). In these instances, the energy is unnecessarily converted twice, resulting in additional losses. In a system where a BSS is installed these batteries are charged via the excess energy from the PV system, with consumed energy being AC (Speidel & Bräunl 2016). Both of these systems do not use DC energy without converting to AC first.

This poses the question, should DC energy be utilised directly from the generation source or ESS? The resulting dissertation will explore this question and seek to answer if there is an efficiency gain by using DC energy directly. Any efficiency gain will be reviewed with respect to energy consumption and consumer cost. The project’s research question is “Can energy savings be attained by using DC energy for domestic applications, and what financial benefit can be achieved?” To answer this question models of both an AC domestic installation and a DC domestic installation have been created. Some of the literature has studied DC supplies and DC microgrids in other countries but at this point in time no information has been found on domestic systems being installed in Australia.

The literature review is wide ranging and provides the history of DC power and why AC power systems became so dominant. It then looks at protection differences between AC and DC. The introduction of DC into a domestic installation involves different protection devices (Company 2007). A review of available and proposed energy storage systems has been undertaken to see

what options are available to the domestic consumer. The next challenge of using a DC power supply is obtaining the appropriate appliances. DC has long been successful in caravanning, camping and small remote off-grid installations with a vast range of appliances now readily available. However, there is not the demand or market for larger items for the regular domestic consumer and hence the supply range is limited. Research in this area confirms what products are available to the market and what, if any, benefits can be obtained. For the items that already operate internally on DC, there is a comparison between inverting DC to AC and then rectifying back versus the utilization of DC/DC converters.

From initial research it is anticipated that a small gain in efficiency will be achieved by using a DC supply bus in a domestic application (Rodriguez-Diaz et al. 2015). The value of this efficiency gain varies depending on the literature and methodology used but there are indications of a successful outcome.

## 1.1 Project Aim

The aim of this research project is to examine the energy usage of a domestic installation in Australia and determine if an efficiency gain can be achieved by utilising a DC supply in place of the existing AC. When referring to efficiency, the primary objective is to determine if a reduction in losses is possible with a secondary objective of establishing economic viability.

## 1.2 Objectives

The completion of this research project is to determine if an efficiency gain is possible when utilising DC supply at a domestic level. In order to achieve this objective, the question can be expanded into the following:

1. Is the utilisation of DC distribution in a domestic installation more efficient than the accepted AC?
2. If there is a benefit, is it an energy saving and or financial saving for the consumer?



3. What are the proposed voltage levels for DC supply?
4. Is the installation of PV and a BSS a viable option?

To achieve answers to these questions a number of key objectives have been determined. These are:

- Conduct a thorough literature review of the topic, including the following:
  - History of DC power distribution.
  - Why did AC power distribution become dominant?
  - The challenges of DC protection compared to AC applications.
  - Safety.
  - DC microgrids.
  - DC generation and storage.
  - DC domestic appliances.
  - Residential energy use.
- Obtain logging data from a selection of domestic installations to compare to the averages presented in literature. Although only a small number of houses will be logged it will give an indication of “typical” consumption and usage patterns.
- Develop models to simulate both AC and DC domestic installation consumption. MATLAB will be used to model energy consumption with HOMER Pro used as a second model for energy consumption and financial analysis. These models will utilise the obtained data, researched data and some justified assumptions.
- The AC model will utilise DC internal appliances as they are typically more energy efficient. Where a suitable DC internal appliance is not available sensible assumptions will be made.
- The DC model will omit the AC/DC rectifiers that will be present in the AC model.
- Determine a common DC bus voltage/s and determine any efficiency gain by using DC instead of AC.
- Research the cost of a BSS and determine if they are a sound investment.

## Chapter 2 Literature Review

The intention of the literature review contained in this chapter is to analyse the available information from reputable sources regarding the use of domestic DC power distribution, specifically focussing on determining if an efficiency gain is possible. Before creating models it is important to explain the history of DC power distribution and the reasons why AC power became dominant. Following this, a look into the challenges of DC protection compared to AC will be studied before moving onto the dangers associated with both current types. DC microgrid operation will be discussed as well as DC appliances, DC generation and storage and finally, residential energy use.

### 2.1 History of DC power distribution

DC power was in development during the 1870's and 1880's with Casazza (2007, pp. 50) reporting that in 1882 a 2400V DC line was constructed over 37 miles (59km) in Germany. Thomas Alva Edison is one of the iconic names in the development of electricity generation with Sulzberger (2003a) identifying him as most publicly remembered for bringing lighting to the streets of New York City in the form of DC powered incandescent globes in 1882.

Edison was responsible for setting up the world's first industrial research laboratory that encouraged a systems approach to inventing rather than a component approach. The facility was well equipped with resources; including people, materials and equipment (Sulzberger 2003b). Following Edison's successful invention of the incandescent globe in 1879, which occurred simultaneously with that of British inventor Joseph Swan, he turned his focus to the invention of a generator or dynamo, that was capable of producing the required constant voltage for the operation of the incandescent globe rather than the constant current required for existing arc lighting (Sulzberger 2003b).

The original lighting system was supplied in 1882 from the famous Pearl Street station located in lower Manhattan. Its position was strategically chosen by Edison to ensure maximum publicity as it was close to financial institutions, media offices and the financial heart of the United States, Wall Street (Sulzberger 2003b). This station operated at 110V DC supplying a radius of approximately 1.6km (Andrade & Leao 2012). According to Lobenstein and Sulzberger (2008) Edison's central station design, distributing low voltage DC, was installed not only in many parts

of New York City but also in other cities and towns across North America, Europe, South America and Japan.

The use of low voltage DC was plagued with some significant limitations. These included the restriction of DC distribution to approximately 3km, due to the difficulty in changing the voltage level, and the need to install large, expensive copper cables in an effort to minimise electrical losses. The limitation on the distribution area combined with the cost of installation meant that DC systems were really only suited to densely populated regions.

DC distribution is however still strong today in the transport sector with many networks around the world continuing to utilise, expand and install DC systems. This is true in Australia with the Melbourne and Adelaide tram networks operating on 600V DC, Sydney and Gold Coast light rail networks operating on 750V DC and Sydney and Melbourne trains operating on 1500V DC. The study of these networks is beyond the scope of this project as there is a specific focus here on domestic DC utilisation.

## 2.2 Why did AC power distribution become so dominant?

The names George Westinghouse and Nikola Tesla are well known as names associated with AC power, but how and when did these two gentlemen achieve this status? Sulzberger (2003a) identifies George Westinghouse as an American inventor, entrepreneur and engineer who obtained the American rights to the alternating current transformers built by Lucien Gaulard of France and John Gibbs of Britain in early 1886. Initially these transformers were installed on an AC line but the voltages present on the secondary terminals were varying in nature due to the changing of secondary loads affecting the primary voltage levels (Sulzberger 2003b). This effect was a result of series connecting the primary terminals. This is much the same result as connecting a string of lights in series where as the number of lights, or load increases, the brightness of each globe decreases.

William Stanley, one of Westinghouse's employees, solved this problem by redesigning a transformer to allow parallel connection to the AC line which prevented the primary voltage variation that was previously produced by the varying secondary load (Sulzberger 2003b). This can easily be related back to the light bulb example presented above where in a parallel configuration, the light bulb brightness did not change despite increasing the number of globes connected.

By September 1886, following the redesign of the Lucien Gaulard and John Gibbs transformer, Westinghouse Electric Company was in a position to market their AC system and by November 1886 had commissioned America's first commercial AC electric power system in Buffalo New York (Sulzberger 2003b).

Meanwhile in 1884 Nikola Tesla arrived in America from Europe. His purpose was to liaise with Thomas Edison in an effort to obtain the necessary financial backing to complete the designs from his theory around rotating magnetic fields and the AC induction motor concept (Sulzberger 2003b). Edison however, was focussed on the development of DC power systems and as a result did not take to the AC ideas of Tesla. They went their separate ways after several months. Tesla did however secure financial support for the development of his AC system and in November and December of 1887 he submitted his application for seven U.S patents covering polyphase AC motors, power transmission, generator, transformers and lighting (Sulzberger 2003b). These patents were purchased by Westinghouse Electric Company in July 1888 for which Tesla then worked for a short period continuing his development of AC products (Sulzberger 2003a; Tesla 1984).

(Sulzberger 2003b) explains that in 1888 Edison, in an effort to promote DC, presented the following key advantages:

- Superior reliability since parallel operation of DC generators was possible, a technique that at the time was not available for AC.
- An AC energy meter did not yet exist.
- An AC motor had not been developed.
- DC could be used for charging batteries and electroplating applications.
- The recognised "absolute safety" of DC supplies of 110 and 240 volts compared to the higher AC transmission and distribution voltages.

Westinghouse's company invented solutions to many of the problems presented by Edison over the following years. Sulzberger (2003b) outlines the development of a magnetic disk meter in 1888 that exceeded that of Edison's electrolytic meter and by 1892 an AC induction motor was completed along with the development of two and three phase distribution. During 1892-1893 a synchronous rotary converter was developed which allowed the use of DC from an AC supply

During 1888 the battle intensified with Edison and his colleagues concentrating their efforts on trying to discredit and give bad publicity to AC power systems, primarily by focusing on the safety risks associated with AC power and using the electrocution of animals as reinforcement (Sulzberger 2003a).

Despite this debate, Westinghouse continued to develop and advance the production of AC power, and also the construction of transmission lines, with AC use reaching industrial applications in 1891 (Sulzberger 2003a). Transmission line lengths also continued to grow and by 1892 a 70 mile line operating at 40kV had been commissioned (Sulzberger 2003a).

General Electric was formed in 1892 by the merging of Edison General Electric and Thomson-Houston. Following the merger, the new company immediately entered into the AC market. Edison was not happy and after a short time he resigned from his position as a director (Sulzberger 2003a).

1895 saw the first AC generator installed at Niagra Falls and by 1905 there were 21 generators installed across two power stations providing power to the town of Buffalo (Sulzberger 2003a).

Cunningham (2013, p. 97) reports the New York Edison company (now known as Con Edison), not to be confused with Edison General Electric, was still growing the DC network up until 1928 when then president Matthew Sloan announced the following:

*“In light of the reliability, economy, and efficiency of the automatic AC network perfected by the United Company, there is no justification for continued extension of DC service”*

This statement sparked the gradual retirement of the DC assets by New York Edison with the last piece of the network isolated on 14 November 2007 (Cunningham 2013; Lobenstein & Sulzberger 2008). Many other countries had completely retired their DC systems much earlier with Andrade and Leao (2012) listing the following dates:

- 1940s - Helsinki, Europe.
- 1970s – Stockholm.
- 1981 – London.

Elsayed et al. (2015) identifies one of the main reasons for the success of AC as being the ease of changing voltages with transformers to improve distribution. At that time this was a difficult task to undertake using DC.

As technology advanced, power electronics have since enabled efficient DC/DC conversion, a task that in the battle of currents could not be completed. This was one of the major reasons AC succeeded (Mackay et al. 2014). So although the battle was essentially resolved through Matthew Sloan's 1928 statement, recent advances in technology and changes in the way we generate, use and store our energy have now reignited this century old battle.

This resurgence has generated discussion around the possibility of DC distribution and the use of DC power directly. Hence the topic of this dissertation and the search for improved efficiency by utilising DC power without inverting.

### 2.3 The challenges of DC protection compared to AC applications

This section will be specifically referring to the protection used on DC circuits that would be typically used in domestic installations. The protection of distribution, sub transmission and transmission DC circuits is beyond the scope of this research.

Before discussing protection, it is important to recap the difference between DC and AC waveforms. Company (2007) provides a good description of the two currents. It describes DC as having a charge level that remains unchanged in relation to time, whereas in AC the charge alternates between positive and negative values 50 times per second (or 100 direction changes) in a sinusoidal waveform. This alternating between positive and negative values results in two natural zero points per period and hence simpler and faster arc extinguishing. DC however does not cross a zero point and requires the current to be decreased to zero. Failing to adequately cool the arc plasma can result in arc instability where the arc may not extinguish (Gregory 1995). These different characteristics of current require different methods of protection. Monadi et al. (2015) highlights AC circuit breakers are not suitable for DC use. This is not entirely correct today as many domestic circuit breakers are available with dual ratings, however, the ratings for AC and DC are very different and care must be taken to ensure that the correct device is installed (Elsayed et al. 2015). The direction of current in DC systems is very important as incorrect polarity can cause incorrect operation and safety issues (Company 2007).

In order to easily relate between AC and DC values there is a term called RMS. Company (2007) describes that the AC current and/or voltage can be converted to RMS values which will then

represent the same thermal effects as the corresponding DC value. To calculate the RMS value, the maximum AC current is divided by the square root of two as shown in the following formula.

$$I_{rms} = \frac{I_{max}}{\sqrt{2}} \quad (2.1)$$

Protection devices for use in the domestic market are traditionally limited to fuses and circuit breakers. Salomonsson et al. (2009) describes fuses as a fuse link and heat absorbing material located inside a ceramic cartridge where AIRPAX (2013) describes the fuse link as being usually constructed of lead alloy material. RMS values are used to rate the voltage and current of fuses so they are applicable to both AC and DC systems. This rating however does have some variation as the interruption is caused by the melting of alloy which is not exact (AIRPAX 2013; Salomonsson et al. 2009). The system time constant also has an effect on fuse operation in the DC environment as it determines the rise time of the current transient, hence the ability of the current to be interrupted by the fuse.

Gregory (1995) defines a circuit breaker as a device that will automatically operate, or open, at a predetermined current without any damage to itself. They can also be used for manual open and close of a circuit using a handle or lever. Salomonsson et al. (2009) go into a little more detail and describes that a MCCB consists of a contactor, a quenching chamber and tripping device with the voltage and current ratings in RMS values which allow consistency across DC and AC values. The thermal tripping operates at the same value for both AC and DC but the magnetic tripping operates off the instantaneous current, hence the DC value is  $\sqrt{2}$  times larger than the AC current (Salomonsson et al. 2009).

In a microgrid, regardless of whether it is AC or DC, protection is required to work in both directions if connected to the utility grid, as the system can work in connected or islanded configurations (Planas et al. 2015). DC is beginning to have a growing number of protection devices available such as fuses, circuit breakers, moulded-case circuit breakers, LV power circuit breakers and isolated case circuit breakers (Planas et al. 2015).

When choosing a circuit breaker for protection of a DC circuit the following, obtained from Company (2007), identifies key parameters that require consideration:

- Rated operational voltage – the system voltage.
- Rated uninterrupted current – current that can be carried continuously.

- Rated current – the current that the circuit breaker is rated to operate at.
- Rated ultimate short circuit breaking capacity – the maximum short circuit current, at rated voltage, that the circuit breaker can break twice.
- Rated service short circuit breaking capacity – maximum short circuit current, at rated operational voltage and defined time constant, that the circuit breaker can break three times.
- Rated short time withstand current – the current that the circuit breaker can carry whilst waiting for downstream protection devices to operate ensuring adequate discrimination.

Circuit breakers typically have three regions in which they operate. These are the long lead time region, the transition region and the instantaneous region. Gregory (1995) defines these three regions as follows:

- Long lead time region – This typically operates from 100% to 500% of the rated current by heating up a bimetal which initiates the circuit breaker operation. As this is current based it will operate in the same time for a RMS AC value and a DC value. Within this region is what AIRPAX (2013) defines as the ultimate trip current, also known as overcurrent, which is usually about 115% of the circuit breaker rating.
- Transition region – This region is typically between 400% and 1200% of the rated current and operates either the same as the long lead time region by heating up the bimetal or by magnetic tripping. Magnetic tripping occurs as the current through the circuit breaker activates an electromagnet which in turn initiates the trip. AC and DC do have a difference in this region but the manufacturer normally adjusts the rating by revising the multiplying factor from 1.1 up to 1.4.
- Instantaneous region – As the name suggests this is the region where the circuit breaker opens instantaneously, above 1200% of the rated current, in both AC and DC circuits again by the use of the electromagnet. Clearing times do vary between AC and DC circuits but the maximum clearing time from the manufacturer satisfies both. AIRPAX (2013) defines the instantaneous region as approximately ten times the circuit breaker rating which is just below where Gregory (1995) defines it, although the difference is not significant.



The final type of protection system as defined by Salomonsson et al. (2009) is Power-Electronic Protection Devices. These devices allow for decreased operation time and increased inductive current interruption capability. These devices help overcome shortfalls, such as long circuit breaker operation time and large time constants, with fuses and circuit breakers in LV DC systems. These devices do suffer higher losses than the traditional mechanical switch.

The difference between AC and DC also translates into different types of faults being present on each system. An AC system has symmetrical and asymmetrical faults whereas a DC system has pole-pole faults and pole-ground faults (Monadi et al. 2015). Monadi et al. (2015) and Salomonsson et al. (2009) both identify pole-pole faults as low impedance which means they can be destructive to a system. Pole-ground faults can be both low impedance and high impedance and are the most common DC faults, with insulation breakdown being the main cause (Monadi et al. 2015; Salomonsson et al. 2009).

The location of faults in a DC system is the same as an AC system and can be either at the bus or on one of the corresponding circuits. Salomonsson et al. (2009) describe that when a bus fault occurs and is supplied by a battery the total fault impedance is the addition of the battery ( $R_{batt}$  and  $L_{Batt}$ ) and cable ( $R_{LB}$  and  $L_{LB}$ ) impedances. Capacitance in a pole-pole fault can be ignored. Therefore, the battery fault current is:

$$i_{batt}(t) = \frac{u_{batt}}{R_{batt} + R_{LB}} \left( 1 - e^{-\frac{t}{\tau_{batt}}} \right) \quad (2.2)$$

$$\text{Where } \tau_{batt} = \frac{L_{batt} + L_{LB}}{R_{batt} + R_{LB}}$$

This formula is confirmed by Dragicevic et al. (2016). Battery design determines fault duration before internal battery damage is caused.

Dragicevic et al. (2016) also explains that if a battery is connected through a power electronics converter then the current is equal to:

$$i_c(t) = \frac{u_{dc}}{R_c} e^{-\frac{t}{\tau_c}} \quad (2.3)$$

*Where  $u_{dc}$  is the common DC bus voltage and  $\tau = C_{dc}R_c$  is the time constant of the effective converter /common DC bus RC system.*

Therefore,

$$i_{fault}(t) = i_{batt}(t) + \sum_{j=1}^N i_{c,j}(t) \quad (2.4)$$

Where  $N$  is the number of source converters.

Salomonsson et al. (2009) also highlight that grounding is an important part of any protection system and has many different configurations that result in different system performance. Grounding provides a mechanism for detecting ground faults and providing safety to both personnel and equipment. An LV DC microgrid can be ungrounded, high resistance grounded (known as a IT grounding system) or low resistance grounded (known as a TN grounding system). In the IT grounding system, the presence of a grounding resistor controls the magnitude of the currents. Brief explanations of these two systems were provided by Oliveira et al. (2014). In the TN grounding system extremely high fault currents are present as one of the system conductors is solidly grounded. In the double pole IT system both of the system conductors are grounded through a high resistance. In a DC system that operates between 380 and 400V there is a potential for electric shock and fire hazard if high resistance grounding is not used (Oliveira et al. 2014). Systems that operate below 60V DC can operate ungrounded if they have high galvanic isolation from the system main grounding electrode (Oliveira et al. 2014).

The arc condition present in a DC circuit breaker presents a dangerous condition for not only human safety but also results in degradation of the circuit breaker contacts, short lifetime and high maintenance costs. It is therefore essential to implement the correct protection devices and grounding system in order to control these issues.

## 2.4 Safety

It is well understood that contact with electricity can cause injury and/or death dependent on the voltage, volume of current flow through the body, current path through the body and type of current (AC or DC).

Australian Standard AS/NZ 60479 defines effects of current on human beings and livestock. This standard identifies the likely injury from a defined range of current for both AC and DC. The amount of current that will flow through the body is dependent on the impedance of the body and

the voltage level that is contacted. The best explanation for these are the tables directly from the standard. Below is a table and a graph for both AC and DC displaying the zones and effects from contacting the two respective currents. It is evident from these tables and graphs that on average the body can withstand a higher DC current than an AC current.

Zones	Boundaries	Physiological effects
AC-1	Up to 0,5 mA curve a	Perception possible but usually no 'startled' reaction
AC-2	0,5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected
AC-4 <sup>1)</sup>	Above curve $c_1$  $c_1$ - $c_2$  $c_2$ - $c_3$  Beyond curve $c_3$	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time  AC-4.1 Probability of ventricular fibrillation increasing up to about 5 %  AC-4.2 Probability of ventricular fibrillation up to about 50 %  AC-4.3 Probability of ventricular fibrillation above 50 %

<sup>1)</sup> For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, this figure relates to the effects of current which flows in the path left hand to feet. For other current paths, the heart current factor has to be considered.

Figure 2.1 – Time/current zones for AC 15Hz to 100Hz for hand to feet pathway (Australia 2010, p. 15)

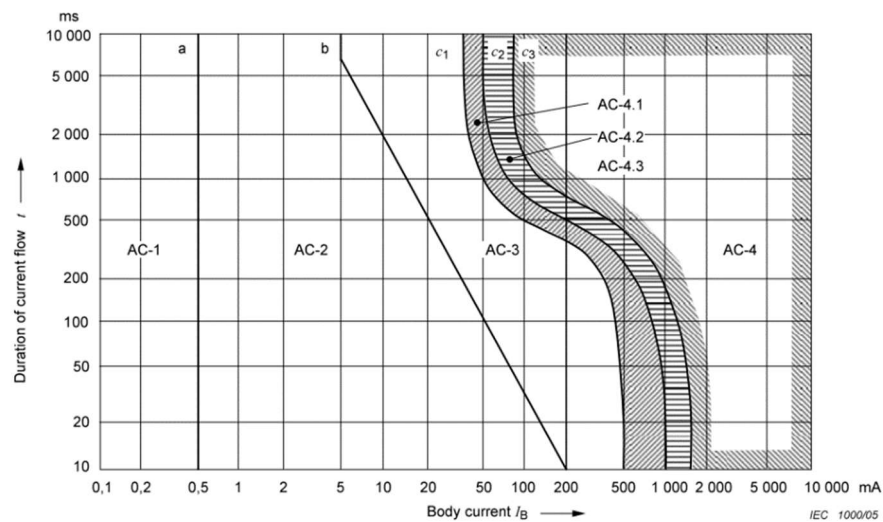


Figure 2.2 – Conventional time/current zones of effects of AC currents (15Hz to 100Hz) on a persons for a current path corresponding to left hand to feet (Australia 2010, p. 35)

Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects
DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
DC-4 <sup>1)</sup>	Above curve $c_1$  $c_1$ - $c_2$  $c_2$ - $c_3$  Beyond curve $c_3$	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time  DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %  DC-4.2 Probability of ventricular fibrillation up to about 50 %  DC-4.3 Probability of ventricular fibrillation above 50 %

<sup>1)</sup> For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feet and for upward current. For other current paths the heart current factor has to be considered.

Figure 2.3 – Time/current zones for DC for hand to feet pathway (Australia 2010, p. 18)

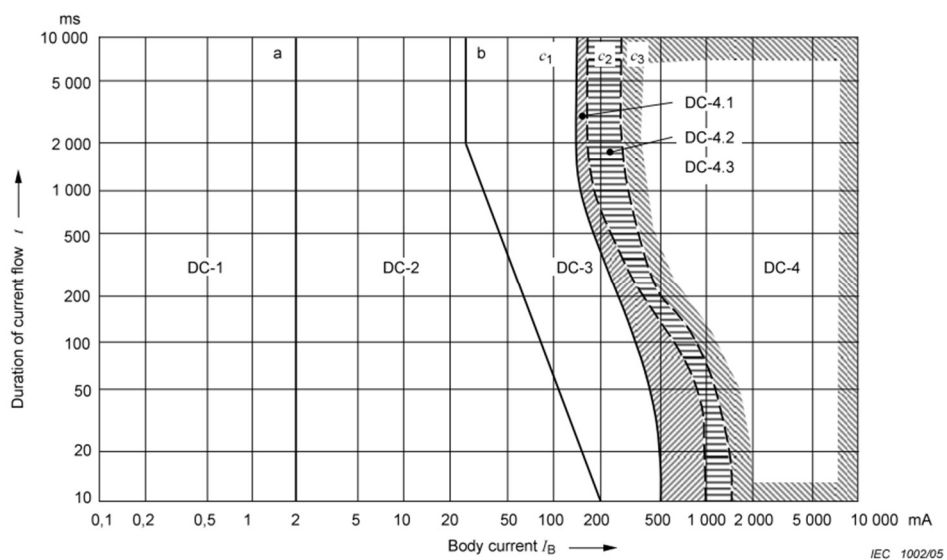


Figure 2.4 – Conventional time/current zones of effects of DC currents on persons for a longitudinal upward current path (Australia 2010, p. 36)

## 2.5 DC Microgrids

The term microgrid has been referenced previously in this document but it is worth clarifying the meaning before advancing any further. Salomonsson et al. (2009) define a microgrid as single or multiple generation sources at a domestic level. This definition is supported by Elsayed et al. (2015, p. 409) who, in reference to DC microgrids, states:

*“Microgrids are local energy networks that involve renewable energy sources and storage systems.”*

Microgrids can operate in AC, DC or hybrid configurations depending on system design and can be configured to be interconnected to the utility grid at low voltage or to operate independently. The configuration (AC or DC) impacts the type and volume of inverters, converters and rectifiers used in the system. Planas et al. (2013) identifies the following advantages for AC and DC microgrids.

Advantages of an AC microgrid include:

- Easy transformation between voltages in comparison to the more complex DC/DC converters.
- Circuit protection is better understood.

Advantages of a DC microgrid include:

- Ease of connection for renewable energy sources such as batteries and PV.
- Improved reliability due to lower impedance and no skin effect. This also enables use of smaller diameter cable.
- No reactive power is present in DC lines resulting in greater use of generator capacity.
- Avoids the need for multiple voltage rectification stages for connecting common household DC loads. Only smaller DC/DC conversions are required.
- No exposure to 50/60Hz frequencies.

Planas et al. (2013) highlighted that almost all experimental microgrids throughout the world utilised AC distribution, however only a couple of years later Rodriguez-Diaz et al. (2015) identifies a number of examples of DC microgrid trials conducted globally. These were:

- A demonstration facility in Fukuoka City, Japan. It operates 380V bus connected renewable generation, storage and DC loads.

- Microgrid in Tohoku Fukusi University in Sedai City, Japan. Operates 400V DC bus which interconnects renewable generation, valve-regulated lead acid batteries and loads.
- A demonstration facility built in Taiwan by the Elegant Power Application Research Centre. It is formed by energy generators, storage devices, DC loads, a monitor and control centre, and an interconnection to the main grid.

While (Vossos et al. 2012) highlighted that:

- in 2009 a residential DC demonstration project was undertaken by Samsung in Korea that resulted in a 1.5-3% efficiency gain over AC.

Europe by contrast has limited LV DC microgrids. The most notable is an office lighting test bed constructed by Philips Research in Eindhoven. This installation utilises 380V DC and 230/400V AC. The DC system has returned an improvement of 2% over the AC system, mainly due to reduced conversions. There have been no reports of a domestic DC microgrid being installed in Australia, which is surprising given the favourable conditions for PV installation.

Microgrid energy sources can be in the form of PV arrays, fuel cells, wind turbines and micro turbines. Electronic converters interface the generation sources to the microgrid with the energy being used by the consumer. If the microgrid is connected to the utility grid then any additional generation, not consumed, is exported back to the grid through their point of common coupling. In addition to this, if the power being consumed exceeds that being generated the consumer will import power from the grid. This type of system requires an intelligent connection to the grid with fast operating protection schemes in order to island the microgrid in the event of an outage or fault on the main utility grid. This prevents the microgrid energising the utility grid in these situations.

If the microgrid has an ESS, such as a battery, then it would operate differently. Excess generation would go to recharging the battery before being exported to the grid, assuming it was connected to the grid. Excess consumption would come from either the grid, the battery or an additional source such as a generator, depending on system configuration. The configuration being referred to here would likely depend on the tariff structure and control mechanisms in place. In order to maximise cost savings, the battery energy would be consumed during times of peak prices with grid energy consumed during off peak times if battery capacity was not sufficient to supply the

entire load. These statements are assuming that the consumer is unable to maximise profits by selling their energy to the utility during peak times. At this stage this is not an option in Australia as a domestic consumer cannot trade directly on the NEM but this may develop in the future.

(Elsayed et al. 2015, p. 408) made the following statement in relation to our energy usage:

*“Many of today’s consumer loads are DC supplied. Electronic based office and home appliance, such as computers, laptops, tablets, phones, printers, TV, microwave ovens and lighting, consume electricity in DC form”*

Fluorescent and solid state lighting (LEDs) involve DC stages and hence it is more efficient to supply them directly with DC rather than complete a conversion at each lighting fixture (Elsayed et al. 2015; Hammerstrom 2007). Variable Speed Drives for pumps, heating, ventilation, A/C, fans, elevators, mills and traction systems also operate on a DC voltage (Elsayed et al. 2015; Hammerstrom 2007). Lotfi and Khodaei (2015) support the expected outcome of this dissertation highlighting that higher efficiency and reduced losses may be possible through the use of DC microgrids in place of AC. These DC grids will allow for easier connection to DC generation sources and reduce the losses resulting from single or multiple conversions. Rotating generation sources in DC do not require synchronising allowing them to operate at their optimum output (Lotfi & Khodaei 2015). During research on this topic it was found that a wealth of information is available on AC microgrids however hybrid and DC microgrid operation is only now starting to become topical. To date the information available on domestic DC microgrids in Australia has been limited.

The following figures obtained from Lotfi and Khodaei (2015, p. 2) display a simple comparison between AC and DC microgrid construction. The microgrid in Figure 2.5 operates on a DC bus whereas the one in Figure 2.6 operates on an AC bus. Both systems are connected to the utility grid. It can be seen that in both configurations there are a number of inverters, rectifiers and converters to make the systems operate. The question to be addressed in this research is to determine which one provides the most efficient configuration for the domestic installation?

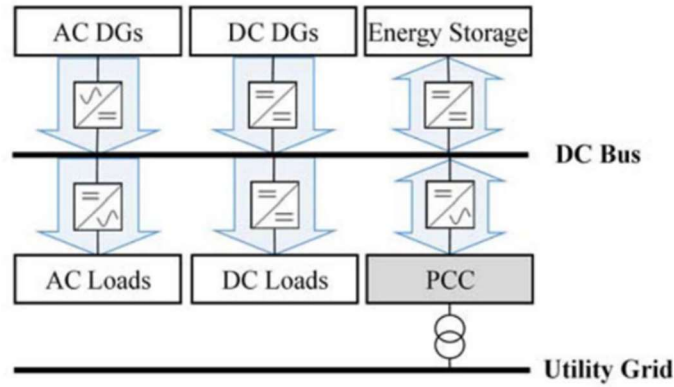


Figure 2.5 – Simple DC microgrid arrangement (Lotfi & Khodaei 2015, p. 2)

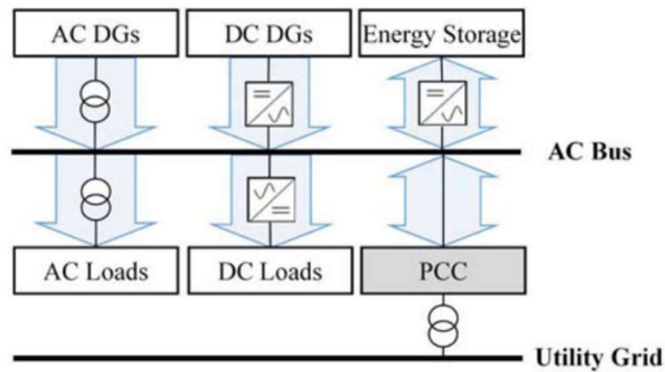


Figure 2.6 – Simple AC microgrid arrangement (Lotfi & Khodaei 2015, p. 2)

Elsayed et al. (2015) estimate that approximately 30% of the AC power distributed is passed through a rectifier and used as DC. The lost energy due to this occurring varies but is normally between 10% and 25%. Hammerstrom (2007) also supports the potential for an energy saving by utilising a DC bus but only predicts a 2.5% to 10% saving, while Dragicevic et al. (2016) and Sechilariu et al. (2015) both reported that a DC bus can be up to 15% more efficient than rectifying from AC to DC. This is quite a significant difference and could be a result of different modelling parameters and appliances. Hammerstrom (2007) professes that approximately 2.5% of energy is lost in each power conversion stage. In a slightly different approach Boeke and Wendt (2015) recorded an efficiency gain of 2% in a DC microgrid test situation by utilising PV energy directly for LED lighting and believe 5% energy savings are potentially a reality in this situation.

Hammerstrom (2007) reviewed a model that proposed the use of a 326V DC system in place of the existing 400 V three phase AC system and concluded that system losses can be reduced, efficiency improved and the same conductors can be used without modification. This proposed model also concluded that the addition of battery storage would provide emergency backup more



efficiently than the use of multiple uninterruptible power supplies. Hammerstrom (2007) highlighted that additional advantages of changing to a DC system would be avoidance of electromagnetic field exposure and less danger if contact with the energy was made.

Renewable energy sources such as PV and fuel cells naturally operate on DC. Wind turbines can eliminate one conversion step if connected to DC and micro turbines are also easier to connect to DC systems (Elsayed et al. 2015). Both AC and DC microgrids can island themselves from the utility grid if they are required to disconnect due to a utility fault. They can also assist the grid by injecting reactive power to provide voltage support (Elsayed et al. 2015).

From a financial perspective the consumer is better off consuming power as it is generated from wind and solar in domestic installations as the return from the grid for excess generation is not significant. Consumers in the future will be looking to have increased control over their energy generation, storage and consumption in order to minimise both the cost and the pollution resulting from their energy usage. There is also a strong possibility of real time pricing being imposed on the consumer in an effort for the utility grid and large generators to better relate charges to consumption patterns.

There are three common configurations for DC microgrids. These are single bus, multi-bus and reconfigurable (Dragicevic et al. 2016). Dragicevic et al. (2016) provides the following summary of each system:

- Single bus is the most basic system configuration where all generation, storage and loads are connected. The limiting factor of this system is that the single bus is uncontrolled and depends mostly on the batteries state of charge and current. If multiple battery banks are installed on the bus then reliability can be improved, however deterioration of the batteries can take place due to unregulated charging from multiple converters.
- Multi-bus configuration improves reliability and works by the load automatically selecting the most appropriate bus, normally based on voltage. A microgrid cluster configuration is where several individual microgrids are connected together, for example neighbouring houses, where they form their own distribution network. This network can then also be connected to the utilities AC grid.
- Reconfigurable configurations offer flexibility during faults or periodic equipment maintenance. Options for this configuration include ring bus - allowing supply from two directions on a single bus; zonal configuration - where multiple sources, with two buses each are connected in series and the load can be provided from either source.

Due to the age and presence of AC power there is a comprehensive list of standards available for generation, transmission and distribution, however it is well documented that there is a lack of LV DC standards. There are a number that are currently in development or being modified to suit DC microgrids. Dragicevic et al. (2016) briefly outlines these standards as follows:

- European standard ETSI EN 300 132-3-1 – mainly focusses on data/telecom equipment up to 400V DC. Voltage range is typically  $365 \pm 15$  V DC. Fault clearance times are specified and maximum steady state and inrush current considered.
- EMerge Alliance was founded in order to promote DC microgrids in energy efficient buildings. It primarily focuses on developing DC microgrid standards in relation to occupied spaces, data/telecom centres and the exterior of buildings.
- IEEE Standard 946 was originally composed for lead acid battery-based auxiliary systems used in generation stations. However, some of the content such as sizing of batteries, determination of battery duty cycles, maintenance, testing and replacement are all still useful today. Battery charger specifications are also discussed.
- IEC SG4 has a focussed committee for standards relating to the LV DC distribution system, up to 1500V. Their primary goal is to coordinate the standards of LV DC distribution across the different areas of use. The committee takes into account energy efficiency, reduction in EMC and reduced consumption of natural resources whilst also discussing protection measuring methods and grounding.
- The recently formed IEEE DC Home committee is also working on standards and a roadmap for both research and commercialisation of DC microgrids. The goal of the DC Home committee is to:
  - create a business case for DC by determining the actual energy losses;
  - identify research required to advance DC;
  - make preliminary recommendations on how DC would be delivered into the homes; and
  - determine the standards that should be followed.
- REbus is an open standard proposing the residential and commercial operation of DC microgrids. REbus operates beside the AC grid and coordinates between the two. The nominal DC bus is 380V, however, this can be changed if required.

- IEEE Standard 1547 is designed for AC distribution with Renewable Energy Systems. It has some important concepts that apply to DC such as grid connected operation and island operation. Normal and abnormal operation are also discussed.

It seems likely that 380V DC will become the standard domestic voltage level with 48V or 24V DC being commonly used for auxiliary supplies.

## 2.6 DC Generation and Storage

DC generation and storage is not a new thing and has been used by those in remote locations for many years, however the systems did not have the capacity to run a modern home without spending an excessive amount of money on storage and generation infrastructure. With constant advances in technology and government subsidies the economic restriction on installing renewable generation in populated areas has reduced. Figure 2.7, commonly known as the duck curve, represents a feeder in Energex's distribution area located in Queensland. It clearly displays the increase in solar PV connections on this feeder over a six-year period. This graph shows the challenges faced by the electricity market in dealing with the increase in domestic PV installations. The growth of rooftop PV installations is confirmed in Figure 2.9. This figure displays four graphs highlighting the cumulative solar installations and capacity within Australia and also the annual volume of installations and capacity. There was clear peak in 2011 and 2012 with a steady decline to present day. This can be attributed to the generous subsidies and feed in tariffs mentioned previously.

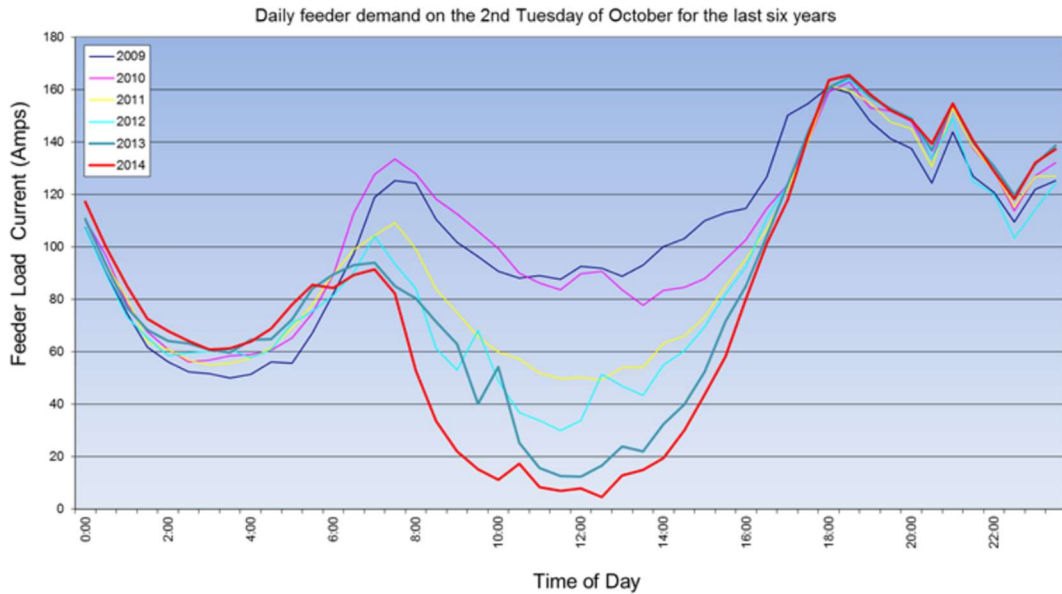


Figure 2.7 – Impact of Solar PV (Stewart 2016)

Another interesting trend in solar connections is the size of the installations being installed. The Australian PV Institute has detailed information on PV connection sizes and volumes with Figure 2.8 showing the trends. As of May 2016 the average system size in Australia was 5.16kW. These two trends tell us that the removal of the generous subsidies and tariffs has reduced the installation rate of new PV systems but conversely there has been an increase in the average system size due to both technology advancement and cost reduction.

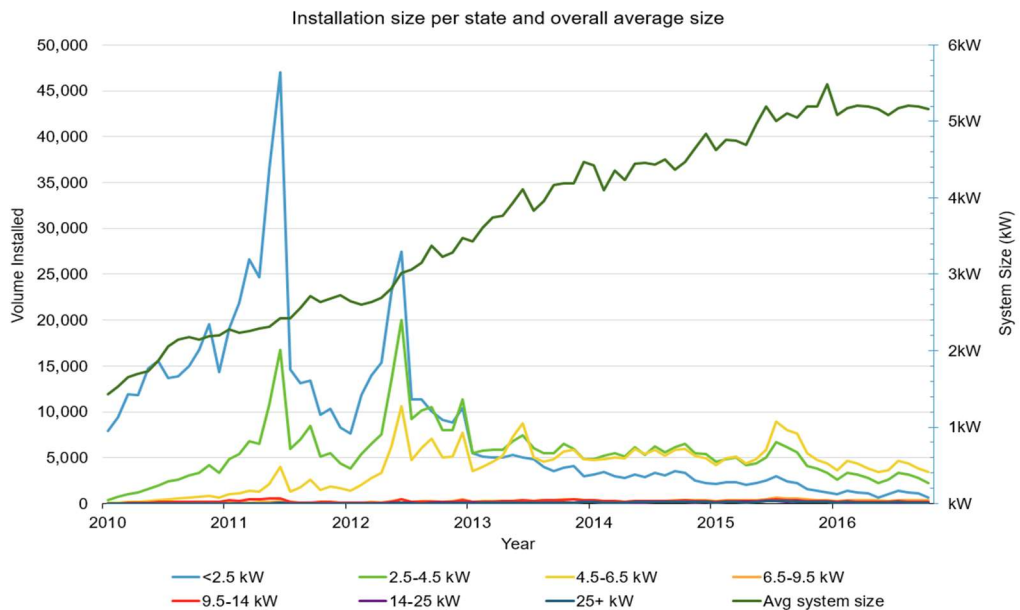


Figure 2.8 – Monthly solar installation volume and overall average size (2016)

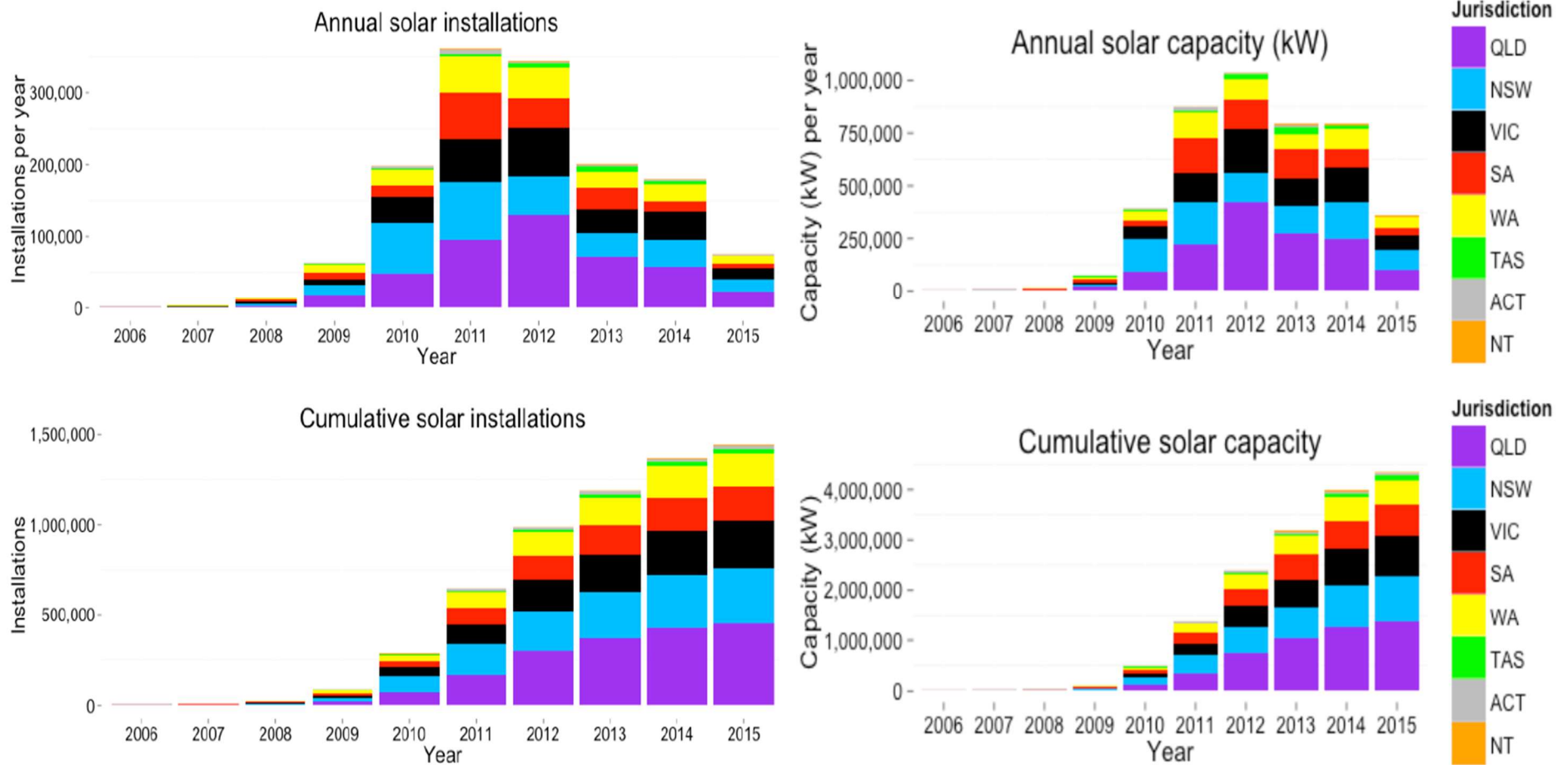


Figure 2.9 – Annual and cumulative solar installations and capacity (Mountain 2016)

The electricity market is faced with the challenge of dealing with this changing consumption profile, however, the introduction of ESS's at either the consumer or utility level may assist in smoothing out the peaks and troughs. One major challenge to adopting DC distribution in the home is the need to still be connected to the utility grid or alternatively install adequate storage capacity as, unlike commercial applications, the load profile generally does not match the generation profile (Vossos et al. 2014).

In typical off grid installations involving battery storage the dynamic stability of the system is assured due to the high capacitance of the battery. The system basically relies on the battery to regulate the voltage and it will alter due to load and charge conditions. By connecting through power electronic converters the voltage can be regulated (Dragicevic et al. 2016).

Battery technology is currently developing quite rapidly but the cost is still too high to make it financially viable. However, with the discontinuing of the high feed in tariffs offered by governments it will likely drive consumers to install their own storage system in an effort to reduce or eliminate their connection to the grid. This decision will not purely be based on economics; it will likely have an emotional component as well. In Australia the tariffs vary quite considerably between states and retailers depending on the network configuration and demand. The current rates vary from \$0.052/kWh to \$0.50/kWh although six out of the eight states/territories are \$0.10/kWh or below (Market 2016). Within the Ausgrid distribution region (Sydney, Central Coast, Newcastle and Hunter regions of NSW) the current flat usage rate is approximately 22c/kWh when referring to the Ausgrid website, therefore it is obvious that the consumer pays noticeably more for consumption than they get paid for excess generation. Most consumers are also required to pay monthly service connection charges to have a service from the grid connected, hence this further sparks interest in renewable energy storage (Speidel & Bräunl 2016).

There are many opportunities for commercial renewable energy generation with Speidel and Bräunl (2016, p. 1214) quoting the following technologies:

*"...solar PV, thermal electric, wind/wave converters, bio fuels, tidal schemes, hydroelectric energy and geothermal energy"*.

However, at a domestic level the only real options for Australians are solar PV and wind.

Solar PV is generated in DC with the panels connected in either series or parallel depending if a high voltage or high current is desired. Solar panels are best used for charging batteries through a DC/DC charger or supplying the domestic installation energy usage through a DC/AC inverter. There are many sources of information now available to help determine expected solar PV output

with Speidel and Bräunl (2016) identifying that modelling using solar radiation and ambient temperature data from the intended installation location is available.

Wind power, as the name suggests, converts wind into electricity via the use of a wind turbine. Wind turbines are available as both commercial and domestic installations. Domestically they are typically under 10kW in size with a cost between \$2,000 and \$10,000 per unit (Speidel & Bräunl 2016). The effectiveness of a wind turbine depends predominately on wind speed which varies according to many different environmental factors (Speidel & Bräunl 2016).

There is an expectation from all consumers that when they want to use electricity it will be there and hence the network must be able to cope with this, particularly during extreme weather events, ie: several cloudy days or extreme temperature, both hot and cold. One of the largest constraints of utilising renewable generation and battery storage is the need for oversizing a system in order to deal with these extreme weather events. This situation sounds familiar with the NEM currently having to manage this (Fairley 2015).

Energy storage techniques are currently undergoing significant development, particularly in the area of batteries. This review will briefly cover the different types of battery storage currently available for domestic installations as they are the natural choice for storing solar PV and wind generated energy.

Lead acid batteries have been around for a long time and are widely used in conventional vehicles, uninterruptable power supplies and operation of protection systems. They come in three different variations; wet cell, gel cell and AGM. Speidel and Bräunl (2016) describes the main disadvantages of lead acid batteries as having a low energy density, long recharge time, regular maintenance on unsealed variations, shortened life when used in residential installations due to the cycling profile and they require hazardous disposal. Their efficiency is between 70 and 90% with a capacity ranging from 0 to 40MW (Planas et al. 2015). Helwig and Ahfock (2015) report that the AGM battery is currently the cheapest battery available for residential storage installations.

The next type of battery is Nickel Cadmium. They also come in three configurations; pocket-plate, sintered-plate and sealed. Despite some advantages and disadvantages over lead acid they are not well suited to domestic installation due to suffering memory effect, negative environmental impact due to cadmium use and high cost (Speidel & Bräunl 2016). Their efficiency is between 60 and 65% with a capacity ranging from 0 to 40MW (Planas et al. 2015).

Nickel Metal Hydride is the third battery type. Speidel and Bräunl (2016, p. 1217) considers them superior to NiCd batteries providing:

*“...excellent safety, abuse resistance, cycle life, and energy density”.*

However, they suffer from a drop in capacity after only a limited number of cycles and in a domestic system, life expectancy of the installation is important and NiMH falls short on this requirement.

The fourth battery type is Nickel Iron. Helwig and Ahfock (2013) report a turnaround efficiency of 65%, a long cycle life with deep discharge, can withstand overcharge, does not suffer thermal runaway and contains a corrosive alkaline electrolyte; however, this does not present any significant environmental constraint. This battery type has been largely unchanged for over 100 years and with some modifications as a result of modern technology and knowledge it presents an economical, environmentally friendly option if space is not at a premium (Helwig & Ahfock 2013)

The fifth battery type is Lithium Ion which are available in various chemistry compositions but all contain the same advantages. Speidel and Bräunl (2016, p. 1217) quotes the following:

*“They are sealed cells, requiring no maintenance, have a long cycle and shelf life, low self-discharge rate, and have high power and energy densities”.*

The main disadvantages to Li-Ion is the initial cost and the protective circuitry required to prevent over power and energy charge and discharge (Speidel & Bräunl 2016). Helwig and Ahfock (2013) also identify the high fire risk in the event of thermal run away during charging, operation or battery management failures. Based on the mentioned positive information they are widely used for electric vehicle energy storage and are very suitable for domestic energy storage. With this dual use it is possible to recycle the batteries from electric vehicles and use them in domestic applications as they are expected to still have around 80% capacity after 10 years (Speidel & Bräunl 2016). This should help to provide greater options and reduced cost of domestic battery installations. Their efficiency is between 85 and 90% with a capacity ranging from 0 to 1MW (Planas et al. 2015).

Speidel and Bräunl (2016, p. 1217) presents the sixth and final battery option as flow batteries, which;

*“...consist of two reservoirs of electrolyte fluid that flow through an electrochemical cell”.*

Zinc/Bromide and Vanadium Redox are the most common compositions with advantages of energy efficiency, low cost environmentally friendly materials, quick recharge and are adequately



power dense (Speidel & Bräunl 2016). They do however require electrolyte to flow, resulting in the need for pumps and control systems. This increases costs and possible points of failure (Speidel & Bräunl 2016). Redflow advanced energy storage currently develop Zinc Bromide flow batteries with approximately 80% round trip efficiency and 100% depth of discharge (Redflow 2016). These batteries are also very suitable for domestic energy storage.

Another type of storage that is available is demand side management. At first glance this does not seem like a storage medium but what it allows is the distribution company to control usage based upon available energy. This can occur via a number of different strategies. Tariff structures such as “time of use” seek to shift the demand profile by changing consumer behaviour, however, this is a long term change and may not always be successful. Some customers can be paid to reduce consumption during periods of high demand, while others may be subject to demand dispatch where devices are installed that allow the utility operator to switch certain loads on and off to manage the peak demand (Fairley 2015). Items such as fridges, freezers, air conditioners and water heaters are switched on and off in order to control peak demand, relying on the stored heat energy in them to have virtually zero impact on the consumers. The aim of this type of demand management is to defer network investment to satisfy the demand spikes that occur only a few times a year. However, with the rise of renewable generation and the variability in relation to output these strategies could be used to create a smarter system. The director of the Florida Institute for Sustainable Energy in Gainesville, Sean Meyn, has stated:

*“We can accommodate a grid powered 50% by renewable energy without the use of batteries.”*  
(Fairley 2015, p. 103).

This type of demand dispatch could be used in an isolated microgrid or in the wider distribution system by adjusting the consumer’s energy usage depending on the available energy in the system. For example, solar forecasting could assist in predicting low generation days allowing consumption to be adjusted before, during and after the event to minimise the risk of running out of power (Speidel & Bräunl 2016).

## 2.7 DC Domestic Appliances

In recent years the installation of domestic rooftop PV systems has been growing rapidly with solid advancements being made in the area of energy storage, particularly BSSs. Vossos et al. (2014) confirms that interest in utilising DC in its raw form rather than inverting to AC is growing,

particularly now that many energy efficient appliances operate internally on DC, referred to as DC-internal from here on.

Common household items that are DC-internal include: all consumer electronics such as television, computers, laptops, DVD players, florescent lighting with electronic ballasts, solid state lighting (LEDs) and brushless DC motors operating on many different voltage levels. Goikoetxea et al. (2013) concluded that one of the most important energy improvements was the connection of LED lighting to a common DC bus. In comparison to an AC induction motor, 5-15% of energy can be saved by utilising an advanced DC brushless motor (Vossos et al. 2014). This figure is increased to between 30-50% where an advanced DC brushless motor replaces a variable speed AC motor (where traditionally conversions from AC to DC and then DC to variable frequency AC take place) in applications such as pumping, refrigeration and fan operation (Amin et al. 2011; Vossos et al. 2014). Finally 50% or greater savings can be achieved by using DC motor driven heat pumps in place of existing resistance heating elements (Vossos et al. 2014).

Vossos et al. (2014) conducted a thorough literature review with the key points listed below:

- The replacement of individual AC/ DC rectifiers with centralised rectifiers and utilisation of DC distribution could yield an estimated 25% saving
- 5% saving when utilising LED's supplied by DC from solar PV over those supplied with AC from solar PV.
- In contrast a 2002 UK study stated;  
*“...a residential PV powered DC distribution system was 3% less efficient compared to the equivalent AC distribution system.”* (Vossos et al. 2014, p. 224)
- Another study found that 326V was the preferred supply voltage but savings and losses of DC distribution largely depended on assumptions of power efficiencies, load timing and type, distribution voltage and the presence of net metering.

The model constructed by Vossos et al. (2014) utilised average residential electricity loads with PV output predicted on geographic location. This model consisted of an AC and DC installation where the AC installation had all appliances with DC internals but supplied by AC (i.e. AC/DC rectifier) whereas the DC installation utilised DC directly except for when grid power was required and an AC/DC inverter was utilised. Apart from the rectifier all appliances were identical. This was done for consistency as it would not be a fair comparison between AC and DC

if the appliance were changed. DC-internal appliances are commonly more energy efficient with an estimated 33% saving over traditional appliances.

Garbesi et al. (2012) established a table of efficiencies based on their literature review in compiling their report. A summary of these are shown in Table 2.1.

<b>Power System Component</b>	<b>Model Efficiency</b>
PV Inverter, includes MPPT	95%
DC Rectifier (Meter to DC supply)	93%
DC Inverter (DC supply to meter)	97%
Charge controller or MPPT	98%
DC/DC converter: 380V to 24V	95%
Battery (one way)	90%

Table 2.1 – Power system full-load conversion efficiencies  
(Garbesi et al. 2012)

Another model was constructed by Amin et al. (2011) comparing 240V AC with 48V DC and 24V DC. This model noted that high power devices are typically located in the laundry and kitchen, which accounted for approximately 1/3 of the load in residential homes in the United States. This model assumed an 85% efficiency for the DC to AC inverter. This literature reports that the 230V AC system has the highest energy consumption whereas the 48V DC system with optimised cable area has the lowest consumption.

Excluding any gains by replacing appliances with more efficient DC internal units, a 7.4% efficiency gain was recorded for a DC house with no storage and a 12.8% gain for one with storage (Vossos et al. 2014). These gains were based on a comparison with a standard AC house.

A model created by Chauhan et al. (2016) utilised three DC voltage levels; 96V, 24V and 12V; with AC/DC rectifier efficiencies between 78-90%. The results of this model show that a DC system does present energy savings when compared to an AC system.

It can be seen that the models above use a range of different DC voltages as each of the authors/researchers seek to find the optimum voltage level. Rodriguez-Diaz et al. (2015) questions the need for utilising 380V DC as it only presents a 0.3% improvement in efficiency over 120V DC and suggests use of a bipolar supply where  $+V_{dc}$ ,  $-V_{dc}$  and  $2V_{dc}$  can be obtained. This improves reliability due to utilising two lines for supply.

Electric Vehicles are a DC load that is forecast to expand rapidly in the near future. As technology advances and the cost of production and hence purchase price reduce their presence in the market will increase. Without an ESS the charging of electric vehicles will receive no benefit from a direct DC connection as they are likely to be charged at home after their users have returned from work. If the charging occurred from a PV connection whilst the user was at work then the benefit would be large (Garbesi et al. 2012).

DC appliances are beginning to increase in availability as the idea of connecting directly to DC sources is increasing. There has always been a market for off-grid and recreational vehicle applications but with the increase in residential PV installations this is now beginning to gain momentum in the residential sector. Vossos et al. (2012) highlights a number of manufacturers of DC components. A brief list of the available items is as follows:

- DC air-conditioning units that can be used with and without battery storage systems
- LED lighting technology. There are a number of manufacturers that produce these and they are easily operated from a DC supply.
- DC Refrigeration. Small number of manufacturers listed. A direct comparison between AC and DC models of the same physical capacity proved that the DC item, on average, was twice as efficient as the AC item.
- Assortment of other items such as fans, microwaves, hair dryers, blenders and heaters are also available, predominantly in 12V DC. This is due to their popular use in recreational vehicles.

In order to promote the adoption of DC-internal devices one option would be to build devices that operate on both AC and DC. Therefore, the product could be sold to either consumer and hence reduce the financial burden and risk associated with the development of pure DC appliances (Mackay et al. 2014).

## 2.8 Residential Energy Use

Energy usage is a term used to describe the total energy consumed regardless of fuel type. Therefore, for residential energy usage per dwelling the major fuel types are Wood, LPG, Natural Gas and Electricity. Other fuel types, such as oil and kerosene, have been excluded due to their minor and declining consumption.

In order to accurately construct models and determine if an efficiency gain is possible by utilising DC distribution in domestic applications the average energy consumption per household for certain appliances must be determined, as well as the usage profile. EnergyConsult (2015) produced a report for the Department of Industry and Science that studied the usage within Australian residential dwellings. Figure 2.10 displays the breakup of energy by end use averaged for all of Australia. These figures vary significantly between states primarily due to climate. This is not a split of electricity consumption but total energy consumed by the residential household.

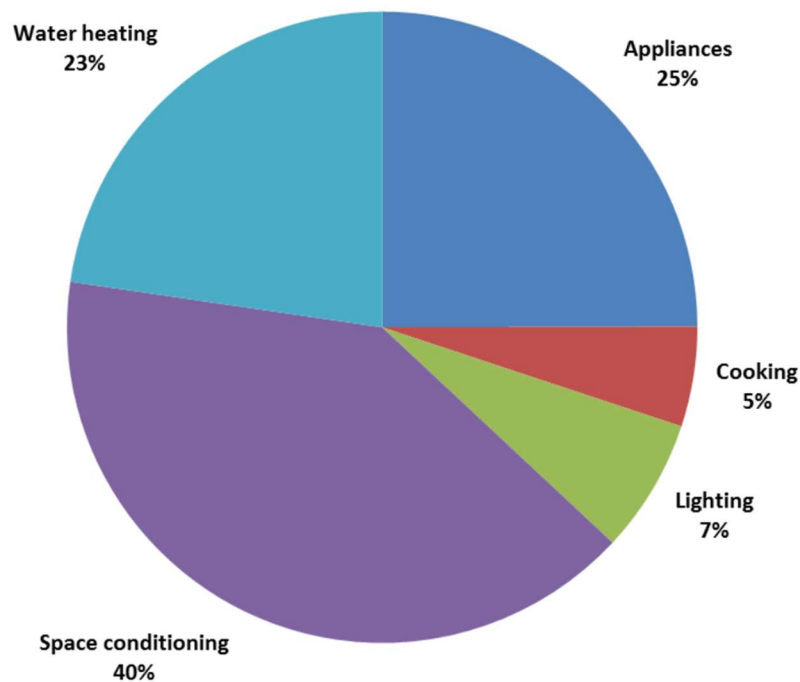


Figure 2.10 – Australian residential energy by end use (EnergyConsult 2015)

Figure 2.11 displays the distribution of energy consumption in the Australian residential sector. In order to address the key objective of this research project, focus is only on the electricity portion of this graph, which is the largest component. Depending on geographic location this percentage

can be significantly different. Some areas do not have access to natural gas, hence, it would be a reasonable assumption that electricity would take a majority of its place.

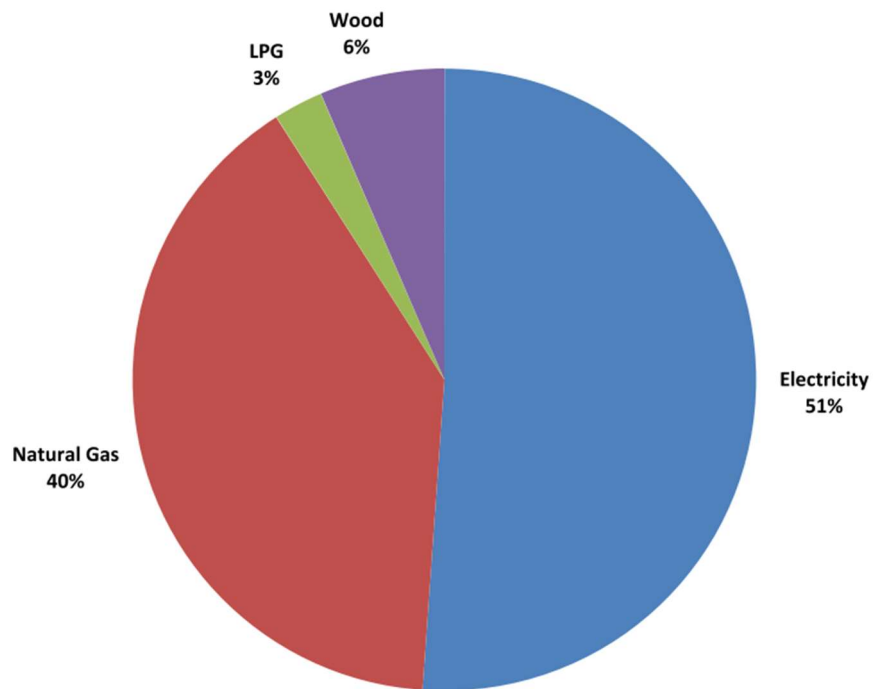


Figure 2.11 – Residential consumption by fuel type (EnergyConsult 2015)

Although the above data is applicable to Australia, it does not supply the breakup of end use for electricity consumption to the same degree of detail as that presented by Garbesi et al. (2012) in Figure 2.12.

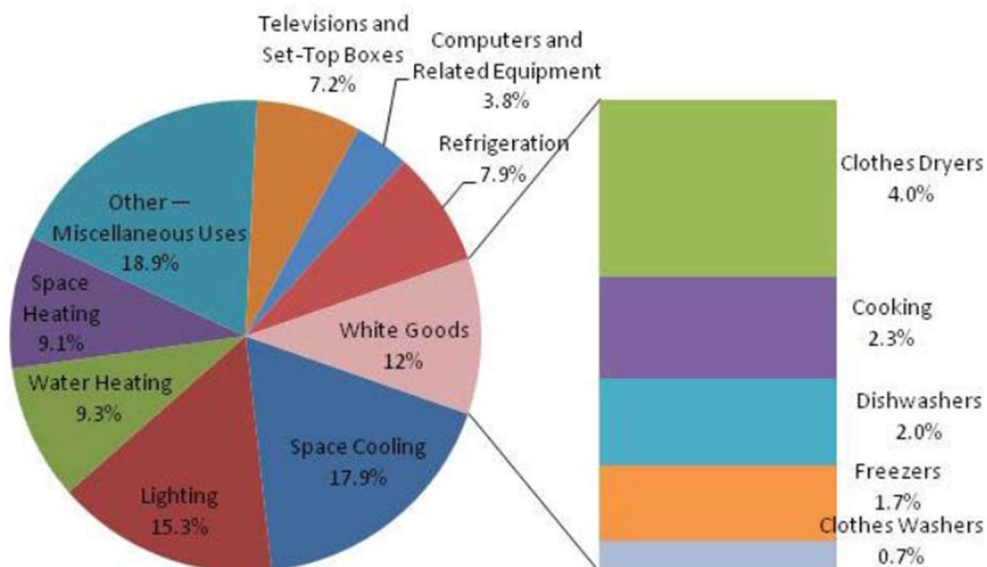


Figure 2.12 – U.S. average residential electricity consumption by end-use in 2009 (Garbesi et al. 2012)

There is limited detailed end use electricity consumption data available for Australian domestic consumers, hence a combination of the available data from both Australia and the U.S. will be compared with results of the logging to create justified loads for the models. It is clear from Figure 2.10 and Figure 2.12 that the biggest consumers of energy are space heating/cooling and water heating.

Actual electricity consumption per household varies depending on many factors including but not limited to; appliance type, house construction, geographic location, climate, human behaviour, lifestyle and number of occupants. Utilising the Energy Made Easy website (AER 2015) an approximation of seasonal and annual household electricity use could be obtained for a specific postcode area. The postcode of 2333 was utilised as this is where a majority of the data was obtained. When defining the parameters, no gas was connected and no pool installed. The results are in Table 2.2 below.

	Summer (kWh/day)	Autumn (kWh/day)	Winter (kWh/day)	Spring (kWh/day)	Annual Consumption (kWh/day)
1 Residents	9.8	10.1	11.1	9.7	10.2
2 Residents	16.7	17.0	19.6	16.4	17.4
3 Residents	20.6	20.2	24.7	20.4	21.5
4 Residents	21.6	20.6	26.9	21.7	22.7
5+ Residents	28.2	26.3	33.3	28.5	29.1

Table 2.2 – Season household electricity usage (AER 2015)

To allow further interpretation of the information of the values presented in Table 2.2 it is important to display the average household size. This information could not be itemised down to a geographical region and only achieved as a regional NSW average. The resulting table is shown below. This table shows that the average number of occupants in a regional NSW household is 2.44, whilst the national average is 2.60. Using the information from both Table 2.2 and Table 2.3 it can be assumed the average household energy consumption in Muswellbrook is equal to 19.20kWh per day.

Number of persons usually resident	Number	%	Australia %
1 person	255,344	26.9	24.3
2 persons	346,967	36.5	36.0
3 persons	135,424	14.3	16.0
4 persons	126,473	13.3	15.7
5 persons	58,588	6.2	6.7
6 or more persons	27,088	2.9	3.3
Total classifiable households	949,884	100.0	100.0

Table 2.3 – Regional NSW average household size

## 2.9 Literature Review Summary

The rivalry between DC and AC systems goes back to the late 1890s where heated public debate occurred between George Westinghouse and Thomas Edison. Ultimately AC emerged as dominant, primarily due to ease of changing voltage levels and hence superior transmission characteristics.

In recent years there has been a significant increase in the installation of solar PV, resulting in a changing consumption profile for domestic customers. An ever increasing volume of electronic devices that operate internally on DC has seen a change in the type of energy we utilise. Finally, there is an impending revolution in regards to BSSs that will further contribute to a change in domestic generation, storage and consumption. Together it is these three key items that have raised the question of domestic DC distribution.

There are many advantages to the use of DC directly including improved efficiency due to the reduction in inverters and rectifiers, improved reliability, improved safety, improved power quality and simpler installation of local generation. The challenges for DC distribution include



protection design, lack of standards and an absence of domestic appliances such as fridges, washing machines, dryers, ovens, stoves and space heating units.

There have been a number of research papers and models built internationally in relation to the use of DC, with many reporting efficiency gains. However, within Australia there is limited information, hence the desire to complete this dissertation to determine if an efficiency gain is possible in an Australian residential installation with and without PV and a BSS.

# Chapter 3      Methodology

## 3.1 Overview

The following section identifies the methodology followed to complete the research project.

1. Initial topic scoping based on preliminary research. This was completed and formed part of the Project Specification document that has been submitted and approved.
2. Conducted thorough research into the use of DC in a domestic installation by reviewing available literature. Areas of focused research were:
  - a. History of DC power distribution.
  - b. Why did AC power distribution become so dominant?
  - c. The challenges of DC protection compared to AC applications.
  - d. Determine if DC is more dangerous than AC, as consumers are not likely to accept a decrease in safety.
  - e. DC microgrids. Provide explanation into their setup and comparison to AC microgrids.
  - f. DC generation and storage options available to the domestic consumer.
  - g. Available domestic DC appliances. If an efficiency gain is possible with DC supply but there is not support from the electrical goods manufacturers, then progress will be halted.
  - h. Residential energy use. This is a key area that will indicate the loads most likely to result in efficiency gains.
3. Obtained data for use within the models. Data was obtained from logging information gathered from a selected number of domestic installations within an urban environment, researched data and justified assumptions.
4. Determined if an efficiency gain could be achieved by eliminating some of the conversion processes by operating on a common or set of common DC voltage levels. This involved producing a number of models using MATLAB to compare energy consumption between AC and DC circuits. These models were produced assuming that identical appliances

were available in both situations. HOMER Pro was utilised to confirm models and determine the economics of each option.

5. Presented findings for efficiency and cost. These figures are backed by comprehensive modelling of domestic installations.

## 3.2 Domestic Load Profiles

### 3.2.1 Logging Information

In order to gather real world data a select number of households in Muswellbrook NSW were logged with a PQ-Box 100 manufactured by a-eberle. This device is an advanced measurement device and when combined with the manufacturers analysing software is able to display a significant volume of data. A summary of the key features as follows.

- Frequency Measurements
- Voltage Measurements, including:
  - phase to neutral
  - phase to phase
  - total harmonic distortion
  - DC voltage
- Harmonics
- Current Measurements, including:
  - line current
  - total harmonic distortion
  - positive, negative and zero sequencing system
  - DC current
- Power Measurements, including:
  - real power – per phase and total
  - apparent power – per phase and total
  - reactive power – per phase and total
  - power factor – per phase and total

- Energy Measurements, including:
  - real energy – per phase and total
  - reactive energy – per phase and total

Each installation was logged for a minimum of seven days with instantaneous measurements taken every thirty seconds. Individual circuits could be logged if necessary, however, time constraints prevented this data being obtained as the logger can only monitor three circuits at one time and the installations studied had up to nine circuits each. This would have resulted in a minimum four-week logging period per household, which was not possible given the project and device time constraints. However, when analysing the loads on each circuit the power usage of cyclic appliances such as fridges could be determined. The main aim of obtaining this data was to assist in developing a realistic model for the average daily energy consumption of a domestic installation. The images below show the logging equipment installed. Note, not all the images are from the same installation.



Figure 3.1 – PQ-Box 100 installed in main switch board

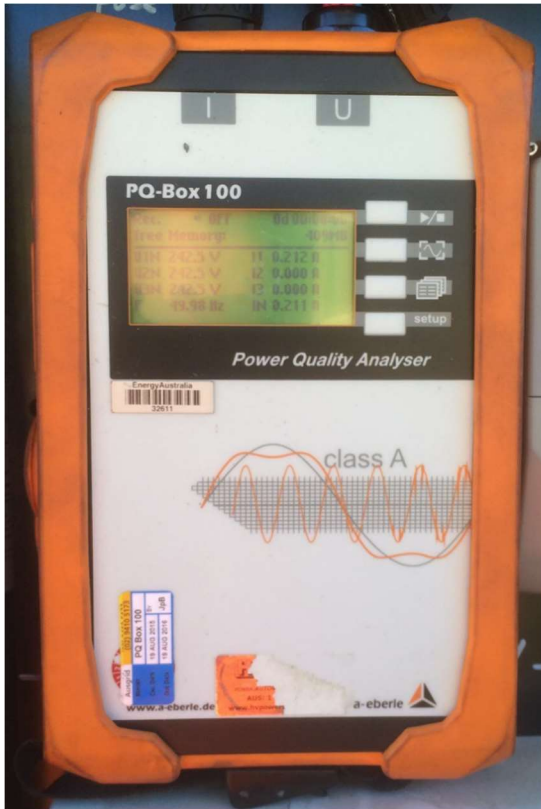


Figure 3.2 – Close up of PQ-Box 100

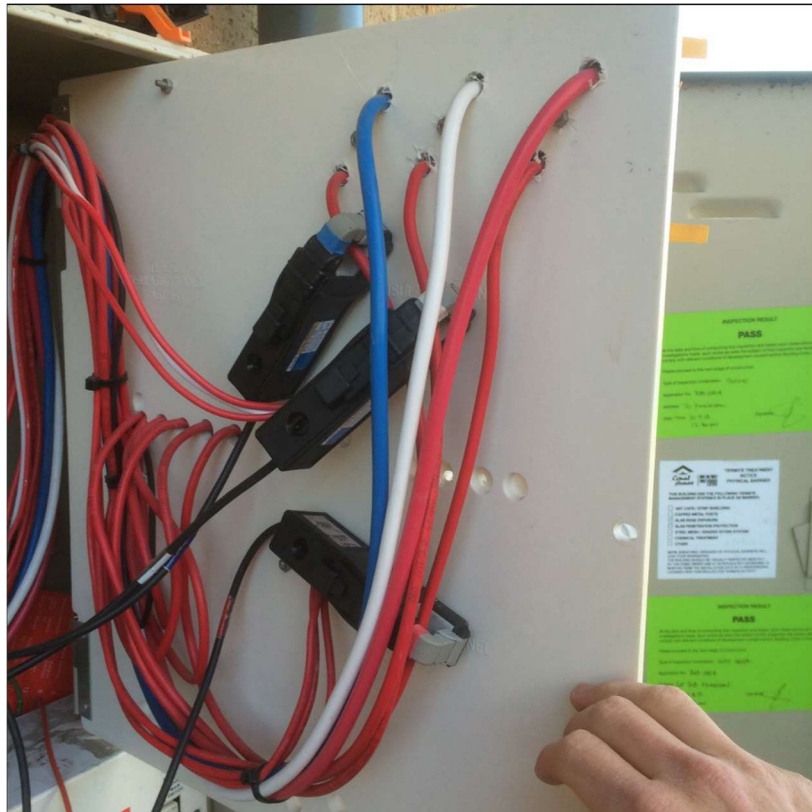


Figure 3.3 – CT's connected to each of the three phases exiting the service fuses

In order to average out the load profile and make the data useful for importing into HOMER Pro the obtained daily data was configured to produce one twenty-four-hour profile per installation in one-minute data increments. As the logger took instantaneous measurements at thirty second intervals for the duration of its logging timeframe, the additional measurements were ignored by removing every second row of data. As there was a substantial amount of information a MATLAB add-on package was used that allowed Excel and MATLAB to communicate directly making the calculations much faster. Once the desired number of measurements were obtained, those occurring at the same interval each day were utilised to create an average consumption for that installation. For example: all the measurements taken at 00:01:00 each day were added together and divided by the number of days logged. This is shown by equation 3.1.

$$\text{Average instantaneous power} = \frac{\text{Day 1 interval} + \text{Day 2 interval} + \dots + \text{Day } n \text{ interval}}{n \text{ days}} \quad (3.1)$$

The resulting average daily profiles for each of the four houses is shown in Figure 3.4. The average maximum, average minimum and average daily temperature information was obtained from the Bureau of Meteorology website where the information can be downloaded for the nearest weather station. For the houses logged, the closest weather station that provided temperature information was Scone Airport which is approximately 30km north of the logged sites.

Table 3.1 details this weather information and the individual house information. It can be noted that the temperatures for the logging period of houses 1 and 2 were quite mild, hence the use of space heating and cooling was generally not required, contributing to a lower average consumption figure.

	House 1	House 2	House 3	House 4
Logging Dates (Complete Days)	12/04/2016 to 18/04/2016	24/04/2016 to 30/04/2016	16/05/2016 to 23/05/2016	30/05/2016 to 09/06/2016
Avg. daily max. temperature for logging period (°C).	27	26.09	24.78	18.29
Avg. daily min. temperature for logging period (°C).	11.39	10.14	6.71	7.74
Avg. daily temperature for logging period (°C).	19.19	18.11	15.74	13.01
Number of adults	2	2	2	2
Number of children (Under age 12)	2	2	0	0
Grid Supply	3 Phase	3 Phase	1 Phase	3 Phase
Hot Water System	Heat pump with electric boost element	Heat pump with electric boost element	Solar with electric boost element	Solar with electric boost element
Solar	No	No	No	1.5kW Net Metered
Average daily grid energy consumption (kWh)	19.09	23.13	24.12	23.51

Table 3.1 – Individual house information

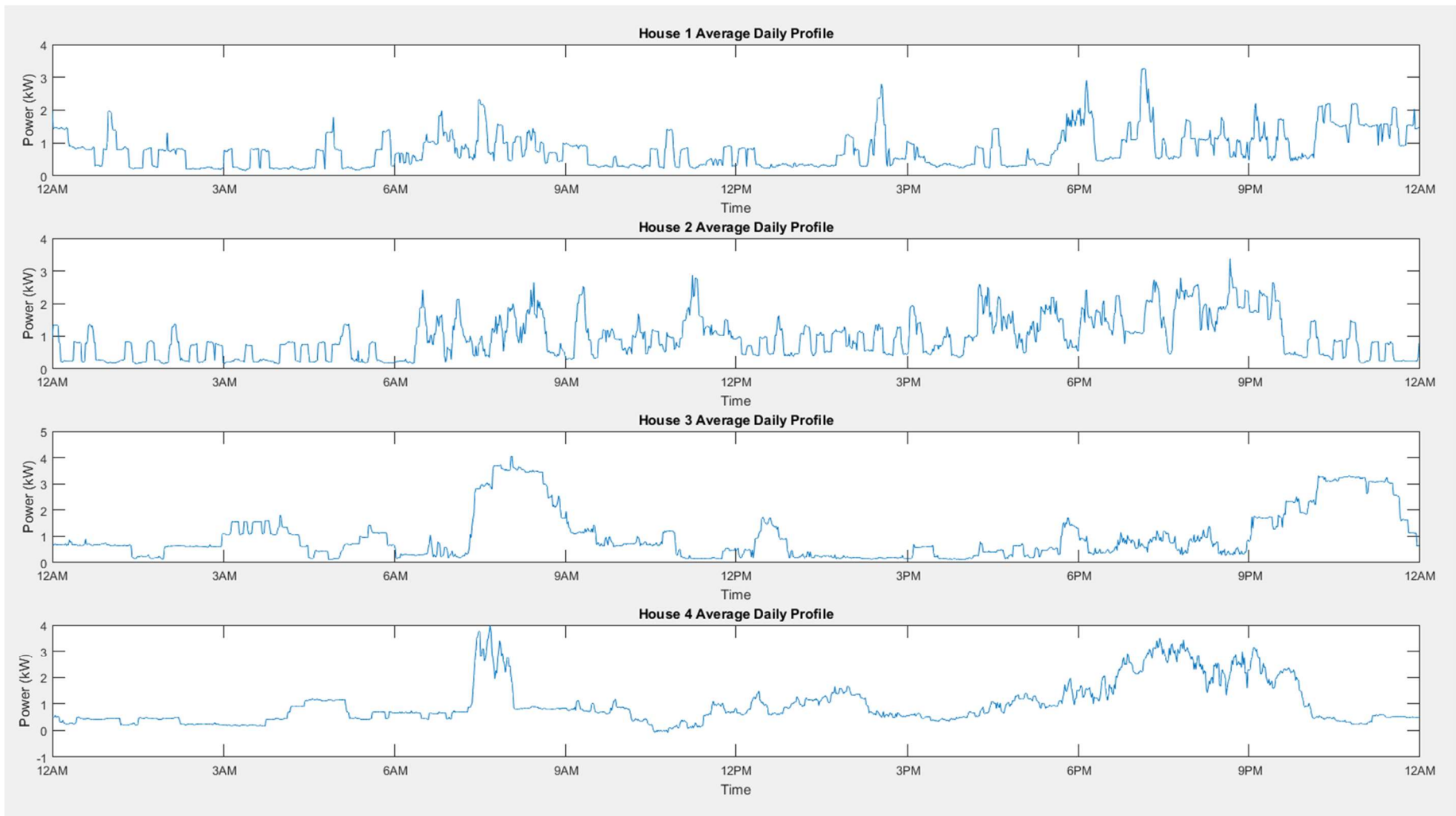


Figure 3.4 – Average daily profile for each of the four houses logged



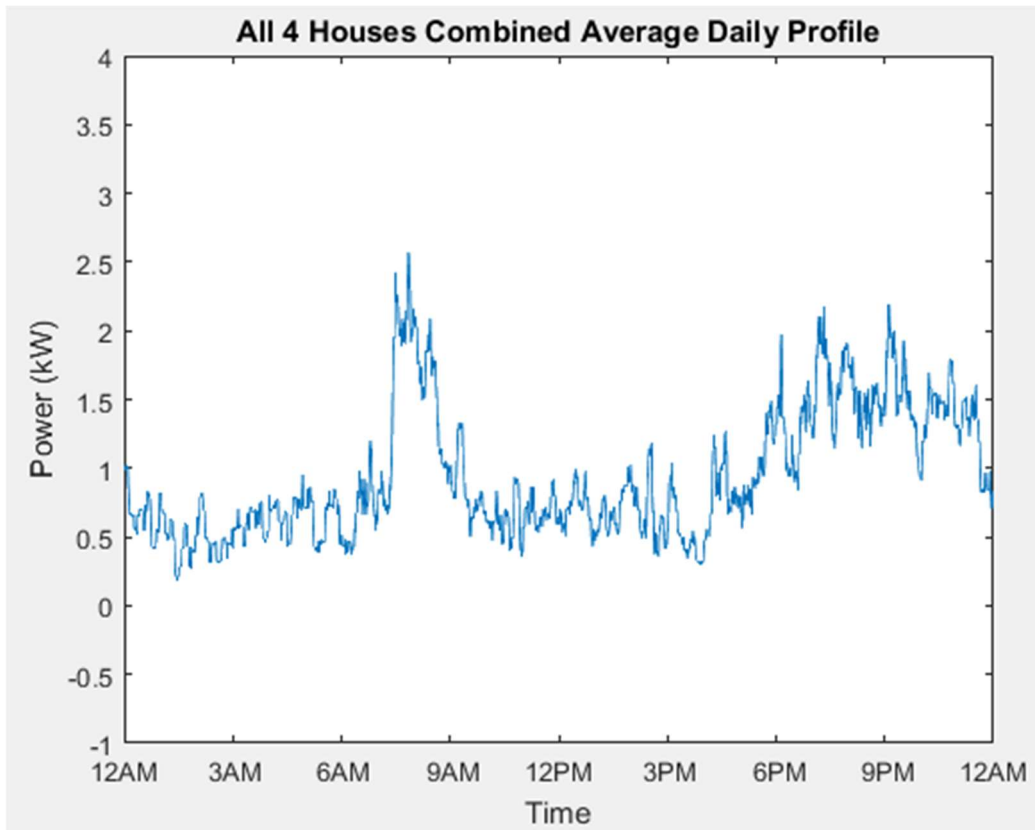


Figure 3.5 – Combined Average Daily Profile for All Four Houses

The combined average profile, shown in Figure 3.5, displays a significant peak around 8am in the morning with a gentler and longer peak in the evening. This profile does vary from the individual household profiles when compared with Figure 3.4 as all the morning peaks are around the same time. The evening peaks however, are distributed over a wider timeframe. When analysing the profiles in Figure 3.4 there are some interesting peaks throughout the day. These are a result of combining weekday and weekend profiles in order to obtain an average. The consumption patterns of a residential household can vary considerably between weekdays and weekends due to the occupant's different usage requirements. This is not so evident in households whose occupant/s work shift work or those that are permanently occupied.

### 3.2.2 Distribution Monitoring System

Monitoring systems are installed on some distribution substations in the Ausgrid network area that measure instantaneous current on each phase at ten-minute intervals. Twelve months worth of data was obtained for four 11kV/400V/230V residential distribution substations in the Hunter region of NSW. This data displays the total load on each phase of the substation, not individual installations.

When analysing the data, it became evident that the logging hardware had not recorded every ten-minute interval for the entire year, which would have totalled 52,560 measurements for each substation. As the devices are powered from the distribution substations themselves any power outages, planned or unplanned, would result in missed measurements. Due to the large quantity of measurements it was necessary to manipulate the data to ensure accurate and consistent interpretation. The manipulation was performed in MATLAB with a script written to perform all functions using the raw data in an excel, xlsx, format.

The first step was to add together the current readings from each of the three phases that occurred at exactly the same timestamp. This provided the total ampere on the substation at that exact moment in time. Once the total current was determined at all the available time instances for the twelve-month period, the readings from the same time each day for a month were added together and divided by the number of readings taken. This then enabled calculation of average daily amperes at that time interval for that month. This task was repeated for the twelve months of the year for all four substations. These current readings were multiplied by 250V to obtain the kVA readings, then multiplied by a power factor of 0.9 to obtain the kW readings. Unfortunately, the true voltage readings for these timestamps was unavailable, therefore, a voltage level of 250V was chosen due to the monitoring equipment being installed on the low voltage bus of the distribution substation. The supply standard specifies that the accepted voltage range is 230V +10% / -6%, so it was determined to set the voltage near the maximum as this is the voltage level at the distribution substation bus and must allow for voltage drop along the LV distributor. The power factor figure was chosen as it is widely accepted that the residential power factor is between 0.90 and 0.95. This was confirmed by discussions with colleagues involved in distribution planning and customer connections. Following this the average daily consumption per substation was established with the results displayed in Table 3.2

It is evident from this table that the figure for substation 4 is noticeably lower than the others. This is a direct result of it being located in a more densely populated area, shown by the large number of installations connected. This large number of connections likely means a high percentage of small dwellings and less occupants, resulting in a lower average consumption per installation.

	Substation 1	Substation 2	Substation 3	Substation 4
Installations connected	44	39	102	196
Grid connected solar (kW)	31.1	12.5	82.9 (incl. 1x30kW + 1x12kW)	83.64 (incl. 1x27kW)
Average daily consumption per installation (kWh)	22.19	15.36	18.94	13.86

Table 3.2 – Distribution substation usage

The data was then divided up into the four seasons; summer, autumn, winter and spring, for each of the four substations by evaluating the three monthly averages. The substation averages were then combined to establish the seasonal averages shown in Table 3.3 and Figure 3.6.

The profiles for all four seasons do not show a rise in energy consumption in the morning between 7am to 9am. This was contrary to the logging of individual households and also the literature referenced in Chapter 2 . This prompted further analysis of the information to verify that it was being interpreted correctly. A selection of manual calculations was completed on the raw data to verify the results, with the outcome being positive. A random number of individual days were also analysed and these did display the expected morning peak but when averaged across the months and seasons it was not present.

The average daily kWh consumption per installation that was recorded for each of the four seasons showed very little variation throughout the year. This is most likely due to the diversity of the installations attached to each substation as there was no way to determine if the installations were vacant, single occupant, dual occupant, families or the type of loads connected to each. Other factors influencing the consumption can be the type of space heating and cooling, such as wood fires and ceiling fans.

	Summer	Autumn	Winter	Spring
Average daily consumption per installation (kWh)	17.70	17.54	17.53	17.59

Table 3.3 – Distribution substation seasonal average

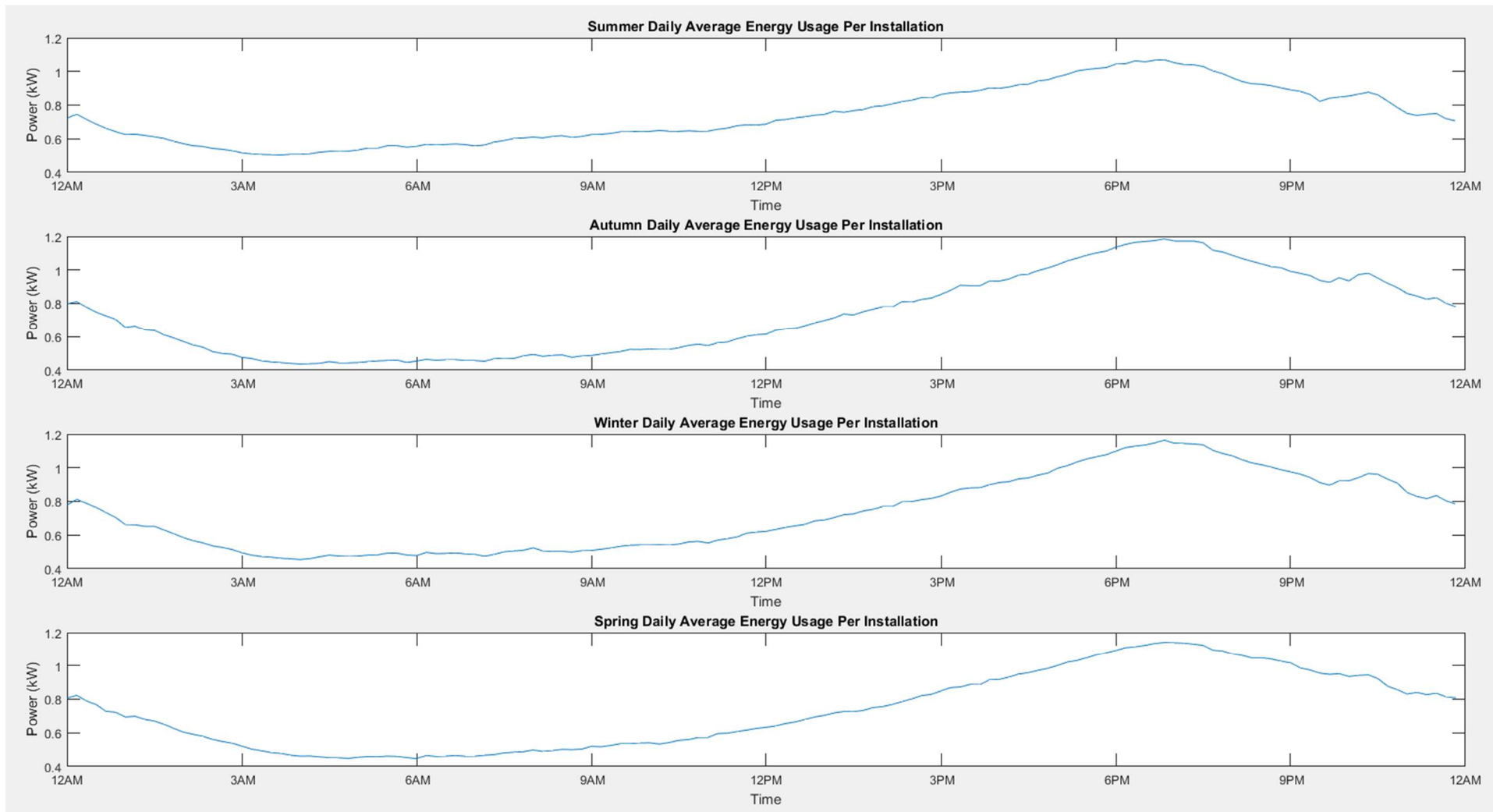


Figure 3.6 – Seasonal daily average energy usage per installation

### 3.3 Model Development and Analysis

Modelling was conducted using a student version of MATLAB and Simulink in addition to HOMER Pro. The modelling of AC and DC domestic installations seeks to identify if an energy saving is present by utilising DC directly rather than DC-internal loads connected to an AC supply.

Preliminary modelling work focussed on modelling each appliance in the home individually using Simulink and the add on packages Simscape, Simscape Power Systems and Simscape Electronics. The use of these packages allows the modelling of the physical system and then interfacing back to Simulink and MATLAB. After some experimentation with this process the decision was made not to model the physical system as there were too many unknown variables that resulted in a large number of assumptions.

The revised modelling procedure established a list of common household appliances and load profiles in order to simulate their usage. Due to the variations in electricity usage depending on time of year, geographic location, climatic conditions, consumer behaviour and appliance type, in a real situation these figures could vary quite considerably. The inputs of the MATLAB model can be varied in order to alter the results in accordance with individual situations if required. The total daily usage built in these models is for a four-person household located in Muswellbrook, a rural town in the Upper Hunter Valley region of New South Wales Australia, shown in Figure 3.7. The installation modelled had no one home during the day (Monday to Friday), no gas connected, no pool installed and no wood heater.

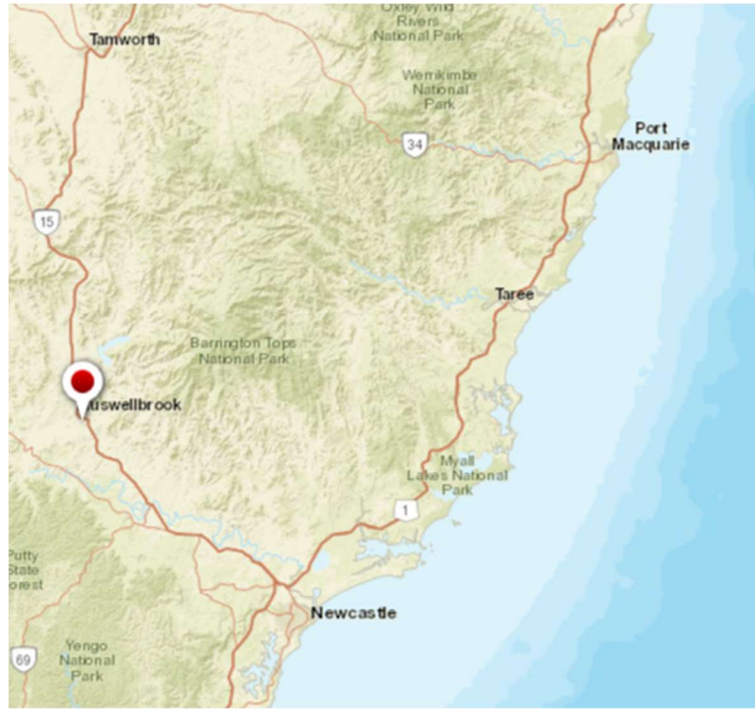


Figure 3.7 – Model location

Typical household loads can be separated into three different load types; constant power, constant current and constant impedance. This is an important feature as for a constant power load, such as fridges and pumps, the current increases if the voltage decreases to ensure the same power is provided to the load. This type of situation has other effects, as a low supply voltage resulting in higher current generally results in lower motor efficiency and the need for the motor to work harder. This often causes a rise in motor temperature. In a constant current load, the current remains fixed regardless of the input voltage. For a constant impedance load, the current varies in proportion to the voltage. For example, if the voltage increases by a multiple of two, the current also increases by a multiple of two. The same relationship exists if the voltage reduces.

For the purpose of the developed models it has been assumed that all connected loads are constant power and DC internal. This method was selected in order to have a set power consumption at each and every load to allow the calculation of energy usage and cable voltage drop. The other reason for constant power is that the run times have been defined and are finite. For a situation where the load is resistive and the voltage and hence current fall, the load would not be producing the power for its intended function. In an example such as a stove element, the result is that the element won't get as hot and will be required to operate for a longer period of time to achieve the same level of work, resulting in the same energy use.

As highlighted above, cable voltage drop is required in order to calculate the energy lost in the cables. To calculate this figure a few parameters and formulas needed to be identified and utilised. Australia (2009, p. 86) revealed the following formula to calculate voltage drop.

$$V_d = \frac{L \times I \times V_c}{1000} \quad (3.2)$$

Where,

$V_d$  = Voltage drop in volts

$I$  = Current in ampre

$L$  = length of cable in meters

$V_c$  = millivolt drop per ampere – meter,  $\frac{mV}{A.m}$

As seen in the Formula 4.1 the current flowing through the conductor is required. To obtain this value the fixed power load was divided by the installation voltage, assumed to be 230V, and for an AC installation a power factor of 0.9 applied. A 230V installation voltage was chosen as this is the nominal voltage level for Australian LV distribution networks. A power factor of 0.9 was chosen as it is well accepted that for residential installations this value is between 0.9 and 0.95 as discussed in section 3.2.2.

The value of  $V_c$  was obtained from the relevant tables within Australia (2009). For domestic house cabling the following figures were obtained from Table 42 located in Australia (2009, p. 103). The  $V_c$  values used were based on a conductor temperature of 60°C and calculated for single phase/DC voltage drop. The important component here is to ensure consistency across the models, hence only one temperature rating was utilised. Nominal wire sizes for a domestic installation are 1mm<sup>2</sup> or 1.5mm<sup>2</sup> for lighting circuits, 2.5mm<sup>2</sup> for socket outlets and larger cables for the oven, stovetop, air conditioner and hot water system depending on location and size.

Conductor size (mm <sup>2</sup> )	Single phase voltage drop per ampere-meter (Vc)
1	49.07
1.5	31.52
2.5	17.21
4	10.67
6	7.14
10	4.24
16	2.67
25	1.70
35	1.22
50	0.91
70	0.64
95	0.48

Table 3.4 – Voltage drop per ampere-meter for domestic cables

As each and every house has a differing number of circuits and circuit lengths depending on house design and appliance location, assumptions have been made in order to establish a model. Again, the importance was on making the installations and loads consistent to ensure a fair comparison. To form the model, the following cable sizes were used; 1.5mm<sup>2</sup> for the lighting circuits; 2.5mm<sup>2</sup> for the power circuits; 4mm<sup>2</sup> for the hot water system; 6mm<sup>2</sup> for the air-conditioning system and 6mm<sup>2</sup> for the stove and oven circuit. A cable length of 30 meters has been applied to each of the circuits. This value can vary quite significantly between different circuits and ultimately depends on the size of the house and the location of the loads. This length can be varied in the model but is a figure that was estimated as an acceptable average for a normal residential installation.

Once the voltage drop  $V_d$  was calculated the figure was multiplied by the current flowing in the circuit to determine the VA lost in the cable. Finally, the VA figure was multiplied by the 0.9 power factor to give kW. This whole process of finding the cable loss has been streamlined in the models by simplifying some formulas but this is the logic behind the processes implemented. This power loss in the cables was then added to the load power consumption or in the case of PV, subtracted from the generation quantity.

To successfully model if an efficiency gain is possible when utilising direct DC all appliances have been assumed to be DC internal. This decision was made as DC internal appliances are inherently more efficient than their equivalent AC counterparts as discussed in section 2.7. To accommodate the DC internal appliances, 88% efficient AC/DC rectifiers were installed on all simulated loads that have the potential to be replaced with more efficient DC internal devices. All appliances that were already DC internal also displayed the AC/DC rectifier. The only variation to these DC internal appliances are those that are purely resistive, such as a stove element or hot water booster element. These appliances yield no benefit by changing from AC to DC. Some



figures for appliances were obtained from the Energy Rating website (Commonwealth of Australia 2016). These are defined by a star rating in the comments column of Table 3.5.

The consumption figures, operating times and appliance duty cycles were chosen in order to simulate a typical domestic installation with four occupants. It is accepted that each installation is unique and these figures could vary widely.

From the logging data the autumn usage for a residential household with four occupants averaged at 21.11kWh/day, based on house 1 at 19.09kWh/day and house 2 at 23.13kWh/day. Table 2.2 displays the autumn average as 20.60kWh/day. The autumn figures set using the simulated appliance data shown in Table 3.5 result in an average daily autumn consumption of 19.53kWh per day. This is slightly below the averages but gaining an exact match is difficult given a finite number of appliances and the limitation of modelling human behaviour. The other three seasons had the runtimes and appliance utilisation adjusted to be within approximately 10% of the Table 2.2 seasonal averages with the average annual daily consumption being within 0.26%.

Appliance/Device	Rated/Measured consumption, including rectifier (W) (M)= measured.	Autumn Operating Time (Duty Cycle)	Winter Operating Time (Duty Cycle)	Spring Operating Time (Duty Cycle)	Summer Operating Time (Duty Cycle)	Comments
Fridge	111	0000 – 2400 (35%)	0000 – 2400 (35%)	0000 – 2400 (35%)	0000 – 2400 (35%)	4 Star 2 Door 300L Fridge 150L Freezer
Bar Fridge	79	0000 – 2400 (20%)	0000 – 2400 (20%)	0000 – 2400 (20%)	0000 – 2400 (20%)	4 Star Single Door 125L Fridge
Dishwasher	315	2200 - 2359	2200 - 2359	2200 - 2359	2200 - 2359	4 Star 14 Place Setting Assume 2 hr cycle
Washing Machine	110 (M)	2000 - 2130	2000 - 2130	2000 - 2130	2000 - 2130	5 Star 8kg Assume 1.5hr cycle Cold wash
Clothes Dryer (Heat Pump)	1026					7 Star 8kg Assume 3hr cycle
Air Conditioner	2100 (Full load is 4200)	1800 – 2200 (30%)	1700 – 0700 (30%) -	1700 – 2200 (30%)	1700 – 0700 (30%) -	Input power based on Daikin (FDYQ140LBV1 / RZQS140AV1)

Table 3.5 – Appliance ratings and operating times for use in models

Appliance/Device	Rated/Measured consumption, including rectifier (W) (M)= measured.	Autumn Operating Time (Duty Cycle)	Winter Operating Time (Duty Cycle)	Spring Operating Time (Duty Cycle)	Summer Operating Time (Duty Cycle)	Comments
TV	80	0600 - 0700 1730 - 2200	0600 - 0700 1730 - 2200	0600 - 0700 1730 - 2200	0600 - 0700 1730 - 2200	5 Star 60" Ultra High Definition LED
Lights	264	0530 - 0630 1800 - 2300	0530 - 0630 1700 - 2300	0530 - 0630 1800 - 2300	0530 - 0630 1900 - 2300	
Heat Lamps	500	0545 - 0600 2245 - 2300	0545 - 0600 2230 - 2300	0545 - 0600 2245 - 2300		
Hot Water (Heat Pump)	1300	0000 - 2400 (8%)	0000 - 2400 (10%)	0000 - 2400 (8%)	0000 - 2400 (6%)	
Hot Water Booster	3200	2300 - 2359	2300 - 2359	2300 - 2359	0000 - 0100 2300 - 2359	
Stove & Range hood	825	1745 - 1800	1745 - 1800	1745 - 1800	1745 - 1800	
Oven	3176 (element on) 124 (element off)	1730 - 1800 (20%)	1730 - 1800 (20%)	1730 - 1800 (20%)	1745 - 1800 (20%)	
Game Console	68	2000 - 2300	2000 - 2300	2000 - 2300	2000 - 2300	
Computer	55	1930 - 2300	1930 - 2300	1930 - 2300	1930 - 2300	
Base Load (eg. standby items, alarm, router)	125	0000 - 2400	0000 - 2400	0000 - 2400	0000 - 2400	

Table 3.5 – Appliance ratings and operating times for use in models

In order to simulate many different scenarios two Simulink models, with various different options internally, and one MATLAB script were created to cover the following configurations:

- Configuration 1 - AC house with DC internal appliances
- Configuration 2 – Removal of appliance AC/DC rectifiers
- Configuration 3 – Removal of appliance AC/DC rectifiers with reduction in baseload
- Configuration 4 - Utilising a common DC bus with central AC/DC rectifier
- Configuration 5 – Two DC buses supplied by AC grid through a central rectifier
- Configuration 6 – AC house with total daily solar contribution
- Configuration 7 – AC house with PV installed, following generation profile
- Configuration 8 – Two DC buses supplied by AC grid through a central rectifier with PV connected to higher DC voltage
- Configuration 9 – AC house with PV and batteries installed
- Configuration 10 – Two DC buses supplied by AC grid through a central rectifier with PV and batteries connected to higher DC voltage
- Configuration 11 - Two DC buses supplied by AC grid through a central rectifier with PV and batteries connected to lower DC voltage

The Simulink models were constructed from load to supply and operated on a purely mathematical and logic simulation. This type of model involved thinking from a different perspective as everything was looking at the energy usage moving progressively upstream from the load device. As each of the configurations is discussed in the following sections, a simple block diagram of each will be displayed. When compared to the Simulink models these block diagrams will visually look much different but they accurately represent the basic structure of each configuration.

These two Simulink models are called from a single MATLAB script depending on the scenario being assessed. This method minimised the number of Simulink models and ensured consistency in regards to each configuration assessed.

In the first instance each configuration was developed for the season of autumn. This was due to the logging data being obtained during that season. Once each configuration was perfected for a typical autumn day the results were repeated for the entire season and then with revised inputs for the subsequent seasons.

During the development of the configurations the efficiencies of a number of components had to be determined in order to make a valid and fair comparison. In conducting the literature review there were many references to the efficiencies of converters, inverters and rectifiers that ranged from 78% to 98% depending on the device and the application. The most comprehensive analysis was developed by Garbesi et al. (2012) with the results displayed in Table 2.1. A detailed analysis of how these figures were determined as well as AC/DC conversion efficiencies is available in Appendix A and Appendix B of Garbesi et al. (2012, pp. 44 - 50). Utilising a majority of these figures Table 3.6 displays the efficiencies used in the models.

<b>Power System Component</b>	<b>Model Efficiency</b>
Appliance rectifier	88%
Solar inverter	95%
Grid rectifier	93%
Inverter	97%
Battery charger	98%
DC/DC converter: 380V to 24V	95%
Battery (one way)	91%

Table 3.6 – Component efficiencies used in models

PV generation introduces a DC source into the electrical installation and was one of the reasons for looking at the potential improvement in efficiency by consuming this energy in its raw form. To allow for PV simulation the generation figures had to be included in some of the configurations. As stated previously the modelling was based in the Upper Hunter Valley of New South Wales and as such it was important to obtain daily global exposure for the solar in this area. Three different sources of information were obtained in an attempt to be as accurate as possible.

The first quantity of data was from the St Heliers weather station located just on the edge of Muswellbrook township. This weather station offered average daily global exposure per month over many years. Using the data from 1990 to 2016 the average monthly global exposure figures were obtained. This monthly data was then used to calculate the average seasonal exposure.

The second quantity of data was from HOMER Pro where the solar GHI information is loaded from the NASA Surface meteorology and Solar Energy database. These figures are loaded into

HOMER Pro and represent to the user the average daily exposure per month. HOMER Pro then applies a profile to this figure to allow exporting of the generation in hourly values.

The third quantity of data was from the Wagga weather station. This is located approximately 455km to the South West of Muswellbrook, however is the closest weather station to Muswellbrook that provided one-minute solar irradiance data for an entire twelve-month period. The data utilised was for the 2014 calendar year as it was the most recent period that was not missing any readings. This data was then modified using Microsoft Excel to determine average daily solar irradiance per minute for each of the twelve months. From these monthly values the data was then manipulated to give the average irradiance per minute for each of the four seasons. One limitation of this data is that only one twelve-month period was utilised due to the data processing required to extract the information.

The three methods described for extracting solar information have their figures available in Table D.1. This table shows that the Wagga data has a maximum variation of 18.1% from the other two data sources for one of the seasons, when comparing average daily solar exposure. But when reviewing the average annual daily solar exposure, it is within 3%. This means it would be a closer representation to utilise either the HOMER Pro data or the Muswellbrook weather station data when establishing a generation profile, however, both of these only provide a daily solar exposure figure and require an approximated profile to be developed. As a result, the Wagga data was utilised as it was already available in 1-minute time increments which allowed better correlation with the load profiles. This does result in an error for the average daily solar exposure for the specified geographical location but does correctly show the process and achieves the correct outcomes given the parameters inputted. If utilising the model to analyse a specific installation it will be important to obtain the correct minute solar irradiance data for that geographic location.

In all of these data sets the figures are in  $kW/m^2$ . In a perfect situation 1kW of energy would be produced per square meter that the sun contacts the earth's surface, however this is not the case due to a number of factors including angle of incidence, orientation and climatic conditions.

In regards to the MATLAB calculations performed on the size of the PV array, the efficiency of the panels has been ignored. This has been done as only energy output is required. In calculating total output, the size of the system has been multiplied by the irradiance value or daily exposure value. This has been done under the assumption that a solar panel that is 20% efficient will require 5 square meters of surface area to achieve a 1kW rating. If the irradiance figure is  $0.8kW/m^2$

then the formula 4.1 can be applied. This results in a figure of 0.8kW, the same as multiplying 1kW by the irradiance value.

$$\text{Generated power (kW)} = \text{PV Area (m}^2\text{)} \times \text{PV efficiency} \times \text{Irradiance} \left( \frac{\text{kW}}{\text{m}^2} \right) \quad (3.3)$$

The operational voltage of the PV array was varied during the modelling process but ultimately a voltage of 240V DC was selected. The lower voltages of 24V and 48V DC were also trialled but due to the high current values the voltage drop was excessive and required multiple strings to be installed. The higher DC voltage reduces the current in the cables between the panels and the inverter, hence minimising the voltage drop. As all power from solar panels must be utilised through either an inverter, MPPT, DC charger or DC/DC converter the utilisation of a higher voltage had minimal effect on these conversion losses.

With the addition of a BSS the model is only concerned with the usable battery capacity and does not account for the different battery types and therefore parameters such as charge rates, discharge rates and depth of discharge. The MATLAB model incorporates a simulated storage system operating on limits, whereas the HOMER Pro model has a generic battery installed from the library.

HOMER Pro was utilised to confirm the MATLAB model and develop a cost comparison. All models were configured to ensure economic minimisation. In order to ensure a fair comparison, the load profiles generated from MATLAB were imported into HOMER Pro. HOMER Pro models are confined to one AC bus and one DC bus which did prove a challenge with some of the configurations based around a dual DC bus arrangement. Details of these models will be discussed in the following subsections.

The AC grid in HOMER Pro was configured to have two sensitivity variables based on the Energy Australia Standard Offer Tariff structures. The two tariff structures selected were Peak usage, which is a flat rate per kWh of consumption, and Residential Time of Use. A breakup of the two is shown in Table 3.7. For the purpose of the model only the higher charge is being utilised when modelling the Peak tariff structure. The feed in tariff for excess solar generation is a fixed rate for all Energy Australia customers in Ausgrid's distribution area and is also defined in Table 3.7.

Tariff Structure	Applicable Charges	Constraint	Price (incl. GST)
Peak	Usage	First 10.9589kWh per day	26.72571 cents per kWh
		Next 10.9589kWh per day	26.1217 cents per kWh
		Balance	25.52869 cents per kWh
	Daily Supply Charge		83.9025 cents per day
Residential Time of Use	Peak Usage	Between 2pm & 8pm, Monday to Friday	53.98844 cents per kWh
	Off Peak Usage	Between 10pm & 7am, Monday to Sunday	12.03719 cents per kWh
	Shoulder Usage	Between 7am & 2pm and 8pm & 10pm Monday to Friday. Between 7am & 10pm Saturday, Sunday & Public Holidays	21.62446 cents per kWh
	Daily Supply Charge		95.6494 cents per day
Feed in Tariff	Usage	Per unit	5.2 cents per kWh (excl. GST)

Table 3.7 – Electricity Tariffs used in HOMER Pro

HOMER Pro required the discount rate (interest), the inflation rate and project lifetime to be selected. Based on RBA data from September 1991 to August 2016 the average cash rate has been 4.98%, therefore this was used for the discount rate value. The target inflation rate for Australia has historically been between 2.0% and 3.0% and when comparing the 25-year data from the ABS from 1991 to 2016 (year to date) it was 2.49%. A period of 25 years was used for the project lifetime.

In order to perform a financial analysis, the cost of the components had to be determined. To accurately perform this task is difficult as installation and connection requirements vary between individual households, climatic environments, installers, component type and component quality to name just a few. When referring to the Solar Choice website (Choice 2016) it has the August 2016 average installation price of \$1.62/W with the lowest figure of \$0.94/W for a 5kW system and up to \$3.58/W on a 1.5kW system. It is well accepted by industry professionals that the price of residential PV is approaching \$1000/kW, and hence this is the figure being used in HOMER Pro.



Solar Choice also states approximate battery storage prices of \$1000 - \$1500 per kWh for lithium-ion and \$500 - \$1000 per kWh for lead acid (Choice 2016). These prices again are highly variable depending on a range of different variables including manufacturer and quality. A decision to utilise \$2000/kWh in the HOMER Pro modelling was made as only usable kWh were being taken into account. It was deemed a more suitable price comparison to utilise a price per useable kWh rather than a price on the total capacity size of the battery. The result of using this figure is that it doesn't matter what the battery constraints are, the cost is calculated by taking the total BSS cost and dividing by the usable battery capacity. For example, if a 10kWh BSS cost \$10,000 with a depth of discharge of 50% it only has 5kWh useable capacity, therefore, the cost is \$10,000/5kWh which equals \$2000 per useable kWh.

Finally, rectifier, inverter and converter costs needed to be determined. As HOMER Pro can only deal with one conversion device the cost was only supplied once. Due to lack of availability on some types this figure was estimated at \$500/kW and was obtained from visiting many inverter/converter manufacturers and distributors online and observing the prices. The cost per kW for residential inverters does decrease noticeably as the size of the inverter increases.

One difference between MATLAB and HOMER Pro was the length of the simulation. MATLAB simulations were performed over a twenty-four-hour period in one-minute time steps for each season with the results repeated for the number of days per season and combined to create average annual data. The HOMER Pro model was run for a twelve-month period with one-minute time steps and as a result the models including batteries allowed carry over capacity. The MATLAB model could have been configured in a similar way but the operating time of the model would have been excessive, therefore, the chosen method was maintained.

The subsections below will detail the arrangement of each of these configurations highlighting the parameters used. The naming of the configurations will be consistent between the MATLAB models and HOMER Pro models.

### 3.3.1 House 1 Model

In order to verify the operation of the MATLAB model it was important to compare the results with that of a known installation. To achieve this an energy audit of house 1 was conducted and the loads, along with the corresponding operating times, were inputted into the model. This allowed a direct comparison between the simulated data and the logged data.

There are some limitations with trying to establish a computer generated model of a house with a large volume of appliances and devices, with some operating for short periods of time in a non-regular pattern. Therefore, a model was developed taking into account the main items used in the home for an average day during the logging period.

The rated or measured consumption data for the loads was either obtained from the energy rating sticker on the device or from measured data obtained from the logging file, the use of a clamp on ammeter or the use of the CABAC Power-Mate Lite. The resulting list of appliances, their operating times and energy consumption are listed in Table 3.8. Those values obtained from measured data are labelled with an (M), in column two of Table 3.8, next to the consumption figure. Figure 3.8 shows the reading for the fridge obtained using the CABAC Power-Mate Lite.

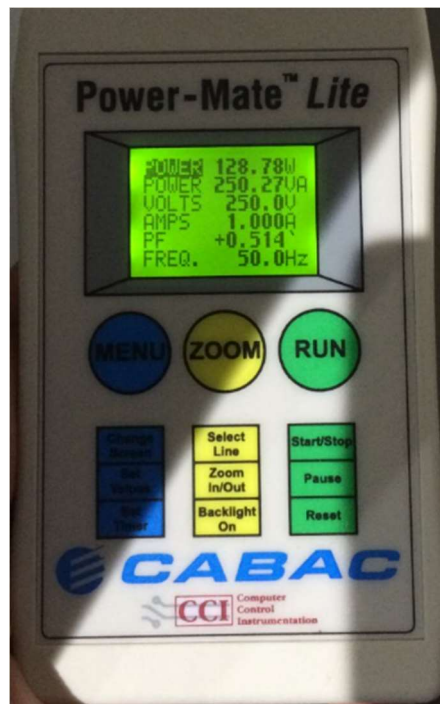


Figure 3.8 – Reading from house fridge using CABAC Power-Mate Lite

Appliance/Device	Rated/Measured consumption (W). (M) = measured.	Operating time	Duty Cycle
Fridge	129 (M)	0000 - 2400	65%
Bar Fridge	106 (M)	0000 - 2400	20%
Dishwasher	395	2200 - 2359	
Washing Machine	110 (M)	2000 - 2130	
Clothes Dryer	2200 (M)		
Air Conditioner	6200 (M)		30%
TV	209 (M)	0600 - 0700 1730 - 2200	
Lights	264	0530 - 0630 1700 - 2300	
Heat Lamps	500	0545 - 0600 2230 - 2300	
Hot Water (Heat Pump)	1300	0000 - 2400	8%
Hot Water Booster	3200	0000 - 0100 2300 - 2359	
Stove & Range hood	825		
Oven	3176 (element on) 124 (element off)	1730 - 1800	20%
Game Console	68	2000 - 2300	
Computer	55	1930 - 2300	
Base Load (eg. standby items, alarm)	125 (M)	0000 - 2400	

Table 3.8 – House 1 model appliance ratings and operating times.

With the above parameters inputted into the model the simulation produced the profile shown in Figure 3.9. The simulated data is shown in blue with the average daily profile from the logging data shown in red. It is evident that the profiles follow each other relatively closely with a morning and evening peak present, the base load operating at a similar level and the presence of cyclic loads, such as the fridges and hot water system. The average daily energy consumption of the MATLAB model was 18.73kWh whereas the logged model was 19.09kWh. This places the figures within approximately 2% of each other which is acceptable. There is some variation between the two profiles which was expected, as the modelling of human behaviour and the use of handheld appliances for a short period is difficult to incorporate.

The important point regarding this part of the modelling was confirmation that the model was producing reliable results against a known load profile and list of appliance parameters. From this result it was determined that the model was operating correctly and could now be utilised to compare the efficiency between AC and DC installations.

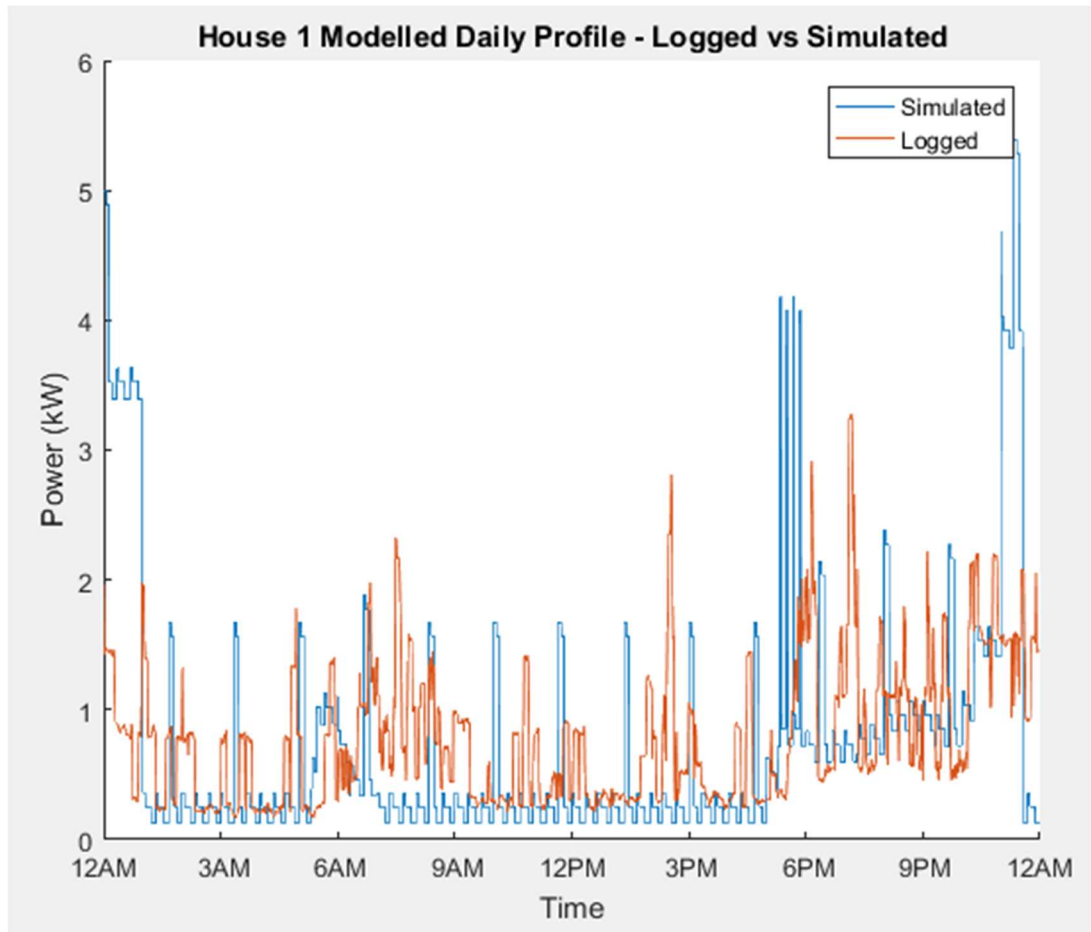


Figure 3.9 – House 1 modelled profile

### 3.3.2 Configuration 1 - AC house with DC-internal appliances

Configuration 1 consisted of a standard AC house that contained DC internal appliances with an 88% efficient rectifier. This is classified as the base case and was used to represent the typical domestic installation. The basic arrangement is shown in Figure 3.10.

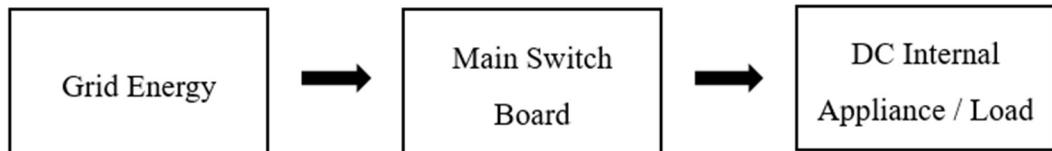


Figure 3.10 – Configuration 1 arrangement

As discussed previously the model was configured to have the following average daily energy consumptions using the appliance run times and power ratings defined in Table 3.5. These produced the average daily usage profile shown in Figure 3.11.

- Autumn consumption of 19.527kWh/day
- Winter consumption of 26.745kWh/day
- Spring consumption of 20.163kWh/day
- Summer consumption of 24.126kWh/day
- Annual consumption of 22.640kWh/day

Figure 3.12 displays the residential end use per day from the developed Simulink model. When compared with Figure 2.10 the percentages displayed are in the expected vicinity. The percentages of hot water heating and air conditioning represent the largest variation from Figure 2.10, however, it must be noted that Figure 2.10 is representing total household energy consumption whereas Figure 3.12 represents electricity consumption only. Figure 2.11 confirms that only 51% of the average residential energy consumption is electricity, however this figure can vary greatly depending on geographic location and availability of alternate energy supplies. As most of the alternatives such as gas and wood are used for heating, hot water and cooking, it was expected that a difference in the consumption of these appliances would exist.

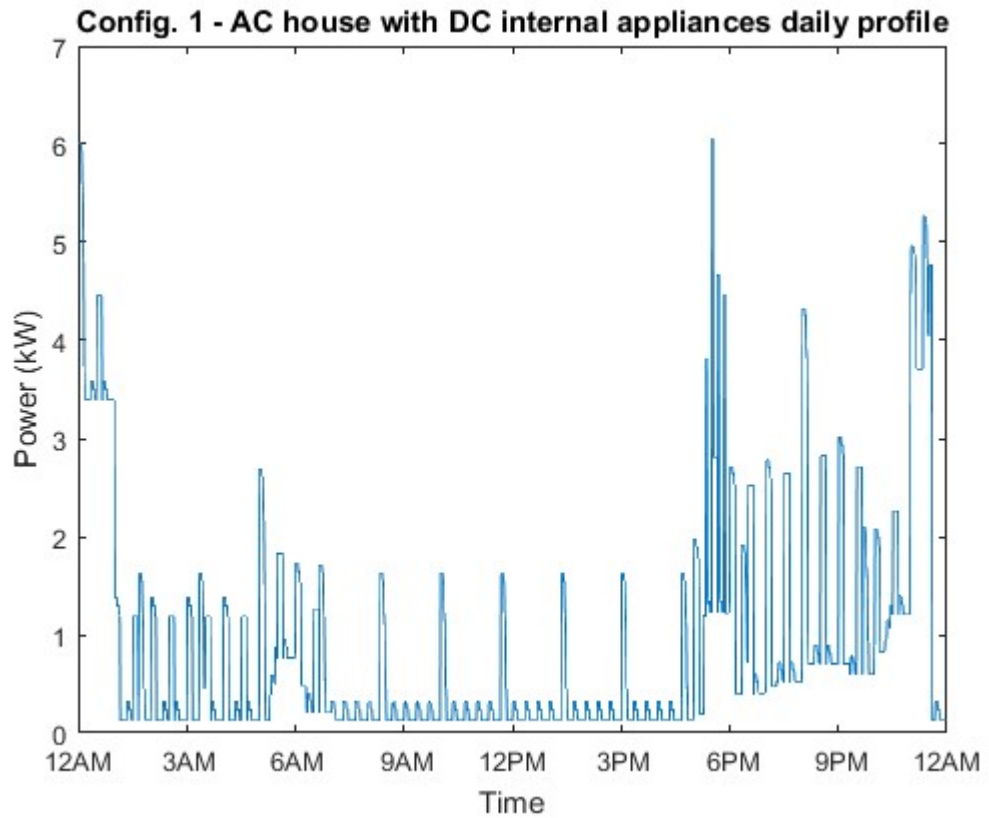


Figure 3.11 – Configuration 1 – AC house with DC internal appliances daily profile

**Config. 1 - Residential end use per day from MATLAB model**

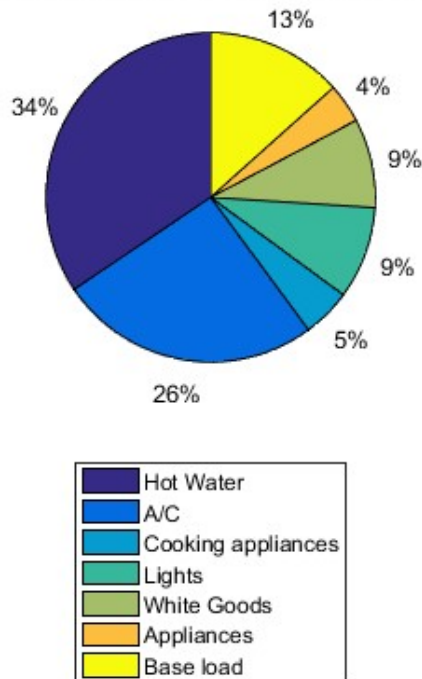


Figure 3.12 – Residential end use per day from MATLAB model

Following the execution of the MATLAB model the consumption data was reconfigured to have 365 days of data based on the average daily seasonal usage in 1 minute increments, resulting in 525,600 readings. The load profile included applicable losses in the installation, which in this case was only cable loss and appliance rectifier loss. To create the HOMER Pro model, the profile was connected to an AC bus supplied by the grid as shown in Figure 3.13

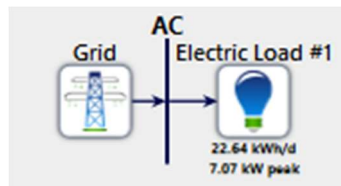


Figure 3.13 – HOMER Pro Configuration 1

### 3.3.3 Configuration 2 - Removal of appliance AC/DC rectifiers

If all of the appliances presented in Table 3.5 were to operate directly off a DC bus, then the AC/DC rectifiers on each of the items could be removed. This resulted in the basic layout shown in Figure 3.14.

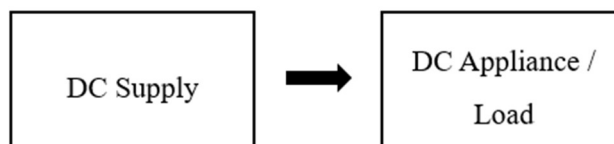


Figure 3.14 – Configuration 2 arrangement

The creation of this model represented the energy consumption if the distribution grid was supplying DC power. The installation operated off a common DC voltage as did all appliances. This scenario is not going to become a reality but it was worth including for completeness of the assessment.

The configuration allowed the appliance rating to remain unchanged and represent a saving by eliminating the rectifier losses while maintaining the same performance from the appliance. For

example; a 100W device with an 88% efficient rectifier was represented by a 100W device multiplied by a gain of 0.88 to give a load of 88W.

HOMER Pro does not have the ability to model a DC grid connection hence it was configured to provide the DC supply through a rectifier that was set to have a 100kW capacity, a life of 99,999 years, 100% efficiency and zero cost. As a result, it's contribution to the consumption and cost was zero.

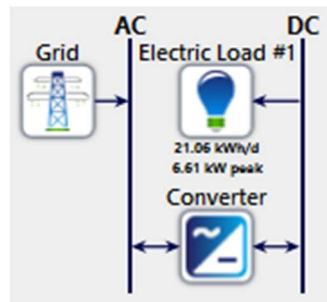


Figure 3.15 – HOMER Pro Configuration 2

### 3.3.4 Configuration 3 – Removal of appliance AC/DC rectifiers with reduction in baseload

The third configuration developed was based on the arrangement displayed in Figure 3.14, however it incorporated a reduction in the base load of the installation by 50W. The base load includes items such as a house alarm system, router, clock, microwave with clock display as well as the standby use of appliances. The reduction of 50W is justified by the removal of the appliance AC/DC rectifiers and hence the removal of their consumption when the appliance is not in use. This figure is difficult to accurately evaluate and was established by an educated estimate determined from the monitoring of standby current of selected household appliances such as televisions, game console, washing machine and dryer.

This configuration again assumes the distribution grid was supplying DC power, the installation operated off a common DC voltage and all appliances operated on the common DC voltage. This scenario is again not going to become reality. What this model did provide was the load profile for DC energy use that was utilised in the following DC models.



### 3.3.5 Configuration 4 - Utilising a common DC bus with central AC/DC rectifier

Configuration 4 advances on the parameters of configuration 3 by including a central AC/DC rectifier as shown in Figure 3.16.

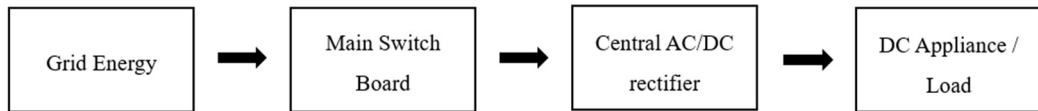


Figure 3.16 – Configuration 4 arrangement

This configuration represents a DC installation supplied by the AC grid. The central rectifier is assumed to have an efficiency of 93% as defined in the introduction to this section and supplies 230V DC. This scenario is unlikely to happen as it would involve all household devices operating on a common DC voltage level of 230V DC. This level is too high for consumer electronics and hence additional appliance DC/DC converters would be required, thus contributing to further losses.

The HOMER Pro model used the profile outputted from the MATLAB simulation of configuration 3. This simulated the removal of the internal AC/DC appliance rectifiers and supplied the load on a common DC bus voltage through a central AC/DC rectifier as shown in Figure 3.17. The load profile accounted for a reduction in baseload and included all installation losses, which in this case was only cable loss. The central converter was configured to have a 97% inverter efficiency and a 93% rectifier efficiency. As this model was consuming energy from the grid only the rectifier was utilised. The optimiser was also enabled for the converter in this simulation with upper and lower limits of 10kW and 6.60kW respectively. These values were chosen due to the peak load of 6.56kW.

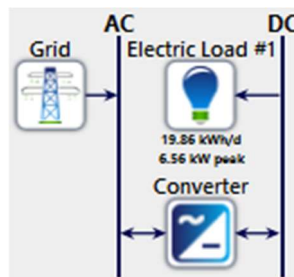


Figure 3.17 – HOMER Pro Configuration 4

### 3.3.6 Configuration 5 – Two DC buses supplied by AC grid through a central rectifier

Configuration 5 represents a much more likely DC installation as it utilises the operation of two DC voltage levels for different components. This model is still supplied from the AC grid via a central 93% efficient AC/DC rectifier with the output voltage set to 380V DC. A 95% efficient DC/DC converter then supplies the 24V DC bus from the 380V DC bus.

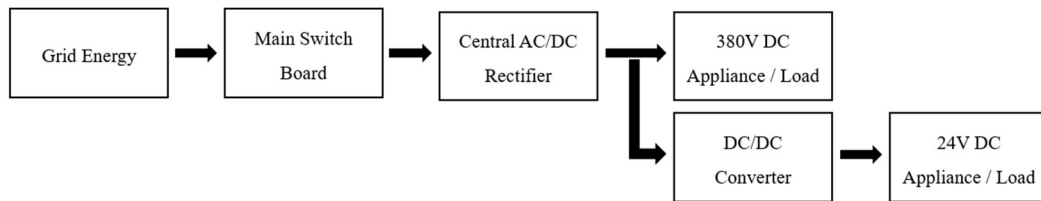


Figure 3.18 – Configuration 5 arrangement

Currently there are no standards for these DC voltage levels, however, literature suggests the likely contenders are 380V DC for the higher voltage and 24V DC for the lower voltage. These voltage levels allow high power use components such as washing machines, air-conditioning units, dryers and cooking appliances to utilise a higher voltage and thereby reduce current and voltage drop. The lower voltage allows for direct connection of lights, fridges, TVs, etc. and is low enough to allow connection of many low power appliances. It would also be expected that if common DC voltages were introduced manufacturers would produce appliances that operate at these voltage levels rather than utilise a DC/DC converter.

With virtually no appliances outside the RV and camping industries commercially available at these voltage levels, assumptions on the supply voltage for appliances had to be made. This decision was made based on the function, location and power requirements of the load. Table 3.9 shows the allocation of loads according to the voltage level. There are some appliances that have not been accounted for due to the unknown nature of their usage but they do present additional challenges in where to supply them from. Examples of these items include the clothes iron, electric frying pan, blender, hair dryer, hair straightener and any other high power use devices. These devices were also ignored in the reviewed literature.

380V	24V
Hot Water	Lights
Air Conditioner	TV
Stove	Dishwasher
Oven	Fridge
Washing Machine	Bar Fridge
Dryer	Game Console
Heatlamps	Computer
	Baseload

Table 3.9 – Appliance split between two DC voltage levels

HOMER Pro does not have the ability to operate a dual DC bus arrangement and as such the DC bus in the HOMER Pro model was set at 380V with the 24V DC bus incorporated into the load profile. Therefore, the load profile includes the losses associated with the 380V to 24V DC/DC converter with 95% efficiency in addition to the cable loss. As a result, the configuration in HOMER Pro is shown in Figure 3.19. The optimiser was enabled for the central converter with upper and lower limits of 10kW and 6.50kW respectively. These values were chosen due to the peak load of 6.50kW.

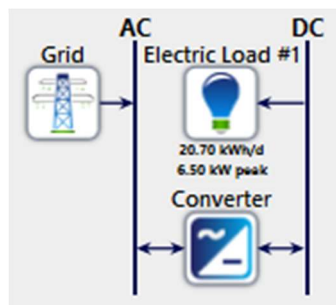


Figure 3.19 – HOMER Pro Configuration 5

### 3.3.7 Configuration 6 – AC house with total daily solar contribution

Configuration 6 is the first simulation that utilises the generation of solar energy, however, it only accounts for total consumption and total generation over a 24-hour period. The load profile utilised is that of the AC installation in configuration 1. To achieve the PV output the average daily global solar exposure figure from the St Heliers weather station, as described in section 3.3, was utilised. This figure was multiplied by the PV array size to determine the average daily generation figure. A 5kW PV array was utilised as the average PV installation size in Australia is

5.16kW as identified previously in section 2.6. For a 5kW PV installation the daily average daily generation is equal to 24.49kWh.

A HOMER Pro model of this configuration was not established as it is not a realistic option. This method would only be significant if the consumer was recognised equally for energy generated and utilised regardless of the time of day, however, this is not the case with the consumption and feed in tariffs being significantly different.

### 3.3.8 Configuration 7 – AC house with PV installed, following generation profile

Configuration 7 represents the installation from configuration 1 with PV connected, where the PV output is equal to that obtained from the Wagga weather station as described in section 3.3. This data was then multiplied by the size of the PV array, in this case 5kW as per the outline in section 2.6, to give the power generated at each one-minute timestamp. The resulting information was then utilised in the simulation to offset the installations energy usage and export any additional generation to the grid. The generated energy was connected to the installation by a 95% efficient solar inverter. The efficiency of these inverters does change depending on the amount of energy passing through them but for this modelling it was set at a fixed value.

The installation configuration with the PV installed is shown in Figure 3.20 with the solar inverter injecting power between the main switch board and the load. This allows the power to flow in either direction depending on the load requirements.

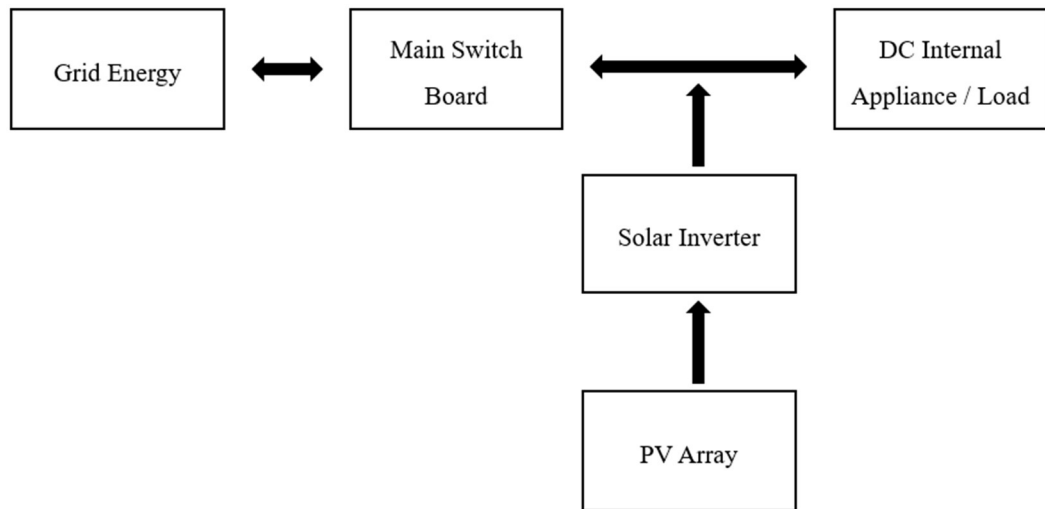


Figure 3.20 – Configuration 7 arrangement

The schematic view obtained from HOMER Pro, shown in Figure 3.21, displays the PV array connected to the AC bus. This connection is through a 95% efficient inverter that is embedded in the array. The PV array was also given a 94% derating factor to account for situations affecting the generation such as dust, shading, aging etc. This figure was determined by comparing the results between the HOMER Pro model and the MATLAB model and adjusting as required to better align the yearly generation figures.

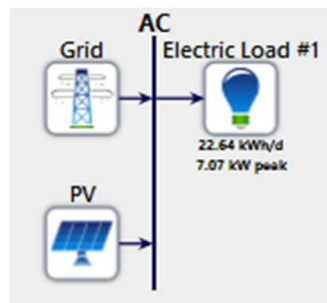


Figure 3.21 – HOMER Pro Configuration 7

### 3.3.9 Configuration 8 – Two DC buses supplied by AC grid through a central rectifier with PV connected to higher DC voltage

The configuration of model 8 is shown in Figure 3.22, where the PV array is connected to the 380V DC bus through a DC/DC converter with MPPT and a combined operating efficiency of 98%. The solar array was 5kW in size and operating at 240V DC as discussed in section 3.3. This

configuration is a simple advancement to configuration 5 with the addition of the PV array and inverter being the only difference.

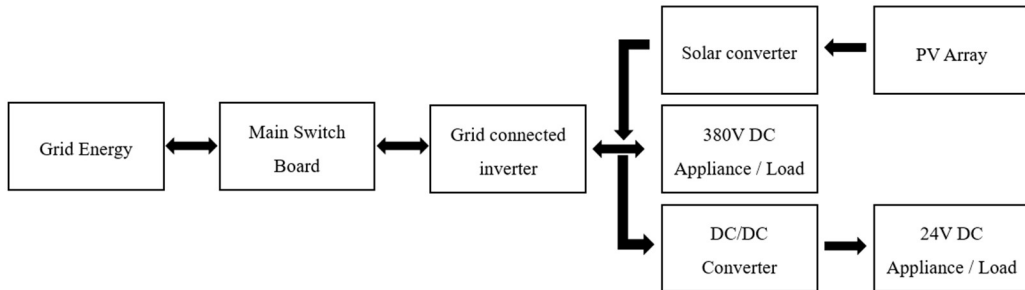


Figure 3.22 – Configuration 8 arrangement

The HOMER Pro model in this configuration was formed by having the load profile, that included the losses of the 380V to 24V DC/DC converter and the cables, attached to the 380V DC bus with the PV array also connected to the same bus. The constraints in HOMER Pro regarding operating reserve were set to zero as the installation was connected to the grid which would provide supply when the system could not. The optimiser was enabled for the central converter with upper and lower limits of 10kW and 6.50kW respectively. These values were chosen due to the peak load of 6.50kW. The central converter was configured to have a 97% inverter efficiency and a 93% rectifier efficiency. In this model both the rectifier and converter functions were utilised as the installation exported and imported power depending on the time of day.

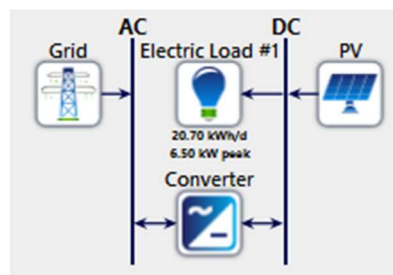


Figure 3.23 – HOMER Pro Configuration 8

### 3.3.10 Configuration 9 – AC house with PV and batteries installed

Configuration 9 involved the addition of a BSS in conjunction with the PV array. This directly builds on configuration 7. When reviewing the Simulink model, it does appear different to Figure

3.24 but the operation is the same. The installation has a 95% efficiency for the solar inverter. The solar is then compared against the load at that point in time. If the load cannot be supplied by the solar it is supplied by the battery with a one-way efficiency of 91% multiplied by a 97% efficient inverter. If the battery does not have capacity, then the energy is obtained from the grid. Once the PV array begins generating power it begins to supply the load. If there is an excess of generation the batteries begin to charge with a corrected efficiency of 98% for charging and a one-way battery efficiency of 91%. Once at capacity, any excess energy is exported to the grid at 95% efficiency. The model does not control the charging current of the battery in order to maintain battery life and function; it is purely focussing on system losses.

If adding a BSS to an installation it may be necessary to determine the required capacity. There are a number of parameters that must be taken into account when determining the capacity of the storage system including; total load to be supplied; number of days the system can survive without charge; turn around efficiency of the batteries and the depth of discharge. Formulas 4.2 and 4.3 display how to calculate the required BSS capacity.

$$\text{Required kWh} = \frac{\text{Avg load (kWh)} \times \text{Days of Autonomy} \times \text{Turn around efficiency}}{\text{Depth of discharge} \times \text{System efficiency}} \quad (3.4)$$

$$\text{Required Ah} = \frac{\text{Require kW}}{\text{Battery Voltage}} \quad (3.5)$$

With a maximum load consumption of 22.42kWh per day it is beyond scope to design a complete off-grid system with several days of autonomy. The intention of the BSS is to offset peak usage and to simulate the likely uptake of batteries in the near future by domestic installations. As a result, a 10kWh battery system was utilised as they are the most likely size that will be commercially available and viable for the average consumer. The battery voltage chosen was 24V in order to match the chosen DC bus voltage, however, 48V is a popular alternative. The modelling was not concerned with the type of battery but more with the configuration and efficiency gain by utilising this volume of storage. In modelling this battery, it has been assumed that the operating range will be 0% to 100%, hence suggesting the battery can be completely discharged. The initial state of charge was set to 0% as the battery energy was anticipated to be completely utilised each evening and commenced the new day at 0% capacity. As the model was simulating an average seasonal 24-hour period the carry over charge of the battery could not be accounted for.

Figure 3.24 shows the basic arrangement of configuration 9. This model involved challenges in order to accurately simulate total energy consumption and represent the losses in the system due to multiple conversion stages that were dependant on load and generation conditions. In a real world installation this would likely be represented by a single hybrid inverter that would control PV generation, battery charging, battery discharging and the import and export of power.

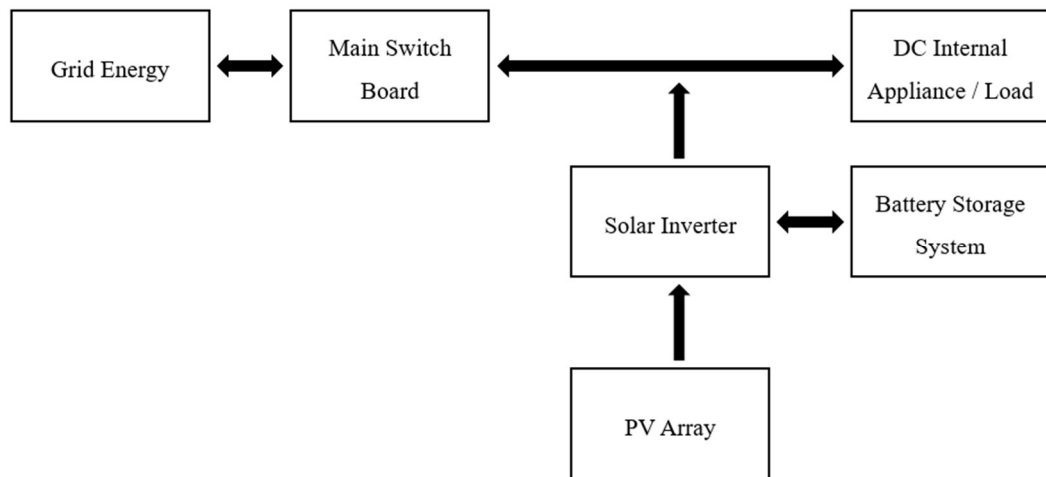


Figure 3.24 – Configuration 9 arrangement

In creating the HOMER Pro model, shown in Figure 3.25, the parameters were all set equivalent to those in MATLAB with the load profile being the same as configuration 1. The PV array had an integrated inverter of 98% representing the MPPT and charger efficiency. The battery round trip efficiency was set to 82.81%, which is equal to a one way efficiency of 91%. The optimiser was enabled for the central converter with upper and lower limits of 10kW and 7.10kW respectively. These values were chosen due to the peak load of 7.07kW. The central converter was configured to have a 97% inverter efficiency and a 93% rectifier efficiency.

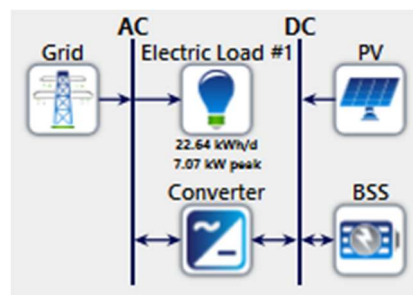


Figure 3.25 – HOMER Pro Configuration 9



### 3.3.11 Configuration 10 – Two DC buses supplied by AC grid through a central rectifier with PV and batteries connected to higher DC voltage

Configuration 10 builds on the configuration 8 arrangement by adding the 10kWh BSS to the 380V DC bus as shown in Figure 3.26. This system is charged by a 98% efficient MPPT/charger and discharged to the load through a 95% efficient DC/DC converter. This is all represented in the image by the solar converter block.

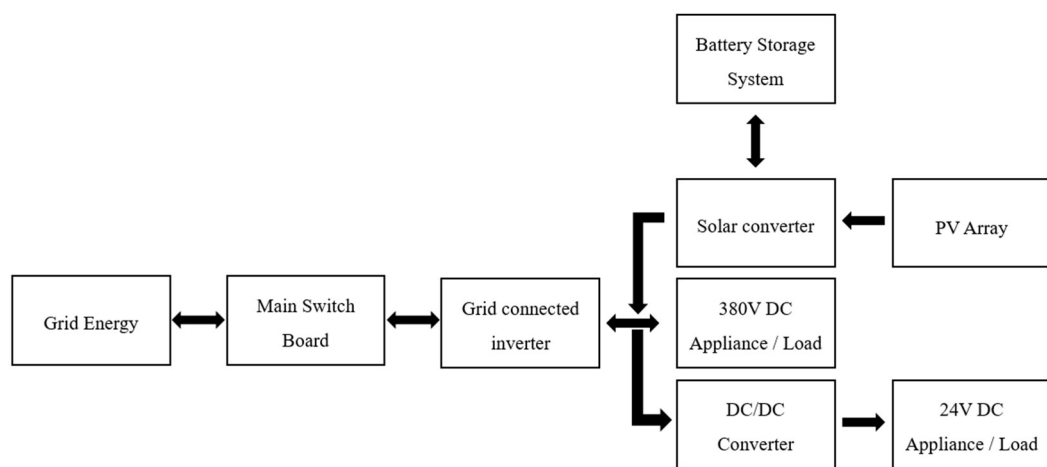


Figure 3.26 – Configuration 10 arrangement

The HOMER Pro model has the 24V DC bus and therefore the associated DC/DC converter to step down from 380V incorporated into the load profile. The battery system has a capacity of 10kWh and operates at 24V with the connection to the 380V bus through a DC/DC converter. It can be seen in Figure 3.27 that this converter appears absent, however the problem is an inability to operate a dual DC bus or place a converter between the battery and the bus in HOMER Pro. To overcome this restriction, the round trip efficiency of the battery was adjusted from 82.81% to 78.67% in order to take the 95% efficient DC/DC converter for discharge into account. In applying the battery efficiency HOMER Pro assumes an even split between input and output efficiency so this is not strictly behaving as it should but the total loss through the battery will be correct. The PV array had an integrated inverter of 98% representing the MPPT and charger efficiency. The optimiser was enabled for the central converter with upper and lower limits of 10kW and 6.5kW respectively. These values were chosen due to the peak load of 6.50kW. The central converter was configured to have a 97% inverter efficiency and a 93% rectifier efficiency.

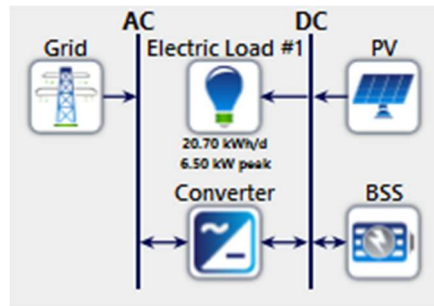


Figure 3.27 – HOMER Pro Configuration 10

### 3.3.12 Configuration 11 - Two DC buses supplied by AC grid through a central rectifier with PV and batteries connected to lower DC voltage

The final configuration produced connects the 5kW PV array and 10kWh BSS to the 24V DC bus as shown in Figure 3.28. This eliminates the DC/DC converter that connected the battery to the bus in configuration 10, as the battery is connected directly to the 24V DC bus. All other parameters at the same as configuration 10.

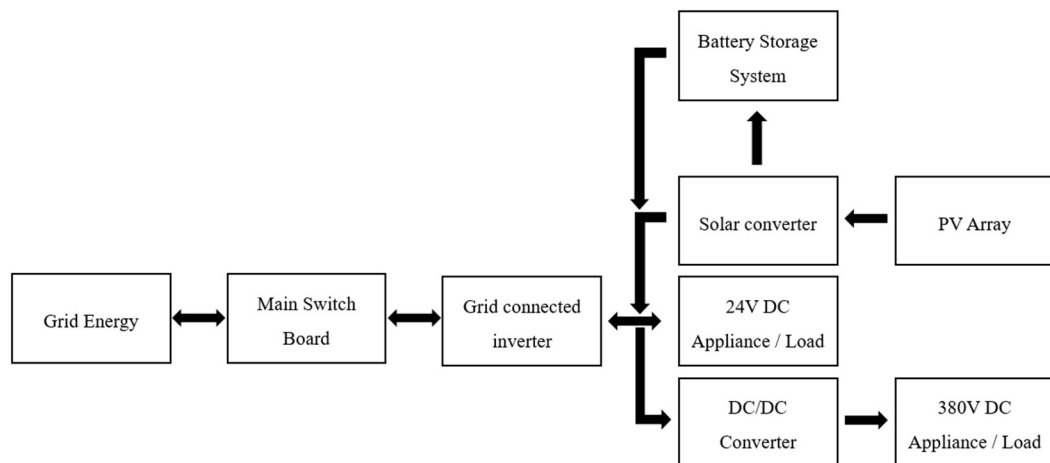


Figure 3.28 – Configuration 11 arrangement

The HOMER Pro model of configuration 11 appears identical to that shown in Figure 3.27, however the common DC bus is set at 24V. This results in the battery round trip efficiency being

set at 82.81% and the load now including a step up DC/DC converter of 95% efficiency to convert the DC voltage to 380V. The PV array had an integrated inverter of 98% representing the MPPT and charger efficiency while the optimiser was enabled for the central converter with upper and lower limits of 10kW and 6.85kW respectively. The central converter was configured to have a 97% inverter efficiency and a 93% rectifier efficiency.

### 3.4 Methodology Summary

The project methodology began by outlining the process that was undertaken to achieve the project objectives. Following this outline, the process of logging four domestic installations and analysis of the obtained data was explained. A second source of load information was obtained from distribution monitoring equipment installed on some residential distribution substations. The combination of these two sources of information allowed a comparison to literature and assisted in the development of average daily consumption figures and load profiles.

Once the load data and desired profiles were obtained the MATLAB model had to be developed to allow analysis of different configurations. This MATLAB model did utilise two separate Simulink models to assist in calculations. This model allowed load run times, appliance power requirements and component efficiencies to be modified for different configurations and ultimately the analysis of losses and efficiencies between AC and DC installations. Verification of the model was completed by inputting the parameters of a known installation and comparing the results. The results were positive and therefore further models were then developed.

PV and BSS parameters were outlined as were the desired run times and efficiencies of appliances for utilisation in the comparisons. The MATLAB model was then expanded to include the four climatic seasons and allowed the appliance parameters to be varied to generate different load profiles.

HOMER Pro was utilised to replicate the MATLAB model for all configurations except configuration 6, as this was not a realistic option. This second modelling software was utilised to provide further confirmation that the developed MATLAB model was operating correctly and also provided financial analysis. The key differences between the models was the ability to obtain more comprehensive information in relation to installation losses when utilising the MATLAB model but it was only executed for an average day per season whilst the HOMER Pro model was executed over a twelve-month period.

## Chapter 4 Results

The analysing of eleven different modelling configurations resulted in a lot of information to interpret and report. This section will look at a number of important comparisons to show the differences between the MATLAB and HOMER Pro models, the differences between equivalent AC and DC configurations, cost comparisons and a summary of all results.

A complete list of results for each configuration is available in Appendix E. This appendix contains a selection of tables, including MATLAB tables for the seasonal and annual average daily consumption figures in addition to the average yearly consumption, while the HOMER Pro tables exclusively display the annual results.

When discussing the results of each of the comparisons the yearly average data was utilised. However, it must be reinforced that the MATLAB models were all run for a one-day period in each of the four climatic seasons. As a result, the figures can vary quite significantly between these seasons due to changing usage profiles and renewable generation variations. To observe these differences, refer to the tables in Appendix E.

### 4.1 MATLAB vs HOMER Pro

The first comparison is between the MATLAB and HOMER Pro total annual consumption figures. Figure 4.1 displays a plot with the MATLAB results shown in red and the HOMER Pro results shown in blue. It is clear from this figure that the models produced almost identical results for each of the ten configurations simulated in both software packages, with the largest variation between the two equalling 0.601%. Configuration 6 was not modelled in HOMER Pro as explained in section 3.3.7, hence its absence from the plot. This confirms the MATLAB model is operating correctly, giving confidence to use it for all energy efficiency comparisons.

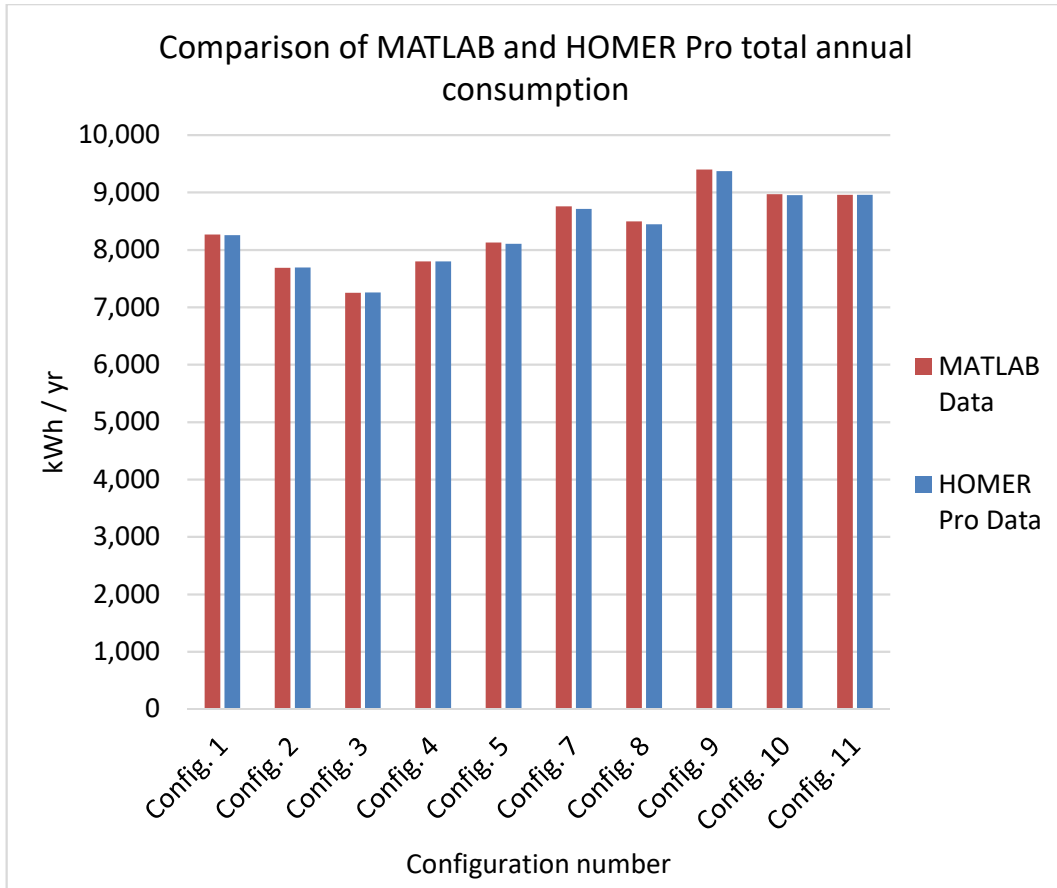


Figure 4.1 – Comparison of MATLAB and HOMER Pro total annual consumption

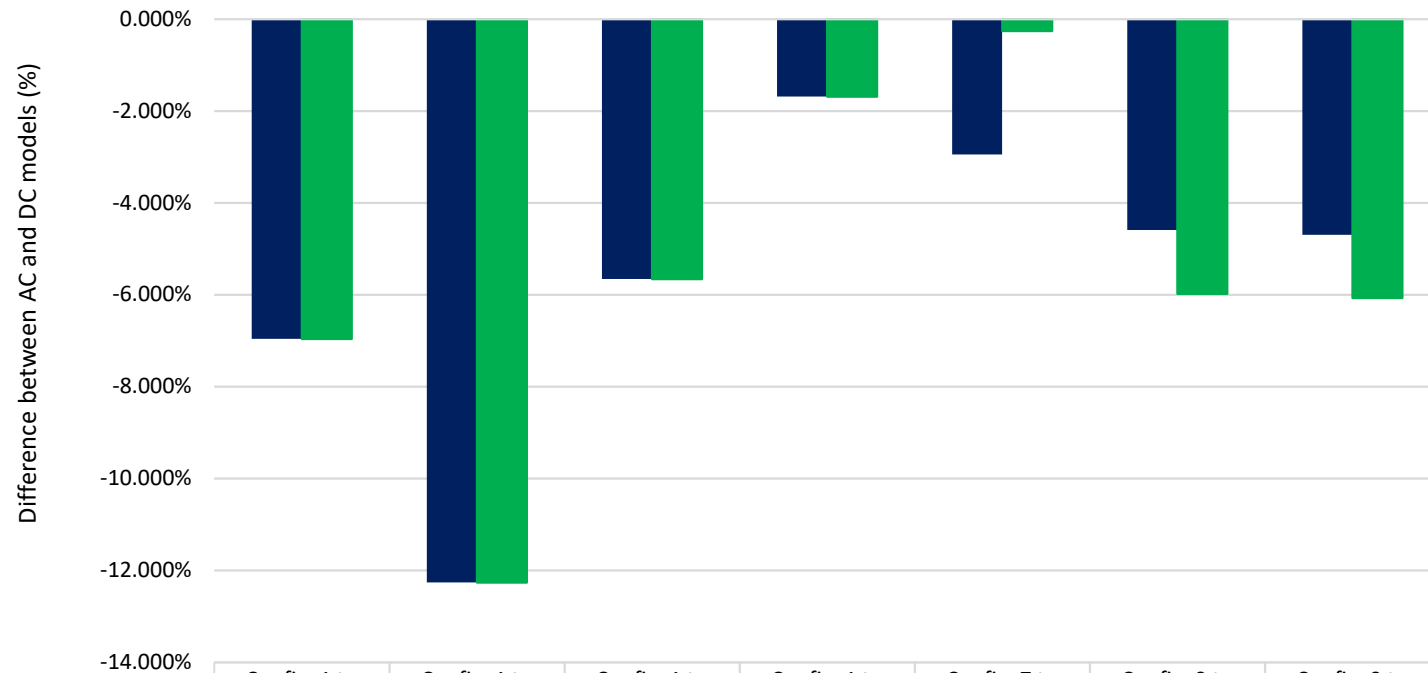
## 4.2 Configuration Comparison

The next analysis of results is between equivalent AC and DC configurations. It is essential that the results are grouped according to configuration type before making comparisons and determining the most efficient option. This means that the configurations only supplied by the grid are compared against each other, the configurations with PV are compared against each other, and finally the configurations with PV and BSS are compared against each other.

In order to compare between equivalent configurations, it is necessary to refer to Figure 4.2. This figure contains the comparison between equivalent AC and DC configurations, displaying two bar graphs for each. The first of these bars is in blue and displays the difference in total consumption whilst the second is in green and displays the difference in total grid consumption. It was important to compare only equivalent configurations to ensure consistent and reliable results. The comparisons highlighted in this plot are listed below and will be analysed in the subsequent sub sections.

- Configurations connected to grid supply
  - Configuration 1 to Configuration 2.
  - Configuration 1 to Configuration 3.
  - Configuration 1 to Configuration 4.
  - Configuration 1 to Configuration 5.
  
- Configurations connected to grid supply with PV installed
  - Configuration 7 to Configuration 8.
  
- Configurations connected to grid supply with PV and a BSS installed
  - Configuration 9 to Configuration 10.
  - Configuration 9 to Configuration 11.

## Difference in consumption between AC configuration and equivalent DC configuration



	Config. 1 to Config. 2	Config. 1 to Config. 3	Config. 1 to Config. 4	Config. 1 to Config. 5	Config. 7 to Config. 8	Config. 9 to Config. 10	Config. 9 to Config. 11
■ Difference in total consumption (kWh)	-6.958%	-12.260%	-5.656%	-1.686%	-2.945%	-4.589%	-4.694%
■ Difference in grid consumption (kWh)	-6.958%	-12.260%	-5.656%	-1.686%	-0.256%	-5.978%	-6.068%

Figure 4.2 – Difference in consumption between AC configuration and equivalent DC configuration

#### 4.2.1 Configuration 1 to Configuration 2

Configuration 1 was created to simulate the normal configuration of an AC installation with DC-internal appliances. The average daily load consumption was determined to be 22.415kWh/day. This usage figure was considered to be the base which all AC load models would utilise and from which the DC models would be created. The appliance rectifier losses are ignored, as they will be identified in upcoming simulation results, therefore there is only cable loss to consider in this configuration. The average daily cable loss equalled 0.225kWh, bringing the total daily consumption to 22.640kWh/day

Configuration 2 represents a DC installation operating from a DC grid at a single voltage level. This means that the appliance AC/DC rectifiers, with an efficiency of 88%, have been removed. As a result of this modification the average daily energy consumption is 21.065kWh, which includes a 0.183kWh cable loss.

Comparing the results of these two configurations it is evident that the removal of the appliance rectifiers has reduced the overall energy consumption of the installation. A drop in cable loss is also present due to the reduced load and hence current. Figure 4.2 shows a reduction in total energy consumption of 6.958%, which is also equal to the reduction in grid consumption since both configurations utilise energy from either the AC or DC grid. The reason the saving is not equal to 12%, as would be expected when the appliance rectifiers are removed, is due to some loads being purely resistive. In these situations, it was deemed that a change from AC to DC would not yield a reduction in consumption.

Configuration 2 is highly unlikely to occur for conventional grid connected installations as the grid is not going to convert to distributing DC power. There are a couple of potential situations where this option could be successful depending on availability of appliances. The first would be the operation of a stand-alone system where the system is fully self-sufficient and all loads operate on a common DC bus supplied from renewable generation and energy storage systems. The second is a DC microgrid cluster where there is a small DC distribution network, either privately owned on a single property but connected to multiple separate loads or a more widespread microgrid system. The successful operation of both of these systems is heavily reliant on appliance availability. With only one common DC bus voltage there are challenges regarding protection and switching. In addition, the appliances will likely still contain DC/DC converters to provide a lower voltage which is not a desirable result.



#### 4.2.2 Configuration 1 to Configuration 3

There is no need to discuss the operation of configuration 1 as it is unchanged. The operation of configuration 3 is identical to configuration 2 but with a 50W/h reduction in base load. This was explained in section 3.3.4. The daily energy usage of configuration 3 totals 19.865kWh, including a 0.183kWh for cable loss. Compared to configuration 1 this is a reduction in consumption totalling 12.260%.

Configuration 3 is essentially the same as configuration 2 and therefore has the same analysis of being an unlikely installation. This is due to the need for a DC grid supply and all appliances to operate off the same DC voltage level.

#### 4.2.3 Configuration 1 to Configuration 4

The simplest DC installation that an AC grid connected residential customer could utilise is that of configuration 4, with a central AC/DC rectifier installed supplying the installation with a fixed DC voltage level, assumed to 230V DC. The average daily energy consumption of this configuration is equal to 21.360kWh, presenting a 5.656 % efficiency gain over configuration 1. These values are identical to the grid consumption and savings as it is the only source of power for this installation.

The addition of the central rectifier has a substantial impact on the total losses with it utilising 1.495kWh per day. However, it is still an improvement over utilising the individual appliance rectifiers presented in configuration 1.

Configuration 4 is fairly unlikely due to the requirement for a low voltage DC supply for certain appliances. There is also the challenge of items that require regular switching, such as lighting, due to the constant interrupting of a high DC voltage and the size and expense of the switches required to do so.

#### 4.2.4 Configuration 1 to Configuration 5

This final comparison to configuration 1 marks the next advancement in the DC configuration by introducing a second DC bus voltage. Configuration 5 contains two DC bus voltages, one at 380V

DC and the second at 24V DC. The introduction of the second DC bus also introduces another conversion step and hence further losses. The appliances that have been moved to the 24V DC bus still have the same power rating and hence require a larger current to operate. This larger current increased the cable voltage drop and resulted in 0.693kWh per day of energy being lost in the cables. There was also 0.326kWh per day lost in the DC/DC converter between the two buses. Since the usage had increased on the installation a greater volume of energy was required through the central rectifier, hence its loss contribution increased to 1.558kWh per day. The addition of all these losses totalled 2.577kWh per day and reduced the total energy saving compared to configuration 1 to 1.686%. Again the grid saving matched this due to it being the only source of supply.

#### 4.2.5 Configuration 7 to Configuration 8

Configuration 7 involved the connection of a 5kW PV array onto the standard AC household. With the addition of embedded generation, an interesting trend begins to emerge. The generation of renewable energy reduces the installations grid consumption but in respect to total energy consumed the value actually rises. This rise is a result of additional losses being introduced into the installation. In this case the addition of a PV array requires an inverter and the average loss from this inverter equals 1.244kWh/day.

Utilising the same AC load profile as used in configuration 1, with the solar connected through a 95% efficient inverter, the average daily consumption is 23.984kWh some 5.937% larger than the configuration 1 value. However, the daily grid consumption is down 15.443% to 19.144kWh. These two values show that only 4.841kWh/day is consumed from the PV array, which includes all PV related losses, with the remaining 20.148kWh of generation being exported to the grid.

Figure 4.3 displays the operation of the installation with three separate plots. The plot on top is the daily average solar generation for a 5kW PV array. This system is set at a fixed angle and orientation and does not have any tracking installed. As expected, the power generated by the system spans just over 12 hours of the day with the peak output occurring around midday. The second plot, in the middle, is the load profile of configuration 1, which is the same as configuration 7 with no PV installed. Finally, on the bottom is the configuration 7 profile showing the impact of PV on the installations energy consumption. As the baseload of the installation is so low due to minimal usage throughout the day, the excess energy is exported to the grid. The exported energy is represented by the negative consumption values. In this example the peak consumption times are outside the peak generation times and therefore there is a mismatch in the profiles.

Although the PV system on average generates enough energy each day to match the load consumption, the inability to use the PV energy as it is generated results in the consumer still requiring a grid connection. The cost savings in this configuration are minimal as consumption tariffs are much higher than feed in tariffs, as shown in Table 3.7. Further detail on costs will be given in section 4.3.

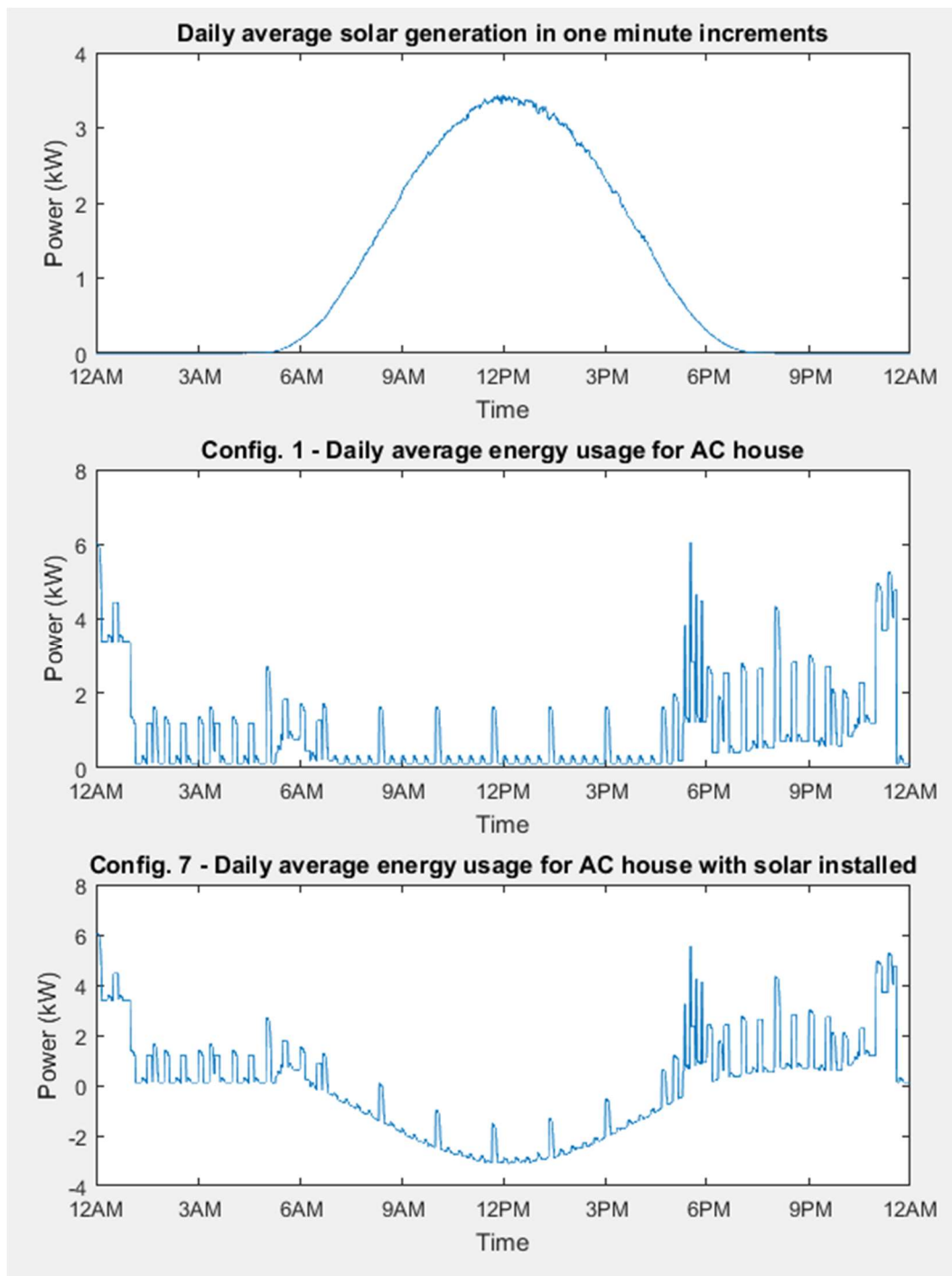


Figure 4.3 – Annual daily solar generation and installation usage.

Configuration 8 is the DC equivalent of configuration 7, operating with a dual DC bus arrangement with the PV connected to the 380V DC bus. Utilising this arrangement allows the removal of the AC/DC appliance rectifiers and a reduction in base load. The utilisation of the DC bus allows the PV array to be connected to the bus via a 98% efficient DC/DC converter with MPPT which will boost the voltage from the PV arrays 240V DC to the 380V DC bus voltage. This configuration has an average daily energy consumption of 23.278kWh and a grid consumption of 19.095kWh.

The above values display that the DC configuration is 2.945% more efficient than the equivalent AC configuration when referring to total energy consumption, but only 0.256% more efficient when comparing grid consumption. The reason for the difference in savings is due to the different operating parameters of the two configurations as detailed below.

- Configuration 8 has a load consumption of 19.682kWh/day which is 12.260% lower than configuration 7.
- Due to the lower load consumption configuration 8 consumes less PV energy than configuration 7 thereby exporting more to the grid.
- Cable losses are higher in configuration 8 due to the operation of dual DC buses. The higher current through the 24V bus being the key contributor.
- There are losses in the DC/DC converter transfer between DC bus voltages in configuration 8.
- All energy used from the grid in configuration 8 must be supplied through a central AC/DC rectifier. This means despite requiring less energy for the load, the grid consumption is very close to configuration 7 due to the rectifier loss.

When referring to the tables located in Appendix E an increasing number of losses appear as renewables are introduced into the installation. Many of these conversion losses will belong to the one device, for example a central device used to rectify the imported energy and invert the outgoing. These have been represented separately in the results to allow for easy identification of the components contributing to the losses.

#### 4.2.6 Configuration 9 to Configuration 10

The addition of a BSS to configuration 7 creates configuration 9. This utilises the PV array to charge the BSS when excess generation is present. This configuration follows the trend of further reducing grid consumption but overall consumes more energy than all previous AC models, with a daily consumption of 25.754kWh. This configuration consumes the most energy of any that have been simulated. This can be attributed to the number of energy conversion processes and the battery round trip efficiency. This configuration had losses totalling 3.387kWh/day.

Configuration 10 extended on configuration 8 to include a BSS and PV array on the 380V DC bus. This configuration looks to have the highest number of components contributing to losses when viewing Table E.5, however, many of these component losses will be situated in a central device controlling battery charge, battery discharge, rectify the imported energy and invert the exported energy. They have been displayed separately for analysing purposes.

Unfortunately, there is a slight error - less than 0.300%, in the MATLAB model when calculating the battery losses. This error occurs around the limits of charging and discharging and was not able to be eliminated. The error is not present in the HOMER Pro models as a library battery was utilised. Due to the minor nature of this discrepancy it has been ignored, as the variation between the MATLAB and HOMER Pro models never exceeded 0.600% and was deemed acceptable.

Configuration 10 offers a 4.589% efficiency gain over configuration 9 when comparing total energy consumption. This figure rises to 5.978% when comparing grid energy consumption. The reason for the larger saving in grid energy compared to total energy is due to the BSS supplying the load for a longer period of time as a result of decreased load requirements. Hence, the reliance on the grid was needed for a shorter period of time leading to less consumption.

#### 4.2.7 Configuration 9 to Configuration 11

The final comparison is between configurations 9 and 11. Configuration 11 differs from configuration 10 by connecting the PV and BSS to the 24V bus. The comparison between total energy usage resulted in configuration 11 being 4.694% more efficient than configuration 9, while the grid consumption was reduced by 6.068%. The same reason for the reduced grid consumption is applicable in this scenario as that described in 4.2.6. The interesting note between configurations 10 and 11 is that they consume an almost equal amount of total energy and grid energy but the losses occur in different areas. Configuration 11 loses a greater amount of energy

in the DC/DC converter due to the volume of energy requiring conversion for use on the 380V DC bus or exporting to the grid. Configuration 10 loses a greater amount of energy in the battery discharge due to using a DC/DC converter

#### 4.2.8 Configuration Losses

Following on from the analysis of the equivalent configurations, Figure 4.4 displays the annual energy loss per model with the AC installations displayed in red and the DC installations displayed in blue. It is evident that in both the AC and DC configurations that the trend in losses is upwards, apart from between configurations 2 and 3. Focussing on the AC results, configuration 1 is the AC house with DC internal appliances, configuration 7 is the addition of PV and configuration 9 is the addition of PV and a BSS. In the DC explanation configuration 2 will be ignored, therefore the trend starts at configuration 3 with the removal of the appliance rectifiers and reduction in base load; configuration 4 introduces a central rectifier; configuration 5 is the operation of a dual bus arrangement; configuration 8 is the addition of PV; configuration 10 is the addition of PV and a BSS on the 380V bus and configuration 11 is the addition of PV and a BSS on the 24V bus.

It is evident in this plot that with the addition of PV and a BSS in both AC and DC configurations, the losses within the installation increase. There are a number of reasons for this. In an AC installation the PV array is connected through an inverter which introduces further losses. For a DC internal installation, the PV array is connected to the DC bus through a DC/DC converter and then the DC bus is connected to the grid through a central inverter/rectifier. When a BSS is added to the AC installation it is also connected through an inverter/charger but in addition to these losses battery round trip efficiency is also present. For a DC installation the same battery round trip efficiency and charger losses are present but depending on the configuration there may also be a DC/DC converter connected between the BSS and the DC bus. The outcome of this is that the connection of renewables and storage systems results in additional components to integrate them into the installation resulting in additional losses.

Clearly displayed in Figure 4.4, and discussed in the above configuration comparisons, is that in every case the DC configuration is more efficient than the equivalent AC configuration. This was the primary objective of this dissertation and has been achieved.

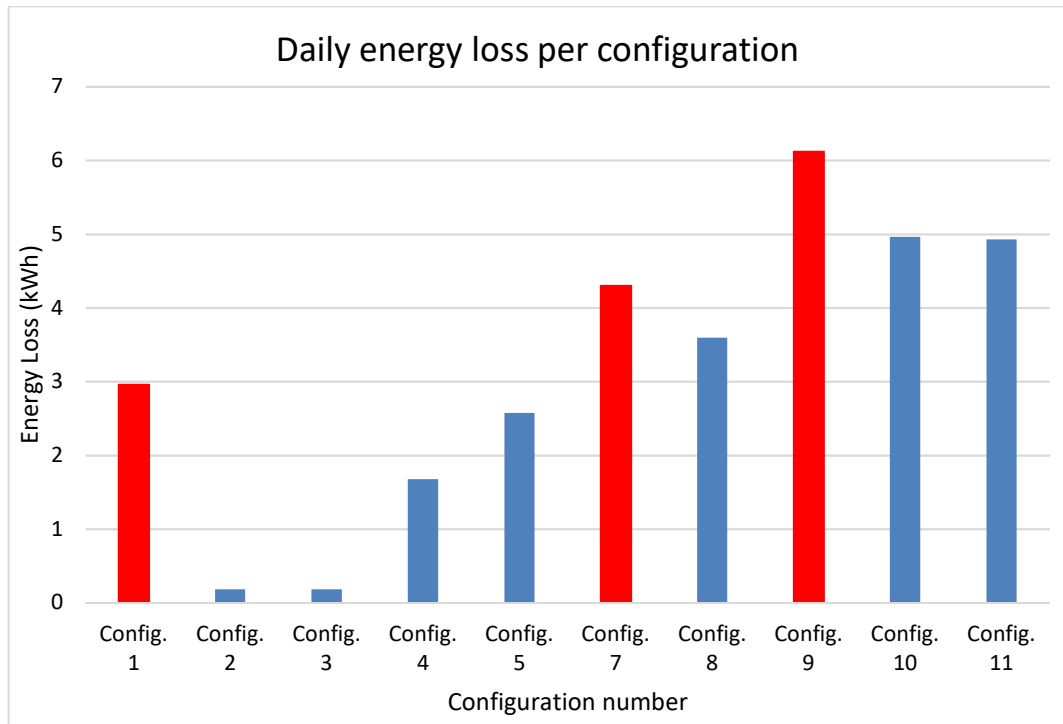


Figure 4.4 – Daily energy loss per model

From Figure 4.4, configuration 9 has the highest energy loss followed by configuration 10. As these are the AC and DC models with PV and a BSS reference to Figure 4.5 and Figure 4.6 show the losses in each of the installations respectively. This analysis was included to demonstrate the number of conversions present in each of these configurations and also to explain what they each refer to.

Figure 4.5 displays the breakup of the 6.120kWh of losses per day in the AC configuration. It clearly shows the 45% contribution to the losses from the appliance AC/DC rectifiers. The next largest contributor is the battery charge and discharge loss, which totals 30%. Battery one-way efficiency is 91% in both directions but the discharge component includes the losses associated with the inverter, hence this figure is higher. The solar inverter loss which includes the battery charger, is also quite high as this was used to convert all generated energy into either AC energy for consumption and export or DC energy for charging the batteries.

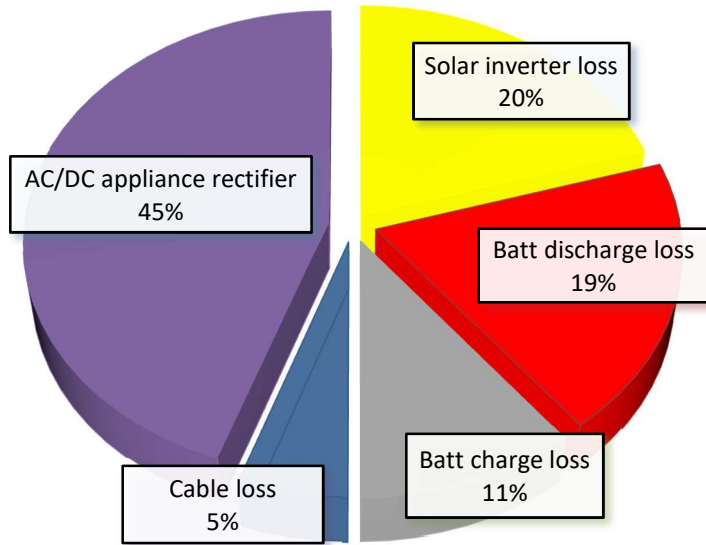
Figure 4.6 displays the breakup of the 4.964kWh of losses per day in the DC configuration with 47% of the installation loss associated with the battery charge and discharge. The discharge loss is higher than the charge loss as it includes a DC/DC converter to change the voltage from the 24V battery voltage to the 380V DC bus voltage. The other significant losses are the grid rectifier due to importing energy from the grid and cable loss, which is higher in the dual bus DC systems due to the operation of the 24V DC bus. There are three smaller loss values for the solar converter,

380V to 24V DC/DC converter and finally the DC/AC inverter for exporting energy to the grid. In a real system many of these loss components would be operating together in the one hybrid inverter but all the losses would still be present for the various functions.

Figure 4.7 is a plot that shows the annual total consumption per configuration, annual grid consumption per configuration and also compares the MATLAB results with the HOMER Pro results. It is therefore a combination of some previous figures already discussed. This figure confirms firstly that the MATLAB and HOMER Pro results are very closely aligned in all configurations. Secondly, it clearly shows the upward trend in total energy consumption and a downward trend in total grid consumption as PV and a BSS are incorporated into the installation. Finally, it confirms that a DC configuration is more efficient than the AC equivalent as each peak in the total consumption line graph corresponds to an AC configuration, being either configuration 1, 7 or 9.



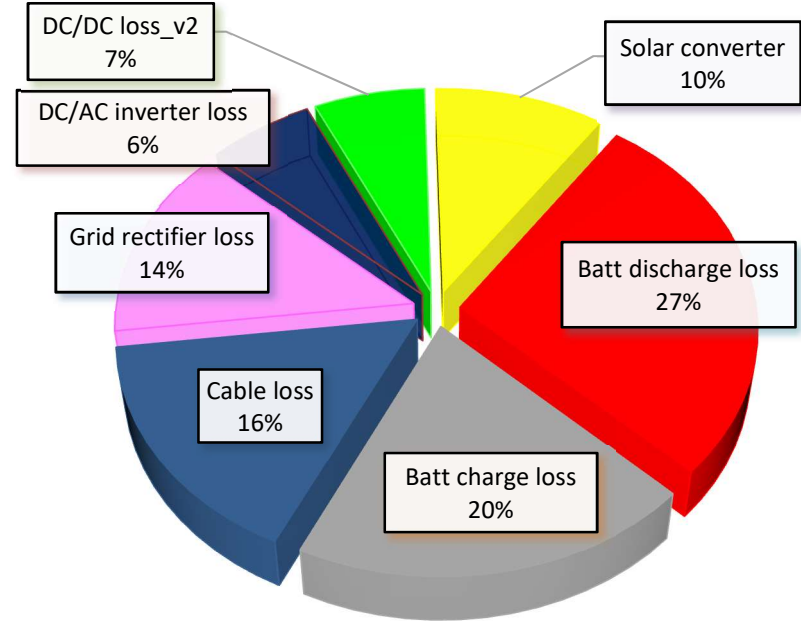
### Model 9 loss Breakup



Total Loss = 6.120kWh

Figure 4.5 – Model 9 loss breakup

### Model 10 loss breakup



Total Loss = 4.964kWh

Figure 4.6 – Model 10 loss breakup

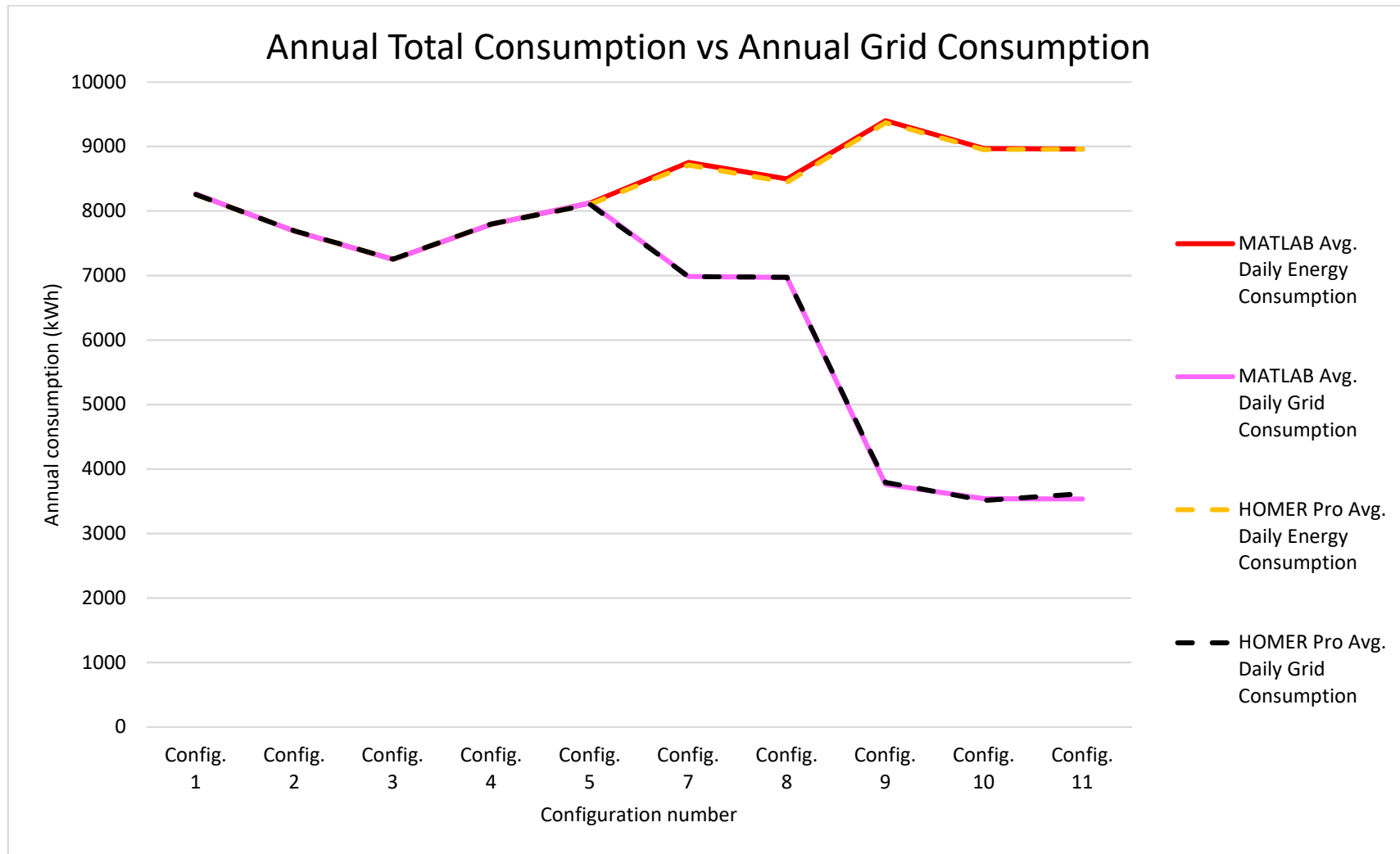


Figure 4.7 – Annual Total Consumption vs Annual Grid Consumption

#### 4.2.9 Remote Area Power Supplies

Given the positive result achieved from comparing the AC and DC configurations on a grid connected installation the next step was to see if the results would be consistent when applied to a RAPS. For this comparison only HOMER Pro was utilised as this was an additional component of the project and the MATLAB model was not configured for RAPS. There are many different configurations available for a RAPS, including:

- PV array and BSS
- PV array, BSS and Backup Generator
- PV array, Wind Turbine and BSS
- PV array, Wind Turbine, BSS and Backup Generator.

When physically constructing a RAPS installation many changes can be implemented when compared to a grid connected installation. These can include the physical design and construction of the building as well as the appliances utilised. The focus of these variations is to minimise energy consumption and system size. As this configuration was outside the primary scope of the project this section was limited to a brief analysis only to see if the same results held true in a simple RAPS system. The analysis was therefore limited to the following four configurations:

- PV and BSS supplying AC reticulated installation through a central inverter with DC internal appliances.
- PV and BSS supplying AC reticulated installation through a central inverter with DC internal appliances with a generator connected to the AC bus.
- PV and BSS supplying DC reticulated installation.
- PV, BSS and generator supplying DC reticulated installation.

All parameters were unchanged when compared to configurations 9 and 11 except for the removal of the grid connection. The size of the PV array, BSS and generator were decided by the HOMER Pro optimiser.

#### 4.2.9.1 AC configuration

This arrangement has the AC installation being supplied by the PV array and BSS through a central inverter and then connected to all the DC-internal loads. Therefore this configuration generates in DC, inverts to AC and then rectifies back to DC again for the load consumption.

In order to calculate the size of the system components a slightly different process had to be used than what was followed previously. The process was as follows:

- The AC load profile was imported into HOMER Pro. This was the same load profile used in configuration 9.
- The HOMER Pro schematic was rearranged as per Figure 4.8. This placed the renewable energy sources on the DC bus and supplied the AC load through a central inverter.
- A generator was included in the schematic for comparison in HOMER Pro
- This model was then executed with the optimiser choosing the most economical component sizes.

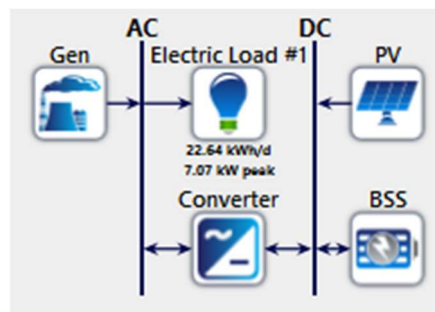


Figure 4.8 – AC RAPS

#### 4.2.9.2 DC configuration

This arrangement has the PV array, BSS and the generator connected to the 24V DC bus. The load profile has taken into account the DC/DC converter to supply the 380V DC bus.

In order to calculate the size of this system the following process was utilised:

- The DC load profile was imported into HOMER Pro. This profile is the same as that from configuration 11.
- The HOMER Pro schematic was rearranged as per Figure 4.9. This placed the renewable energy sources and the load on the DC bus.
- A generator was included in the schematic for a comparison in HOMER Pro.
- This model was then executed with the optimiser choosing the most economical component sizes.

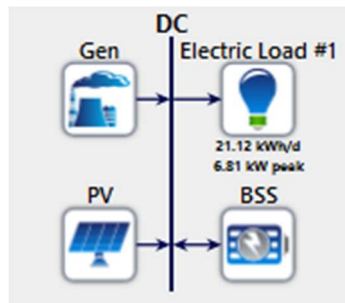


Figure 4.9 – DC RAPS

#### 4.2.9.3 RAPS Results

The HOMER Pro analysis resulted in two sets of results for each RAPS configuration. A result with no diesel generator installed and a result with a diesel generator installed. The determined component sizes for each of the configurations is displayed below.

	RAPS AC No Gen	RAPS DC No Gen	RAPS AC With Gen	RAPS DC With Gen
PV array (kW)	12.93	11.75	9.18	7.03
BSS (kWh)	27	25	19	18
Gen (kW)			5	5
Installation energy consumption (kWh)	9928.32	9036.86	9763.30	8909.675

Table 4.1 – RAPS configuration summary

The results were consistent with those obtained in the previous comparisons, with the DC installation displaying reduced energy consumption when compared to the equivalent AC installation as shown in Table 4.1 and Figure 4.10. The results also display that the system with the generator installed is more energy efficient than the one with no generator. The installation with the generator also operates on load following architecture, so the generator only supplies the required load and turns off as soon as the PV or BSS can supply the load. This is a result of less system losses when utilising the generator as it does not have battery losses. The obvious disadvantage is the operation of the generator and the utilisation of fossil fuel.

These results are only relevant for the load and generation profiles utilised. If alternate consumption patterns are present then the results will vary, as will the relevant size of the system components.

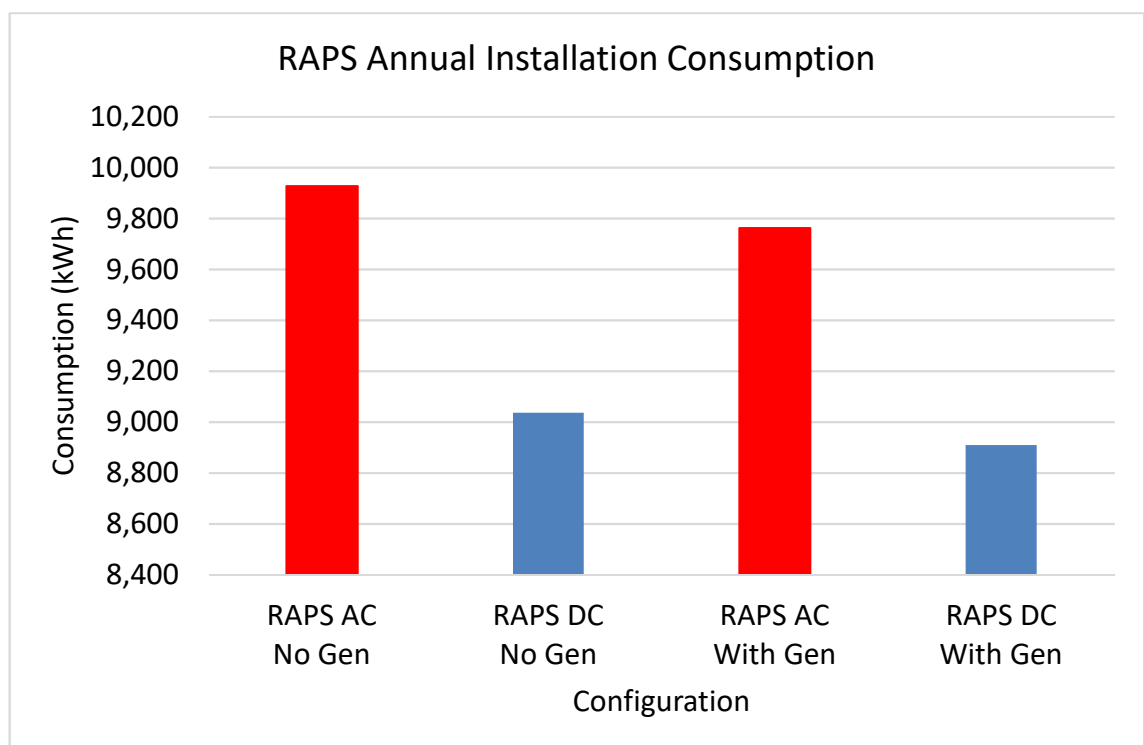


Figure 4.10 – RAPS Annual installation consumption

### 4.3 Cost Comparison

Financial analysis of the various options was conducted using HOMER Pro. The utility grid charges, feed in tariffs and component costs were covered in section 3.3 along with the other financial parameters for a successful analysis.

The two tariff structures used were peak, also known as flat rate, and time of use. The most appropriate tariff structure depends on the nature and timing of the consumers' energy usage. For the developed load profile Figure 4.11 displays the comparison of NPC between all configurations. The time of use structure held a noticeable financial advantage in all configurations utilising the obtained load and generation profile data. This result can change significantly with different usage and generation patterns but for this dissertation only the generated profile will be utilised.

For the NPC analysis configuration 2, 3 and 4 will be ignored. The justification for ignoring configurations 2 and 3 is that both rely on the installation being provided with a common DC bus voltage from the grid or some other supply with the same tariff structure as the existing AC grid. This is a situation that is not going to occur with the only possible scenarios for this arrangement explained in section 4.2.1. Configuration 4 is supplied from the AC grid but depends on the DC reticulation being set at one common voltage. Section 4.2.3 explains this is an unlikely situation so in order to display realistic results this is also being excluded from NPC analysis.

With these three configurations excluded Figure 4.11 identifies the lowest cost installation as configuration 7, which is the AC installation with a 5kW PV array installed. The most cost effective DC configuration is number 8 which is the DC installation with PV installed.

Building on these results another HOMER simulation was run on configuration 7, however, the optimiser was enabled to allow the selection of the best PV system, up to a limit of 30kW. This 30kW limit was imposed as a result of the changes to the connection requirements in the Ausgrid distribution area, where a consumer can connect up to 30kW of embedded generation through a streamlined application process. The installation of this system again recommended the time of use tariff structure and also to install the maximum size PV of 30kW. Although the grid feed in tariff is very low, the system cost and its resulting output actually proved to be cost positive. Although over the course of a twelve-month period the consumer would still need to purchase 6,520kWh of energy from the grid they would export 52,247kWh resulting in a NPC of \$16,726 over a 25-year period and an operating cost of -\$713.86 per annum.

A similar analysis was conducted on configuration 10 as the least cost PV and BSS configuration to determine any benefit. In this optimisation both the PV and BSS were set to 30kW limits. The result of this analysis was again a time of use tariff structure with a 20.2kW PV system and a 13.3kW inverter to give a NPC of \$33,0850.39 over a 25-year period and an operating cost of

\$335.21 per annum. This confirms that the price of a BSS is still too high to be a viable option for the residential consumer resulting in HOMER Pro excluding it as a preferred option.

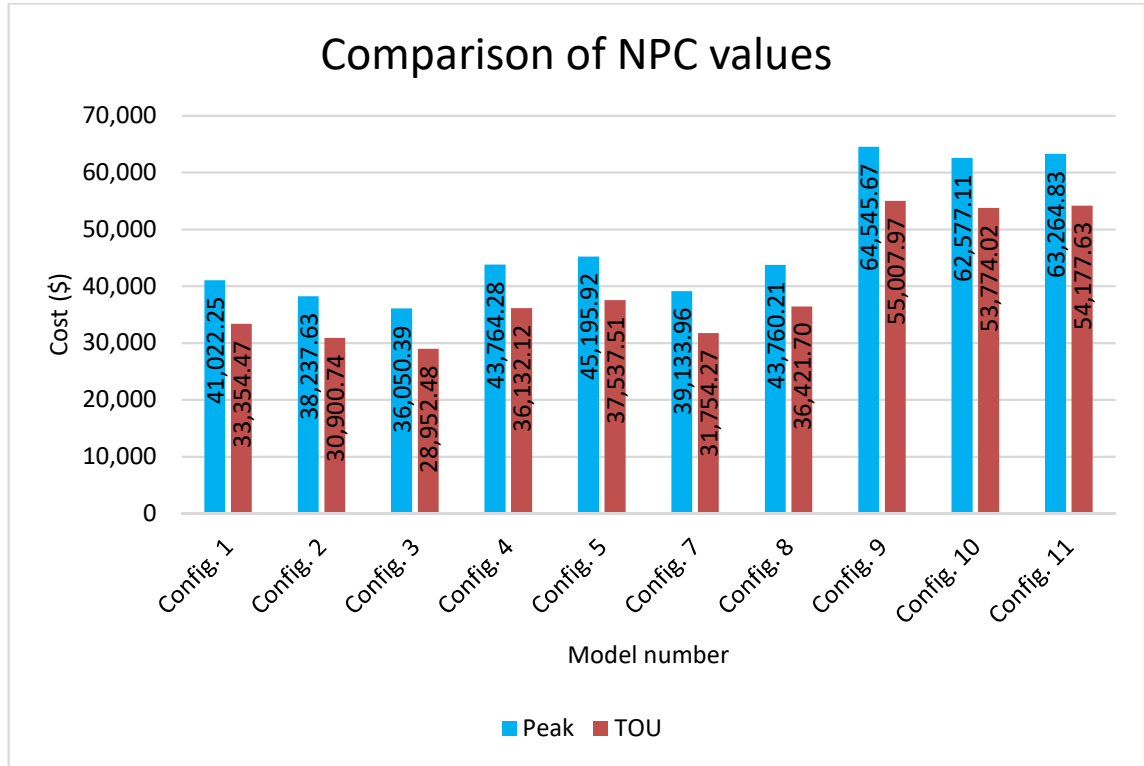


Figure 4.11 – Comparison of NPC values

In the RAPS configurations the same parameters for costs were applied as in all previous configurations except the generator which was an additional component. The generator parameters were primarily maintained as per the HOMER Pro default with the capital cost equal to \$500 per kW. The only alteration made was to the fuel price. This fuel price in Australia is highly variable with a national average diesel price of \$142.91 over the last nine years (Petroleum 2016). Future fuel prices are unknown, therefore a figure of \$1.50 per litre was utilised. This allows a small rise in the nine-year average.

Figure 4.12 clearly shows the annual installation consumption and the NPC of each of the RAPS configurations. In this instance the most efficient in regards to energy consumption is the DC configuration with a generator installed. This option is also the most cost effective installation making it clearly the best option. In comparison to the previous results this is a clear difference. The DC configuration was only economically better than the AC configuration in those options containing PV and a BSS, however these also had the highest overall cost. In a RAPS system the opportunity for a grid connection is unavailable, hence each system is required to have suitable



generation and storage. A system that operates with less load consumption and minimises conversions will always be the most economical and in the modelled configurations this is the case. A number of parameters could however affect this outcome including load and generation profiles, component and operating costs.

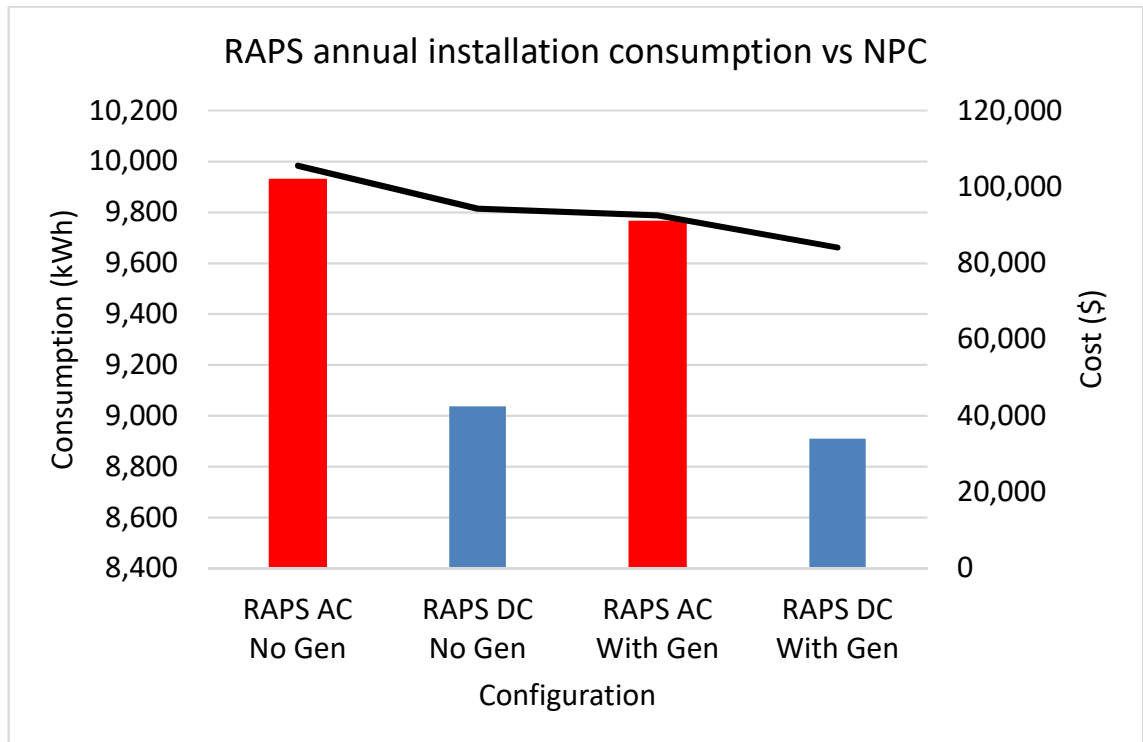


Figure 4.12 – RAPS annual installation consumption vs NPC

#### 4.4 Results Summary

After a comprehensive analysis of results, it is evident that the operation of a DC installation does present an energy saving when compared to the equivalent AC installation in each of the comparisons analysed. The general rise in overall consumption with the introduction of PV and a BSS is a direct result of increased losses within the system. These losses can include the MPPT, battery charger, inverter, rectifier and battery round trip efficiency. The reduction in consumption between equivalent AC and DC systems is a result of removing the internal AC/DC rectifiers and reducing the base load of the overall installation. This reduction in base load is a direct result of removing the internal appliance rectifiers as these consume power whilst in standby mode. The reduction in grid energy consumption occurs as PV and BSS are utilised giving alternate energy sources.

The most suitable DC configuration would come down to the individual electrical requirements. An installation with many high power devices would need to utilise configuration 10 and likely look to incorporate a higher voltage BSS. Many of the lithium-ion manufacturers do operate in the 300V to 400V range. If the installation was slanted more towards consumer electronics and small devices the adoption of configuration 11 would likely be more suitable. An important component is that both systems operate on the same upper and lower voltages, 380V DC and 24V DC. This will give appliance manufacturers clear guidelines where to focus DC appliance development and common DC voltages to utilise.

From an economic perspective configuration 7, which is an AC installation with 5kW of PV installed, is the best option of those configurations modelled. The best value DC configuration, excluding those that are deemed highly unlikely, is the DC installation with a 5kW PV array installed, although it is still noticeably more expensive than the AC equivalent. At this stage the price of renewable components is still too high for DC to be more cost effective than the equivalent AC configuration, despite holding an efficiency advantage.

The result does vary slightly when looking at a RAPS system. The DC configuration holds a clear advantage over the equivalent AC configuration in regards to efficiency, which is consistent with the grid connected installations. When looking at cost effectiveness, the DC installation also comes out in front which is the reverse of the trend found in grid connected installations. Despite DC being cheaper it is still noticeably more expensive than a comparable grid connected configuration and hence, at this stage it is not viable to disconnect from the grid in favour of stand-alone.

There are a number of variables and criteria that have been utilised to make these comparisons including the efficiency of the inverters, rectifiers and converters used in establishing the models, the size of the installation components and also in the load and generation profiles. All of these parameters are user adjustable in the MATLAB model to tailor for a specific situation but using the data, as stated in Chapter 3, provides a clear positive result.

## Chapter 5      Consequential Effects

The completion of this research project was primarily focussed around research and modelling a comparison between AC and DC energy usage in a domestic installation. The aim was to determine if an efficiency gain could be obtained by both reducing energy loss and financial cost.

The research project did not invent anything new, rather it looked at an improved way of utilising a well-known energy source to improve efficiency. The areas of sustainability, safety and ethical issues will be addressed in the following sub-sections.

### 5.1 Sustainability

The results of this research project identify an improvement in energy efficiency by transferring to a DC installation when compared to an equivalent AC installation. As this was a theoretical project no manufacturing or materials were consumed, nor is it recommended at this early stage of research. If further analysis and more widespread simulation of different load profiles is performed and the results remain positive, there would be justification to extend to field trials and possibly more widespread implementation.

Improved utilisation of renewable energy generation and storage will reduce reliance on the grid and centrally generated electricity. This has the effect of reducing our reliance on fossil fuels for electricity generation and would result in a transmission and distribution network that would not need to grow in distribution capacity as more energy will be produced, stored and used locally. This would further decrease the consumption of materials and fuels in these industries but would also have the effect of reducing workforces in these industries and give rise to the social impacts that stem from this.

The utilisation of renewables and energy storage systems is not without its shortfalls. The production of PV arrays and BSSs is still a manufacturing process and all of these items have a recommended lifecycle. Analysing this in detail is beyond the scope of this project but it is important to recognise the environmental impacts that the production and disposal of these items do present. Priorities in the development of battery storage technology include increasing efficiency, increasing lifecycle thereby reducing replacement costs, whilst developing battery types able to have an increased life due to a non-toxic electrolyte change.

The use of DC also comes with a number of potential installation options. The first would be to convert or install DC to the entire installation. If the entire installation utilises DC, then the volume of material consumed would be similar to that of an AC installation. There will be variation in the types of components, such as cable sizes, DC sockets and protection devices but in general the installation would be similar. The second installation option would be a hybrid system which would contain both AC and DC circuits. This type of installation is possibly the more likely scenario as it is easy to convert some loads, such as LED lighting, to a DC supply whilst the remainder of the installations stays as AC. This could involve the use of additional copper cabling, sockets and protection devices if both AC and DC power circuits (i.e. power point sockets) were installed. It also presents a technically more challenging installation that requires clear labelling, standards and rules to be developed to ensure any future work is safe to undertake. This additional use of equipment would result in a negative environmental impact due to increased volume of components used.

Another notable limitation of DC is the need for more robust and specialised switches as there is a requirement to bring the current and voltage to zero due to no zero crossing. The nature of this switching operation results in additional arcing and can mean that some switches need to be replaced more often, resulting in additional wastage. In order to mitigate this situation, it is necessary to install appropriate switches designed for the intended function. This means that switches requiring regular operation need to have a suitable expected lifecycle, likely resulting in additional upfront expenditure.

## 5.2 Safety

There are two areas of safety that need to be addressed in this research project; the safety associated with the completion of the research project and the safety following the completion of the research project. First to be addressed will be the safety following the completion of the research project.

This project's primary function was to research and report any efficiency gain that can be achieved by using DC supply within the domestic environment. All DC installations were obtained from research determined by the author for modelling in a theoretical environment. None of the configurations were physically constructed during the completion of the project. Therefore, the primary risk following this project is that someone will construct the recommended installation.


It is vital that anyone who reads this research project understands that at this stage the content is completely theoretical and although all results have been produced with the utmost diligence and focus on accuracy, a physical installation has not been produced. Practical implementation may result in some complications or hazards that may have been inadvertently missed. Before attempting to construct any installation based on findings in this report it is essential that confirmatory calculations are completed and all relevant standards and electrical installation rules are followed. There is no way for the author of this document to enforce or control these issues.

Safety in relation to the completion of the project was covered by means of a risk assessment recorded in Table 5.1. This table lists the tasks, hazards, risk ratings with no controls implemented, controls to be implemented and final revised risk ratings.

The risk ratings and controls are completed as per the matrix and hierarchy of controls shown in Figure 5.1 and Figure 5.2 respectively. These figures were obtained from Ausgrid and are used to complete the Hazard Assessment Check-sheet for all work undertaken. When implementing controls, it is mandatory to start at the top of the hierarchy and work your way down. This means elimination of the risk is the most desirable outcome with PPE being the least desirable.

		CONSEQUENCE				
		Insignificant	Minor	Moderate	Major	Severe
LIKELIHOOD	Almost Certain	11	16	20	23	25
	Likely	7	12	17	21	24
	Possible	4	8	13	18	22
	Unlikely	2	5	9	14	19
	Rare	1	3	6	10	15

Figure 5.1 – Risk Matrix (Ausgrid 2016b)



The “Hierarchy of Controls” is a hierarchy with the most effective risk control strategy being elimination and the least effective being the provision of personal protective equipment.

Users must work down through the list. In many instances, a combination of controls will be required to reduce the risk to ALARP.

1. **Elimination** – remove the hazard.
2. **Substitution** – change process item to an item of less risk, eg, substances.
3. **Isolation** – use preventative mechanism, eg, guarding.
4. **Engineering** – use machines rather than manual labour.
5. **Administrative** – develop and implement safe work procedures, conduct training, implement a checklist.
6. **Personal Protective Equipment** – use personal protective equipment, eg, hard hats, respirators, hearing protection, insulating gloves, safety protective footwear.

Figure 5.2 – Hierarchy of Controls (Ausgrid 2016b)

### 5.2.1 Risk Assessment for completion of research project

<b>Task</b>	<b>Hazard</b>	<b>Risk Rating</b>	<b>Controls</b>	<b>Revised Risk Rating</b>
Installing logger in main switch board	Electrocution	25	Test meter box to ensure it is not live Isolate the power source whilst making connections Test it is de-energised Inspect cables for insulation deterioration PPE – arc resistant clothing, boots, safety glasses Relevant qualifications to install logger	15
	Spider/insects	13	Clear spider webs Don't put hands where you can't see what is there	6
	Asbestos	17	Gauge the age of the meter board. If prior to approximately 1988 then it is highly likely to contain asbestos (Ausgrid 2016a) Inspect board for asbestos labelling Wear relevant PPE and vacuum out meter box if necessary as per asbestos training course	6
	Weather – sunburn, rain, wind	17	PPE Avoid working in adverse weather conditions Check forecast Do not work on main switch board in the rain Secure meter box lid if windy to avoid it falling down	6
	People	25	Communication Keep people clear of worksite	15
	Inadequate space	13	Ensure adequate clearance from obstacles Move obstacles if necessary Maintain electrical clearances PPE	6
	Inadequate lighting	17	Use of additional lighting, such as a torch Only work with suitable visibility	6

Table 5.1 – Risk assessment for completion of research project

<b>Task</b>	<b>Hazard</b>	<b>Risk Rating</b>	<b>Controls</b>	<b>Revised Risk Rating</b>
Obtain readings using CABAC Power-Mate Lite	Electrocution	19	Ensure device is plugged in correctly Use power point switched to isolate each time	15
Obtain current readings using clamp ammeter	Electrocution	25	Inspect cables for insulation deterioration PPE – arc resistant clothing, boots, safety glasses	15
	Spider/insects	13	Clear spider webs Don't put hands where you can't see what is there	6
	Asbestos	17	Gauge the age of the meter board. If prior to approximately 1988 then it is highly likely to contain asbestos (Ausgrid 2016a) Inspect board for asbestos labelling Wear relevant PPE and vacuum out meter box if necessary as per asbestos training course	6
	Weather – sunburn, rain, wind	8	PPE Avoid working in adverse weather conditions	3
Extended hours in front of computer	Eye strain	12	Regular breaks Exercise eyes – look at items some distance away then back at scree/notes.	3
	Fatigue	8	Regular breaks Ensure quality sleep Nutritional diet Stretches and regular exercise	3
	Musculoskeletal disorders (eg. Repetitive Strain Injuries, back and neck pain)	13	Regular breaks Stretches and regular exercise Correct posture Correct equipment – ergonomic chairs, correct desk height, workstation setup, mouse and keyboard position.	6

Table 5.1 – Risk assessment for completion of research project



### 5.3 Ethics

There are a number of factors that can impact the ethics of undertaking a research project. The following paragraphs will work through these factors.

Firstly, is the topic ethical? This research project topic was undertaken to determine if there can be an efficiency gain achieved by using DC in a domestic household. As such the research project looked to reduce domestic energy consumption and allow better utilisation of the increasing amount of renewable generation and energy storage. The topic does satisfy the Engineers Australia code of ethics sections 4.1, 4.2 and 4.3 relating to promotion of sustainability.

Secondly, are the outcomes of the topic ethical? As covered in the previous paragraph the aim was to gain efficiency by using DC energy, which was confirmed as an ethical topic. The results obtained were positive and hence is encouraging the adoption of DC installations in order to better utilise the energy from the increasing volume of renewable generation and energy storage. This outcome will contribute to an improved and more sustainable environment.

Thirdly, is the methodology, execution and recording of results accurate? The research project and presented information has satisfied these three criteria. Whilst reviewing the literature an unbiased, honest interpretation of the information has been undertaken with all sources of information cited where appropriate. The information reviewed was wide ranging and offered a number of different opinions and results, which all contributed to the formation and execution of this research project. The completion of the modelling and recording of results has been undertaken with the utmost focus on accurately recording the methodology, assumptions, limitations and results.

## Chapter 6 Conclusion

The introduction to the project outlined four key objectives that were to be satisfied in order to achieve the project aim of determining if an efficiency gain can be achieved by utilising a DC supply in place of the existing AC. The key objectives are listed below and will be briefly addressed through this section.

1. Is the utilisation of DC distribution in a domestic installation more efficient than the accepted AC?
2. If there is a benefit, is it an energy saving and or financial saving for the consumer?
3. What are the proposed voltage levels for DC supply?
4. Is the installation of PV and a BSS a viable option?

The completion of the literature review provided the groundwork in determining that there was potential for a residential installation to achieve an efficiency gain by converting to DC. Following on from this literature review logging of individual installations and the analysing of distribution substation data provided confirmation of the daily load values and profiles that were to be used in the modelling process.

A MATLAB model was then developed with its operation confirmed against a known load profile and appliance inventory with the results being within approximately 2%. This was deemed acceptable and allowed the adjustment of the load and generation profiles for analysis in MATLAB and HOMER Pro for energy efficiency gains and economic viability. The analysis incorporated eleven different configurations utilising AC and DC installations with and without PV and a BSS installed. The PV and a BSS were a fixed size across all configurations. This was done to ensure that a consistent comparison was undertaken. The values within the MATLAB model can be varied in order to assess any individual installation requirements and provide the figures for comparison between AC and DC configurations.

The proposed DC voltage levels from this project are 380V DC and 24V DC. The 380V DC value was chosen due to it being proposed by numerous sources in literature, in particular Emerge Alliance. The 24V DC value was chosen to have a compromise between a voltage low enough to safely operate consumer electronics but high enough to minimise the voltage drop in the cables.

The result of these comparisons was that in all equivalent configurations the DC installation was more energy efficient than the AC installation with results yielding an improvement between 1.686% and 12.260%. These results did include some configurations which are highly unlikely to occur due a number of limitations, therefore, the expected benefit places DC between 1.686% and 4.694% more efficient than the equivalent AC.

In regards to economic viability AC configurations are the best option for installations that do not contain a BSS. Where a BSS is utilised DC holds a slight advantage over the equivalent AC configuration but as a collective they are still too expensive for the consumer looking to reduce expenses on energy. Financially the best configuration was an AC installation with a 5kW PV array installed. This is currently the most popular embedded generation connection in Australia. HOMER Pro was utilised to optimise the PV array between 0kW and 30kW to see what size would be recommended. With the inputted parameters the recommendation was for a 30kW system to be installed, this suggests that despite the low feed in tariff it is still economically viable to install large PV arrays and export energy to the grid. The advantage would grow significantly if a larger volume of the energy was consumed directly by the generating installation.

In a RAPS the efficiency results hold true, with the DC configuration being more efficient than the equivalent AC configuration. The difference comes when comparing the financial results where again the DC configuration is the better of the two. Despite DC holding a clear advantage over AC in this arrangement the overall cost is still too high to be financially viable for the grid connected consumer to move to a stand-alone installation. The lack of direct DC appliances is a significant road block to the uptake of direct DC. This is unlikely to change without the formation of standards and increased consumer demand.

In conclusion, despite the energy efficiency benefits of utilising DC directly in the residential installation there are two unavoidable hurdles presently in the way. The first of these is the financial limitation as the equivalent AC system, on average, is more economical to install and operate. The second, and more importantly, is that there is currently an absence of residential appliances that can operate directly on a DC voltage. The main driver of this is the lack of demand and lack of standards within the DC environment. With the constant advancements in technology, the ever increasing volume of PV installations, impending battery revolution and continued development of more electronic devices operating internally on DC, there is a likely future in DC installations and microgrid operation, just not yet.

## Chapter 7 Future Work

### 7.1 Residential DC microgrid

The operation of a DC residential subdivision with a weak grid connection through a central point is an opportunity for future work. This would be created by a central community battery storage combined with PV generation on all connected installations. Each installation would then charge and discharge the battery as required with a central grid connection to export excess energy or provide additional capacity as required.

Changing an entire distribution network from AC to DC is an unrealistic expectation that would involve a huge amount of expense and time. However, to install a residential subdivision with DC reticulation and a weak AC grid connection is a realistic possibility. The installation arrangement could have a number of different configurations but the two most likely would be:

- PV and BSS installed at each installation with a communication system allowing the central control of all the systems to coordinate the import and export of DC energy before ultimately importing or exporting on the AC grid. There are some challenges in this configuration about how each customer receives credit or charges for their generation and consumption and who owns the PV arrays and BSSs.
- PV installed at each installation with a central BSS. Wearmouth (2016) details an AC configuration similar to this proposal located in Alkimos Beach, 40km north of Perth, in Western Australia. This system operates by allocated credits to the individual installations for their excess generation that is stored in the central BSS and then credits are used when the consumer requires them. The grid connection provides back up power and can also charge the BSS during off peak periods.

A similar model could be adopted with each installation operating on DC energy with PV being generated into the central BSS that also has a weak grid connection through a central rectifier for battery charging and providing additional energy as required. With an advanced controller system communicating with each connected installation in addition to accessing predicted weather data, the control of charge, discharge, loads and grid utilisation could be accurately monitored.

## 7.2 Smart Switchboard.

As PV array and battery storage system prices continue to fall their appeal to consumers will continue to grow. There are a couple of different types of consumers that are in the market for these renewable generation and storage devices. They are, the ones that are looking to reduce their carbon footprint and dependency on the grid and as such are looking to become self-sufficient. Then there are the those who are purely looking from a financial perspective with a prime focus on options to reduce consumption and reduce their energy bill. These two scenarios result in very different approaches to the installation configuration.

As highlighted earlier the second option of using renewable generation and storage in order to gain a financial saving by reducing electricity bills is not viable with battery storage systems at their current prices and expected lifecycle. As technology improves and manufacturing costs continue to decrease it is expected they will begin to have a significant presence in the domestic market. However, the installation of PV is currently a good option for the domestic consumer in both an AC and DC configuration. The benefit of the PV system is enhanced greatly by rearranging consumption patterns to match the generation profile. This is due to the low feed in tariff offered by most Australian electricity retailers for excess solar generation compared to the tariff charged for energy being consumed from the grid. A good option in this situation is for the consumer to have a control system in place to utilise this excess energy when it is available.

For an off grid consumer, the focus is the same except they have to have an ESS, which will most likely be in the form of a BSS. The presence of a control system will allow a more strategic approach to sizing their system and be able to maximise their renewable benefit without using backup energy from alternate supplies such as generators or a grid connection if it is present.

The control system being referred to would control items such as electric hot water elements, pool pumps, water transfer pumps for rural consumers, washing machines, dishwashers, refrigerators and freezers. It is quite evident that most of these loads are operated by electric motors, hence, if these were driven by brushless DC motors the voltage could be varied to control the speed depending on the available capacity. An example of this would be an air conditioning unit that varies its output depending on the output of the PV array. The operation would also be controlled in conjunction with the other loads to ensure they cycled in a way to maximise the consumer benefit.

This type of control system could be implemented on an AC or DC installation but as determined by the outcome of this research project the DC installation yielded an efficiency saving that

increased with the introduction of PV and a BSS. Therefore, a greater benefit to the consumer would be available by utilising DC reticulation through the installation.

## References

AER, CoA 2015, *Energy Made Easy*, viewed 18/06/2016, <<https://www.energymadeeasy.gov.au/benchmark>>.

AIRPAX 2013, *Guide to Power Protection*, <<http://airpax.sensata.com/pdfs/guidetoprotection.pdf>>.

Amin, M, Arafat, Y, Lundberg, S & Mangold, S 2011, 'Low voltage DC distribution system compared with 230 V AC', in *Electrical Power and Energy Conference (EPEC), 2011 IEEE*, pp. 340-5.

Andrade, Ld & Leao, Tpd 2012, 'A brief history of direct current in electrical power systems', in *History of Electro-technology Conference (HISTELCON), 2012 Third IEEE*, pp. 1-6.

Ausgrid 2016a, *Asbestos in Electrical Meter Boards*, <<https://www.ausgrid.com.au/~//media/Files/Safety/Fact%20Sheet%20Asbestos%20in%20Electrical%20Meter%20Boards.pdf>>.

Ausgrid 2016b, *NR18 Load Survey Safe Work Method Statement*, Version 4.1, 05/03/2015.

Ausgrid 2016c, viewed 03/05/2016, <[www.ausgrid.com.au](http://www.ausgrid.com.au)>.

Australia, Co 2016, *Australian Bureau of Statistics*, viewed 23/07/2016, <<http://www.abs.gov.au/>>.

Australia, S 2009, *Electrical Installations - Selection of cables*, AS/NZS 3008.1.1:2009, Standards Australia, viewed 16/03/2016, <<https://www-saiglobal-com.ezproxy.usq.edu.au/online/autologin.asp>>.

Australia, S 2010, *Effects of current on human beings and livestock*, AS/NZ 60479 Standards Australia, viewed 07/05/2016, <<https://www-saiglobal-com.ezproxy.usq.edu.au/online/autologin.asp>>.

Boeke, U & Wendt, M 2015, 'DC power grids for buildings', in *DC Microgrids (ICDCM), 2015 IEEE First International Conference on*, pp. 210-4.

Chauhan, RK, Rajpurohit, BS, Hebner, RE, Singh, S & Gonzalez-Longatt, FM 2016, 'Voltage standardization of DC distribution system for residential buildings', *Journal of Clean Energy Technologies*, vol. 4, no. 3, pp. 167-72.

Choice, S 2016, *Solar Choice*, viewed 18/11/2016, <<http://www.solarchoice.net.au/>>.

Commonwealth of Australia, EP 2016, *Energy Rating*, viewed 18/06/2016, <<http://www.energyrating.gov.au/>>.

Company, AG 2007, *ABB circuit-breakers for direct current application*, <[http://www04.abb.com/global/seitp/seitp202.nsf/0/6b16aa3f34983211c125761f004fd7f9/\\$file/vol.5.pdf](http://www04.abb.com/global/seitp/seitp202.nsf/0/6b16aa3f34983211c125761f004fd7f9/$file/vol.5.pdf)>.

Cunningham, JJ 2013, 'An AC Pioneer: United Electric Light & Power Company [History]', *IEEE Power and Energy Magazine*, vol. 11, no. 3, pp. 84-98.

Dragicevic, T, Lu, X, Vasquez, JC & Guerrero, JM 2016, 'DC Microgrids - Part II: A Review of Power Architectures, Applications, and Standardization Issues', *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3528-49.

Elsayed, AT, Mohamed, AA & Mohammed, OA 2015, 'DC microgrids and distribution systems: An overview', *Electric Power Systems Research*, vol. 119, pp. 407-17, <http://www.sciencedirect.com/science/article/pii/S0378779614003885>>.

EnergyConsult 2015, *Residential Energy Baseline Study: Australia*, Dola Science, viewed 22/05/2016 <.

Fairley, P 2015, 'Energy storage: Power revolution', *Nature*, vol. 526, no. 7575, pp. S102-S4, <http://dx.doi.org/10.1038/526S102a>>.

Garbesi, K, Vossos, V, Sanstad, A & Burch, G 2012, *Optimizing Energy Savings from Direct-DC in U.S. Residential Buildings*, <<http://www.escholarship.org/uc/item/66c8n9s8>>.

Goikoetxea, A, Canales, JM, Sanchez, R & Zumeta, P 2013, 'DC versus AC in residential buildings: Efficiency comparison', in *EUROCON, 2013 IEEE*, pp. 1-5.

Gregory, GD 1995, 'Applying low-voltage circuit breakers in direct current systems', *IEEE Transactions on Industry Applications*, vol. 31, no. 4, pp. 650-7.

Hammerstrom, DJ 2007, 'AC Versus DC Distribution Systems Did We Get it Right?', in *Power Engineering Society General Meeting, 2007. IEEE*, pp. 1-5.

Helwig, A & Ahfock, T 2013, 'Long-life nickel iron battery functionality / cost comparison for peak demand SWER network voltage support application', in *Power Engineering Conference (AUPEC), 2013 Australasian Universities*, pp. 1-6.

Helwig, A & Ahfock, T 2015, 'A case study: Is energy storage affordable for further Australian sustainable energy development?', in *Power Engineering Conference (AUPEC), 2015 Australasian Universities*, pp. 1-6.

Institute, AP 2016, 'Australian PV Institute (APVI) Solar Map, funded by the Australian Renewable Energy Agency', viewed 20/08/2016, <[pv-map.apvi.org.au](http://pv-map.apvi.org.au)>.

Lobenstein, RW & Sulzberger, C 2008, 'Eyewitness to dc history', *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 84-90.



Lotfi, H & Khodaei, A 2015, 'AC Versus DC Microgrid Planning', *IEEE Transactions on Smart Grid*, pp. 1-, [http://usq.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMw3V07T8MwELZQJxgQT\\_EUW\\_VGVEjuxHQ8MIYV26IIaJLbIsR3RoSmU9v9jx04aKhhYGeNYpzgn3cvffQdAiAaBv2UTEDU8aTKmH\\_HLtkyluglpxXAJFULS1N8mzyR7JZOHaLyZhLdZ-w-KT9K-KYKtP\\_vDGhVvAFgz2U4n6kajJtOz9Oa2vaG-OpiOtdD-aNIA3c085IVph1trj6pmm3v7t4Xkqn6TzN2yKyDY5kln7VhkgA-WrXegumuWId1ZNdhxj\\_Bnu1vTlmbTkQHL4QGKMGUOrvqN4nrl9bSAwDoVCViuJeRGQt5IMAT\\_oczKtQ3tV-S9TwxUQEIL36SVtLS0IQ-2HWQ0gcCdqbqQDdrf9VZ0lpBNKZAdg3-UAXmJ1dwh2VHUE9jrMkMfgJkk9q0VvmHqtFr1Giycge3rM0rHvZln4gmDoc0xLCQsizXidguogTaF\\_YFIHQla4IFRFI6FwQKsJCjihkOumjDOM4lpxyEpfhKehVi0qdAQ-hknAZSAyJjPS-lqK8UDEnUmfmvFTn4LY5Xv5uGUvy337vxR\\_2XoJd82jLT1egt1qu1bUZIPPxBXTpLg4](http://usq.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMw3V07T8MwELZQJxgQT_EUW_VGVEjuxHQ8MIYV26IIaJLbIsR3RoSmU9v9jx04aKhhYGeNYpzgn3cvffQdAiAaBv2UTEDU8aTKmH_HLtkyluglpxXAJFULS1N8mzyR7JZOHaLyZhLdZ-w-KT9K-KYKtP_vDGhVvAFgz2U4n6kajJtOz9Oa2vaG-OpiOtdD-aNIA3c085IVph1trj6pmm3v7t4Xkqn6TzN2yKyDY5kln7VhkgA-WrXegumuWId1ZNdhxj_Bnu1vTlmbTkQHL4QGKMGUOrvqN4nrl9bSAwDoVCViuJeRGQt5IMAT_oczKtQ3tV-S9TwxUQEIL36SVtLS0IQ-2HWQ0gcCdqbqQDdrf9VZ0lpBNKZAdg3-UAXmJ1dwh2VHUE9jrMkMfgJkk9q0VvmHqtFr1Giycge3rM0rHvZln4gmDoc0xLCQsizXidguogTaF_YFIHQla4IFRFI6FwQKsJCjihkOumjDOM4lpxyEpfhKehVi0qdAQ-hknAZSAyJjPS-lqK8UDEnUmfmvFTn4LY5Xv5uGUvy337vxR_2XoJd82jLT1egt1qu1bUZIPPxBXTpLg4).

Mackay, L, Ramirez-Elizondo, L & Bauer, P 2014, 'DC ready devices - Is redimensioning of the rectification components necessary?', in *Mechatronics - Mechatronika (ME), 2014 16th International Conference on*, pp. 1-5.

Market, S 2016, *Solar Feed-in Tariffs*, viewed 17/04/2016, <<https://www.solarmarket.com.au/learn/tariffs/>>.

Monadi, M, Amin Zamani, M, Ignacio Candela, J, Luna, A & Rodriguez, P 2015, 'Protection of AC and DC distribution systems Embedding distributed energy resources: A comparative review and analysis', *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1578-93, <http://www.sciencedirect.com/science/article/pii/S1364032115006607>>.

*A wide-ranging discussion of Australia's electricity sector, from the customer's perspective*, 2016, PowerPoint slides, created by Mountain, B, viewed 23/02/2016 <.

Oliveira, TRd, Bolzon, AS & Donoso-Garcia, PF 2014, 'Grounding and safety considerations for residential DC microgrids', in *Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE*, pp. 5526-32.

Petroleum, Alo 2016, *Australian Institute of Petroleum*, Australian Institute of Petroleum, viewed 08/10/2016, <<http://www.aip.com.au/index.htm>>.

Planas, E, Gil-de-Muro, A, Andreu, J, Kortabarria, I & Martínez de Alegría, I 2013, 'General aspects, hierarchical controls and droop methods in microgrids: A review', *Renewable and Sustainable Energy Reviews*, vol. 17, pp. 147-59, <http://www.sciencedirect.com/science/article/pii/S1364032112005333>>.

Planas, E, Andreu, J, Gárate, JI, Martínez de Alegría, I & Ibarra, E 2015, 'AC and DC technology in microgrids: A review', *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 726-49, <http://www.sciencedirect.com/science/article/pii/S1364032114010065>>.

Redflow 2016, *Redflow advanced energy storage*, viewed 23/04/2016, <<http://redflow.com/>>.

*Reserve Bank of Australia*, 2016, viewed 23/07/2016, <<http://www.rba.gov.au/>>.

Rodriguez-Diaz, E, Savaghebi, M, Vasquez, JC & Guerrero, JM 2015, 'An overview of low voltage DC distribution systems for residential applications', in *Consumer Electronics - Berlin (ICCE-Berlin)*, 2015 IEEE 5th International Conference on, pp. 318-22.

Salomonsson, D, Soder, L & Sannino, A 2009, 'Protection of Low-Voltage DC Microgrids', *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1045-53.

Sechilariu, M, Locment, F & Baochao, W 2015, 'Photovoltaic Electricity for Sustainable Building. Efficiency and Energy Cost Reduction for Isolated DC Microgrid', *Energies (19961073)*, vol. 8, no. 8, pp. 7945-67, <http://ezproxy.usq.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=108935206&site=ehost-live>>.

Speidel, S & Bräunl, T 2016, 'Leaving the grid—The effect of combining home energy storage with renewable energy generation', *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1213-24, <http://www.sciencedirect.com/science/article/pii/S1364032115017086>>.

*The Customer Centric Grid*, 2016, PowerPoint slides, created by Stewart, H, viewed 23/02/2016 <.

Sulzberger, CL 2003a, 'Triumph of AC. 2. The battle of the currents', *IEEE Power and Energy Magazine*, vol. 1, no. 4, pp. 70-3.

Sulzberger, CL 2003b, 'Triumph of AC - from Pearl Street to Niagara', *IEEE Power and Energy Magazine*, vol. 99, no. 3, pp. 64-7.

Tesla, N 1984, 'A new system of alternate current motors and transformers', *Proceedings of the IEEE*, vol. 72, no. 2, pp. 165-73.

Vossos, V, Garbesi, K & Shen, H 2012, 'Catalog of DC appliances and power systems'.

Vossos, V, Garbesi, K & Shen, H 2014, 'Energy savings from direct-DC in U.S. residential buildings', *Energy and Buildings*, vol. 68, Part A, pp. 223-31, <http://www.sciencedirect.com/science/article/pii/S0378778813005720>>.

Wearmouth, A 2016, *Alkimos Beach Battery Storage Trial*, Engineering Education Australia, Engineering Education Australia, <[http://eeaust.com.au/images/stories/virtuemart/category/presentation-to-the2016api-summer-school-alkimos-battery-storage-project\\_\(no-charge-curve\)-andy.pdf](http://eeaust.com.au/images/stories/virtuemart/category/presentation-to-the2016api-summer-school-alkimos-battery-storage-project_(no-charge-curve)-andy.pdf)>.

# Appendix A Project Specification

## ENG4111/4112 Research Project

### Project Specification

For: Mark Thorley

Title: Using Renewable DC Energy Sources: Improving Domestic Energy Efficiency.

Major: Electrical and Electronics Engineering

Supervisor: Andreas Helwig

Enrolment: ENG4111 – EXT S1, 2016  
ENG4112 – EXT S2, 2016

Project Aim: Determine if an energy efficiency gain can be obtained by using DC energy sources within the domestic installation. The focus will be on energy efficiency with a high level financial analysis.

### Programme: Issue B, 09<sup>th</sup> October 2016

1. Research:
  - a. history of AC & DC sources.
  - b. advantages and disadvantages of AC & DC. This will include a look into the protection systems and safety.
  - c. DC microgrid operation.
  - d. sources of DC generation and storage available to the domestic household.
  - e. DC domestic appliances.
  - f. residential energy use.
2. Obtain logging data for a selection of domestic installations and review their energy usage.
3. Review distribution monitoring equipment to assist in determining average residential installation consumption.
4. Analyse the field data and develop models to allow simulation of AC and DC domestic installations.
5. Determine a common DC bus voltage and determine if there is an efficiency gain by using DC instead of AC.

### Time dependant

6. Determine if results are consistent when applied to a Remote Area Power Supply.
7. Determine possibility and limitations of using the individual household DC system as part of a microgrid.

## Appendix B Timeline

Figure B.1 shows a final version of the Gantt chart originally supplied as part of the Project Specification report. There were a couple of variations to the intended timeframes, with some tasks starting earlier and others later than initially intended, but as a whole the project completion went quite smoothly.

# Mark Thorley - Project Plan

Period Highlight: 33

Plan Actual % Complete Actual (beyond plan) % Complete (beyond plan)

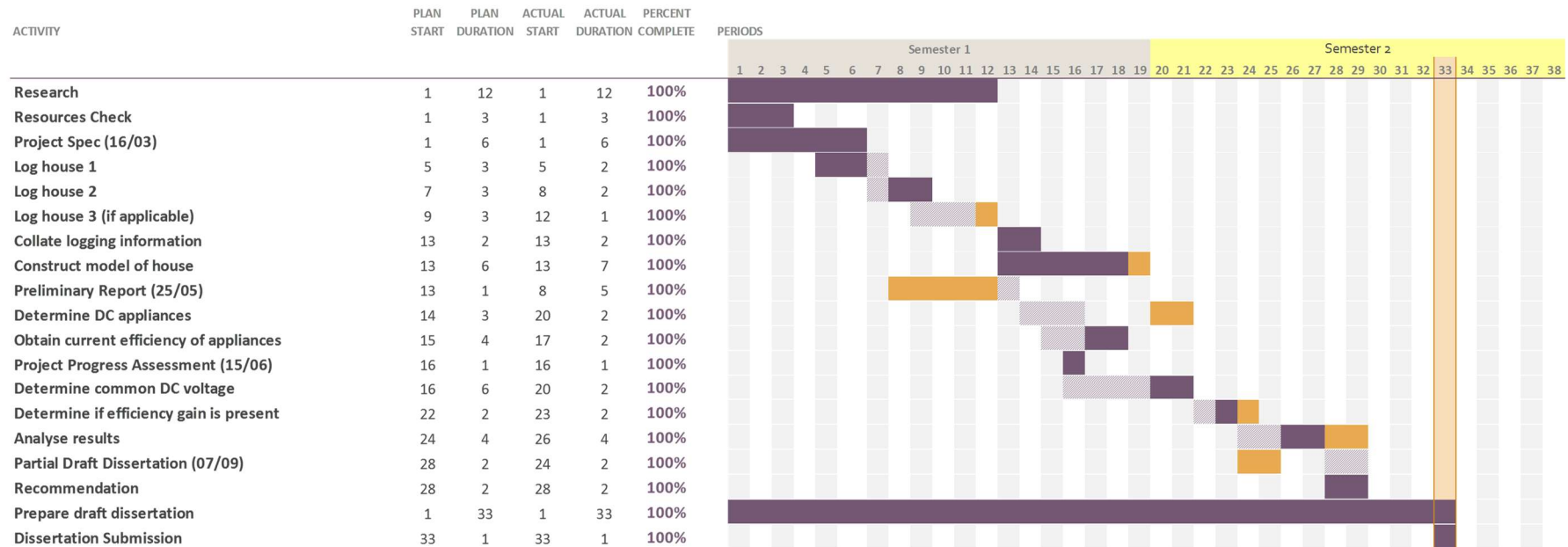


Figure B.1 – Project Plan

## Appendix C Resource Requirements

A number of different resources are required for the completion of this research project. These have been listed in the table below with the current status and cost.

<b>Resource</b>	<b>Status</b>	<b>Cost</b>	<b>Comment</b>
HOMER Pro	Student version purchased on 6-month license. Expired on 8 October 2016	\$140 USD for 6 months	Currently installed and operating.
MATLAB	Owned	\$0	Currently have MATLAB R2016a
Logging equipment	Arranged	\$0	I have arranged to borrow this item from my employer when required.
Logging software	Installed	\$0	Free version is available from manufacturers website.
Domestic houses to log	Arranged	\$0	Will use my own house and friends' houses.
Clamp current meter	Arranged	\$0	I have arranged to borrow this item from my employer when required.
Energy meter	Arranged	\$0	Is available for free loan from local library in periods of 3 weeks.
Microsoft Office	Owned	\$0	Currently have subscription to Microsoft Office 365 giving the latest versions of Word, Excel and PowerPoint.

Table C.1 – Resources required for research project completion

## Appendix D Supporting Tables

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
MBK (BOM) (kWh.m <sup>-2</sup> )	7	6.1	5.2	4.1	3.1	2.5	2.8	3.8	4.9	5.9	6.4	7	4.9
MBK (HOMER) (kWh.m <sup>-2</sup> )	6.77	6.00	5.14	3.96	3.03	2.64	2.81	3.70	4.86	5.94	6.44	6.99	4.86
Wagga (BOM) (kWh.m <sup>-2</sup> )	7.94	6.22	5.25	3.70	2.71	1.76	2.14	3.80	4.99	6.55	7.45	7.46	5.00
		Summer			Autumn			Winter		Spring		Annual	
MBK (BOM) (kWh.m <sup>-2</sup> )		6.7			4.13			3.03		5.73		4.9	
MBK (HOMER) (kWh.m <sup>-2</sup> )		6.59			4.04			3.05		5.75		4.86	
Wagga (BOM) (kWh.m <sup>-2</sup> )		7.21			3.89			2.57		6.33		5.00	

Table D.1 – Daily solar exposure

## Appendix E Results and Comparisons

The below dot points provide a brief explanation of the row titles for the MATLAB tables.

- **Daily energy consumption (net total):** Total net energy consumed by the installation including all losses.
- **Load consumption:** The consumption of the loads within the installation. That is only the loads and not any of the associated losses, other than the internal AC/DC rectifiers if present.
- **Grid consumption:** The volume of energy consumed from the grid. If applicable this includes rectifier loss.
- **Battery consumption:** Energy consumed from the battery including one-way battery loss and DC/DC converter if present.
- **Battery charging:** Energy used to charge the battery including one-way battery loss.
- **Solar generating:** Total solar generated at the panels excluding loss.
- **Solar consumption:** Energy produced by solar that was consumed by the installation.
- **Solar export:** Energy exported to the grid.
- **Grid rectifier loss:** Energy loss resulting from the AC/DC grid rectifier.
- **DC/AC inverter loss:** Energy loss resulting from DC/AC grid inverter.
- **DC/DC loss\_v1:** Energy loss through 24V to 380V DC/DC converter. This is a system that has the primary DC bus set to 24V. ie. The PV and BSS are connected at 24V.
- **DC/DC loss\_v2:** Energy loss through 380V to 24V DC/DC converter. This is a system that has the primary DC bus set to 380V. ie. The PV and BSS are connected at 380V.
- **Solar inverter loss:** Energy loss through inverter connecting solar to installation. This includes battery charging loss where applicable.
- **Batt discharge loss:** Energy loss during battery discharge. Includes one-way battery loss and DC/DC converter if installed.
- **Batt charge loss:** Energy loss during battery charge.
- **Cable loss:** Energy loss in all cables within the installation.



	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Config. 10	Config. 11
Daily energy consumption (net total)	19.527	18.349	17.149	18.440	19.353	-0.067	20.556	20.121	22.377	21.458	21.216
Load consumption	19.332	18.187	16.987	16.987	16.987	19.332	19.332	16.987	19.332	16.987	16.987
Grid consumption	19.527	18.349	17.149	18.440	19.353		16.604	16.807	7.551	7.307	7.116
Battery consumption									10.188	10.146	10.153
Battery charging									10.188	10.146	10.153
Solar generating							19.443	19.443	19.443	19.443	19.443
Solar consumption							3.953	3.314	14.826	14.151	14.100
Solar export							15.490	16.129	4.616	5.292	5.343
Grid rectifier loss				1.291	1.355			1.176		0.511	0.498
DC/AC inverter loss								0.499		0.164	0.165
DC/DC loss_v1											0.604
DC/DC loss_v2					0.326			0.326		0.326	
Solar inverter loss						1.031	0.969	0.388	0.969	0.388	0.388
Batt discharge loss									1.201	1.381	0.919
Batt charge loss									0.666	1.005	1.004
Cable loss	0.195	0.163	0.162	0.162	0.685	0.220	0.256	0.746	0.256	0.746	0.746

Table E.1 – MATLAB autumn results, average kWh/day

	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Config. 10	Config. 11
Daily energy consumption (net total)	26.745	24.698	23.498	25.266	26.259	12.365	27.414	26.695	28.993	27.919	28.124
Load consumption	26.481	24.487	23.287	23.287	23.287	26.481	26.481	23.287	26.481	23.287	23.287
Grid consumption	26.745	24.698	23.498	25.266	26.259		24.118	23.953	16.165	15.090	15.296
Battery consumption									8.948	9.463	9.487
Battery charging									8.948	9.463	9.487
Solar generating							12.828	12.828	12.828	12.828	12.828
Solar consumption							3.297	2.742	12.828	12.828	12.828
Solar export							9.531	10.086			
Grid rectifier loss				1.769	1.838			1.677		1.056	1.071
DC/AC inverter loss								0.312			
DC/DC loss_v1											0.924
DC/DC loss_v2					0.343			0.343		0.343	
Solar inverter loss						0.757	0.640	0.256	0.640	0.256	0.256
Batt discharge loss									1.057	1.292	0.856
Batt charge loss									0.583	0.936	0.938
Cable loss	0.264	0.211	0.211	0.211	0.791	0.278	0.294	0.821	0.294	0.821	0.821

Table E.2 – MATLAB winter results, average kWh/day

	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Config. 10	Config. 11
Daily energy consumption (net total)	20.163	18.908	17.708	19.040	19.950	-7.009	21.880	21.306	23.737	22.592	22.416
Load consumption	19.962	18.741	17.541	17.541	17.541	19.962	19.962	17.541	19.962	17.541	17.541
Grid consumption	20.163	18.908	17.708	19.040	19.950		16.330	16.460	7.232	6.873	6.708
Battery consumption									10.253	10.217	10.225
Battery charging									10.253	10.217	10.225
Solar generating							31.653	31.653	31.653	31.653	31.653
Solar consumption							5.550	4.846	16.505	15.720	15.708
Solar export							26.103	26.807	15.148	15.933	15.945
Grid rectifier loss				1.333	1.397			1.152		0.481	0.470
DC/AC inverter loss								0.829		0.493	0.493
DC/DC loss_v1											0.633
DC/DC loss_v2					0.326			0.326		0.326	
Solar inverter loss						1.430	1.576	0.630	1.576	0.630	0.630
Batt discharge loss									1.205	1.394	0.928
Batt charge loss									0.671	1.009	1.010
Cable loss	0.201	0.167	0.166	0.166	0.687	0.249	0.342	0.828	0.342	0.828	0.828

Table E.3 – MATLAB spring results, average kWh/day

	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Config. 10	Config. 11
Daily energy consumption (net total)	24.126	22.305	21.104	22.693	23.472	-7.637	26.087	24.990	27.910	26.321	26.425
Load consumption	23.887	22.112	20.912	20.912	20.912	23.887	23.887	20.912	23.887	20.912	20.912
Grid consumption	24.126	22.305	21.104	22.693	23.472		19.524	19.160	10.308	9.520	9.631
Battery consumption									10.328	10.298	10.318
Battery charging									10.328	10.298	10.318
Solar generating							36.030	36.030	36.030	36.030	36.030
Solar consumption							6.563	5.830	17.602	16.801	16.793
Solar export							29.467	30.199	18.428	19.229	19.237
Grid rectifier loss				1.588	1.643			1.341		0.666	0.674
DC/AC inverter loss								0.934		0.595	0.595
DC/DC loss_v1											0.824
DC/DC loss_v2					0.309			0.309		0.309	
Solar inverter loss						1.672	1.793	0.717	1.793	0.717	0.717
Batt discharge loss									1.211	1.391	0.921
Batt charge loss									0.675	1.015	1.018
Cable loss	0.239	0.192	0.192	0.192	0.608	0.304	0.408	0.776	0.408	0.776	0.776

Table E.4 – MATLAB summer results, average kWh/day

	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Config. 10	Config. 11
Daily energy consumption (net total)	22.640	21.065	19.865	21.360	22.259	-0.587	23.984	23.278	25.754	24.572	24.545
Load consumption	22.415	20.882	19.682	19.682	19.682	22.415	22.415	19.682	22.415	19.682	19.682
Grid consumption	22.640	21.065	19.865	21.360	22.259		19.144	19.095	10.314	9.697	9.688
Battery consumption									9.929	10.031	10.046
Battery charging									9.929	10.031	10.046
Solar generating							24.988	24.988	24.988	24.988	24.988
Solar consumption							4.841	4.183	15.440	14.875	14.857
Solar export							20.148	20.805	9.548	10.113	10.131
Grid rectifier loss				1.495	1.558			1.337		0.679	0.678
DC/AC inverter loss								0.643		0.313	0.313
DC/DC loss_v1											0.746
DC/DC loss_v2					0.326			0.326		0.326	
Solar inverter loss						1.222	1.244	0.498	1.244	0.498	0.498
Batt discharge loss									1.168	1.365	0.906
Batt charge loss									0.649	0.991	0.993
Cable loss	0.225	0.183	0.183	0.183	0.693	0.263	0.325	0.793	0.325	0.793	0.793

Table E.5 – MATLAB average kWh/day

	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Config. 10	Config. 11
Daily energy consumption (net total)	8263.710	7688.746	7250.558	7796.299	8124.356	-214.276	8754.330	8496.478	9400.329	8968.913	8959.067
Load consumption	8181.536	7621.818	7183.818	7183.818	7183.818	8181.536	8181.536	7183.818	8181.536	7183.818	7183.818
Grid consumption	8263.710	7688.746	7250.558	7796.299	8124.356		6987.517	6969.629	3764.595	3539.546	3536.154
Battery consumption									3624.167	3661.340	3666.694
Battery charging									3624.167	3661.340	3666.694
Solar generating							9120.791	9120.791	9120.791	9120.791	9120.791
Solar consumption							1766.813	1526.849	5635.734	5429.367	5422.913
Solar export							7353.979	7593.942	3485.058	3691.424	3697.878
Grid rectifier loss				545.741	568.705			487.874		247.768	247.531
DC/AC inverter loss								234.864		114.168	114.367
DC/DC loss_v1											272.456
DC/DC loss_v2					118.950			118.950		118.950	
Solar inverter loss						446.210	454.220	181.688	454.220	181.688	181.688
Batt discharge loss									426.492	498.074	330.801
Batt charge loss									236.788	361.863	362.273
Cable loss	82.174	66.928	66.741	66.741	252.884	95.916	118.575	289.285	118.575	289.285	289.285

Table E.6 – MATLAB average kWh/year

	Model 1		Model 2		Model 3		Model 4		Model 5	
	Peak	TOU	Peak	TOU	Peak	TOU	Peak	TOU	Peak	TOU
Architecture/PV (kW)	-	-	999999	999999	999999	999999	-	-	-	-
Architecture/PV-MPPT (kW)	-	-	100	100	100	100	-	-	-	-
Architecture/1kWh LI	-	-	CC	CC	CC	CC	-	-	-	-
Architecture/Grid (kW)	999999	999999	999999	999999	999999	999999	999999	999999	999999	999999
Architecture/Converter (kW)	-	-	100	100	100	100	6.6	6.6	-	-
Architecture/Dispatch	CC	CC	CC	CC	CC	CC	CC	CC	CC	CC
Cost/COE (\$)	0.267	0.217	0.267	0.216	0.267	0.215	0.324	0.268	0.323	0.268
Cost/NPC (\$)	41022.250	33354.470	38237.630	30900.740	36050.390	28952.480	43764.280	36132.120	45195.920	37537.510
Cost/Operating cost (\$)	2206.073	1793.720	2056.324	1661.764	1938.700	1556.992	2176.067	1765.629	2255.747	1843.896
Cost/Initial capital (\$)	0.000	0.000	0.000	0.000	0.000	0.000	3300.000	3300.000	3250.000	3250.000
System/Ren Frac (%)	0.002	0.002	0.003	0.003	0.001	0.001	0.000	0.000	0.000	0.000
System/Elec Prod (kWh/yr)	8254.499	8254.499	7694.178	7694.178	7254.063	7254.063	7800.062	7800.062	8103.382	8103.382
System/Elec Cons (kWh/yr)	8254.637	8254.637	7694.395	7694.395	7254.108	7254.108	7254.108	7254.108	7536.040	7536.040
PV/Capital Cost (\$)	-	-	-	-	-	-	-	-	-	-
PV/Production (kWh)	-	-	-	-	-	-	-	-	-	-
PV/Production removing before losses (kWh)	-	-	-	-	-	-	-	-	-	-
1kWh LI/Annual Throughput (kWh)	-	-	-	-	-	-	-	-	-	-
Grid/Energy Purchased (kWh)	8254.499	8254.499	7694.178	7694.178	7254.063	7254.063	7800.062	7800.062	8103.382	8103.382
Grid/Energy Sold (kWh)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Installation Energy Consumption (kWh)	8254.499	8254.499	7694.178	7694.178	7254.063	7254.063	7800.062	7800.062	8103.382	8103.382

Table E.7 – HOMER Pro results models 1, 2, 3, 4 and 5

	Model 7		Model 8		Model 9		Model 10		Model 11	
	Peak	TOU	Peak	TOU	Peak	TOU	Peak	TOU	Peak	TOU
Architecture/PV (kW)	5	5	5	5	5	5	5	5	5	5
Architecture/PV-MPPT (kW)	5	5	5	5	5	5	5	5	5	5
Architecture/1kWh LI	-	-	-	-	10	10	10	10	10	10
Architecture/Grid (kW)	999999	999999	999999	999999	999999	999999	999999	999999	999999	999999
Architecture/Converter (kW)	-	-	6.5	6.5	7.1	7.1	6.5	6.5	6.85	6.85
Architecture/Dispatch	CC	CC	CC	CC	CC	CC	CC	CC	CC	CC
Cost/COE (\$)	0.134	0.109	0.155	0.129	0.293	0.250	0.299	0.257	0.295	0.252
Cost/NPC (\$)	39133.960	31754.270	43760.210	36421.700	64545.670	55007.970	62577.110	53774.020	63264.830	54177.630
Cost/Operating cost (\$)	1835.639	1438.778	1909.650	1515.004	1935.757	1422.843	1846.026	1372.618	1873.599	1384.912
Cost/Initial capital (\$)	5000.000	5000.000	8250.000	8250.000	28550.000	28550.000	28250.000	28250.000	28425.000	28425.000
System/Ren Frac (%)	55.499	55.499	54.217	54.217	67.979	67.979	68.796	68.796	68.651	68.651
System/Elec Prod (kWh/yr)	15689.980	15689.980	15954.990	15954.990	12775.200	12775.200	12497.660	12497.660	12601.670	12601.670
System/Elec Cons (kWh/yr)	15690.110	15690.110	15228.900	15228.900	11843.740	11843.740	11264.400	11264.400	11544.090	11544.090
PV/Capital Cost (\$)	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
PV/Production (kWh)	8707.793	8707.793	8982.768	8982.768	8982.768	8982.768	8982.768	8982.768	8982.768	8982.768
PV/Production removing before losses (kWh)	9166.098	9166.098	9166.090	9166.090	9166.090	9166.090	9166.090	9166.090	9166.090	9166.090
1kWh LI/Annual Throughput (kWh)	-	-	-	-	3613.484	3613.484	3625.089	3625.089	3631.201	3631.201
Grid/Energy Purchased (kWh)	6982.187	6982.187	6972.218	6972.218	3792.436	3792.436	3514.890	3514.890	3618.902	3618.902
Grid/Energy Sold (kWh)	7435.469	7435.469	7692.856	7692.856	3589.102	3589.102	3728.356	3728.356	3825.945	3825.945
Installation Energy Consumption (kWh)	8712.816	8712.816	8445.452	8445.452	9369.424	9369.424	8952.624	8952.624	8959.047	8959.047

Table E.8 – HOMER Pro results -models 7, 8, 9, 10 and 11



	RAPS AC No Gen	RAPS DC No Gen	RAPS AC With Gen	RAPS DC With Gen
Architecture/PV (kW)	12.9275	11.74801	9.182518	7.03125
Architecture/PV-MPPT (kW)	100	100	100	100
Architecture/Gen	-	-	5	5
Architecture/BSS	27	25	19	18
Architecture/Converter (kW)	4.44277	-	3.696747	-
Architecture/Dispatch	CC	CC	LF	LF
Cost/COE (\$)	0.688	0.658	0.603	0.586
Cost/NPC (\$)	\$105,543.60	\$94,345.70	\$92,523.31	\$84,096.52
Cost/Operating cost (\$)	1957.217	1753.022	2204.469	2073.943
Cost/Initial capital (\$)	69148.880	61748.010	51530.890	45531.250
System/Ren Frac (%)	100.000	100.000	88.555	87.177
System/Elec Prod (kWh/yr)	23224.930	21105.930	17441.580	13621.750
System/Elec Cons (kWh/yr)	8247.830	7710.755	8254.637	7718.145
System/Excess Elec (kWh/yr)	13296.610	12069.070	7678.285	4712.075
Gen/Hours	-	-	754.000	737.000
Gen/Production (kWh)	-	-	944.720	989.721
Gen/Fuel (L)	-	-	451.152	459.942
Gen/O&M Cost (\$)	-	-	113.100	110.550
Gen/Fuel Cost (\$)	-	-	676.729	689.914
PV/Capital Cost (\$)	12927.500	11748.010	9182.518	7031.250
PV/Production (kWh)	23224.930	21105.930	16496.860	12632.030
PV/Production removing before losses (kWh)	-	-	-	-
1kWh LI/Autonomy (hr)	28.653	28.375	20.163	20.430
1kWh LI/Annual Throughput (kWh)	7609.876	7078.961	6799.006	6371.198
Converter/Rectifier Mean Output (kW)	-	-	0.012	-
Converter/Inverter Mean Output (kW)	0.942	-	0.847	-
Installation Energy Consumption (kWh)	9928.320	9036.860	9763.295	8909.675

Table E.9 – HOMER Pro RAPS results

## Appendix F HOMER Pro screenshots

This appendix contains a selection of screenshots from the HOMER Pro modelling. The purpose is to represent the work that was done and some of the parameters and results observed during the completion of the project.

The AC load displayed in Figure F.1 shows a significant peak at the beginning of the day, visible on the left hand side of the daily profile plot. This was a consequence of the model starting many of the cyclic loads at this timestamp, before their operation became more staggered throughout the day. In reality a true profile would not contain this spike.

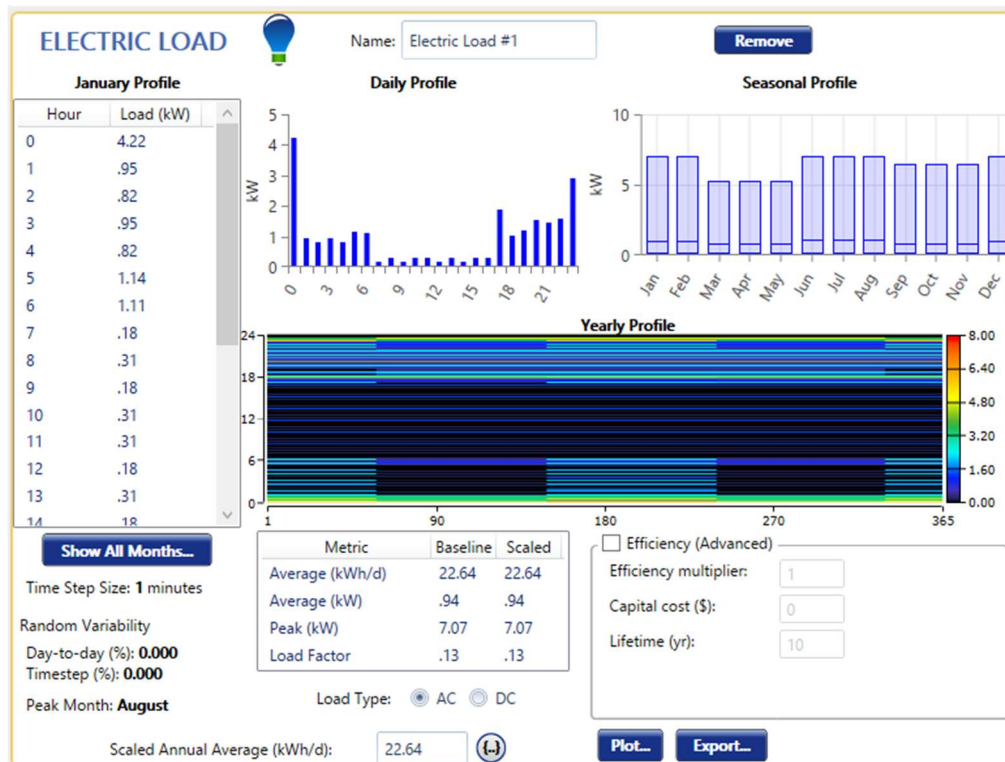


Figure F.1 – AC load in HOMER Pro. Used for all AC models

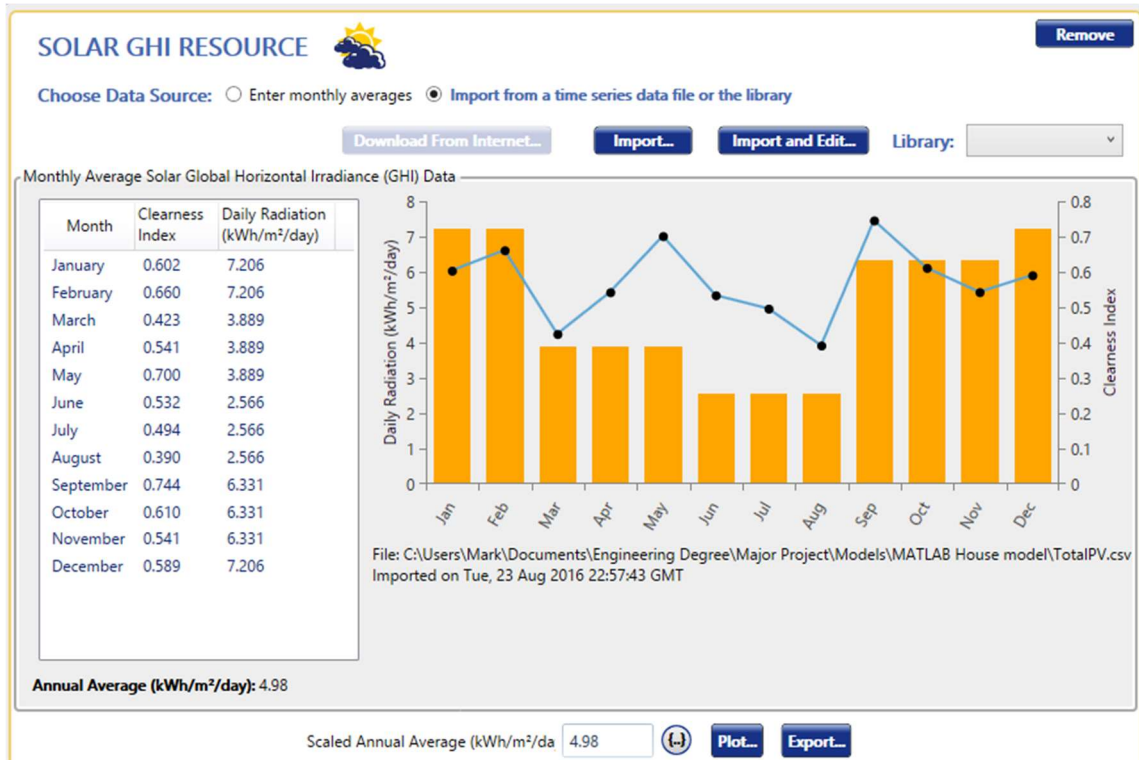


Figure F.2 – Imported solar GHI information from Wagga weather station into HOMER Pro

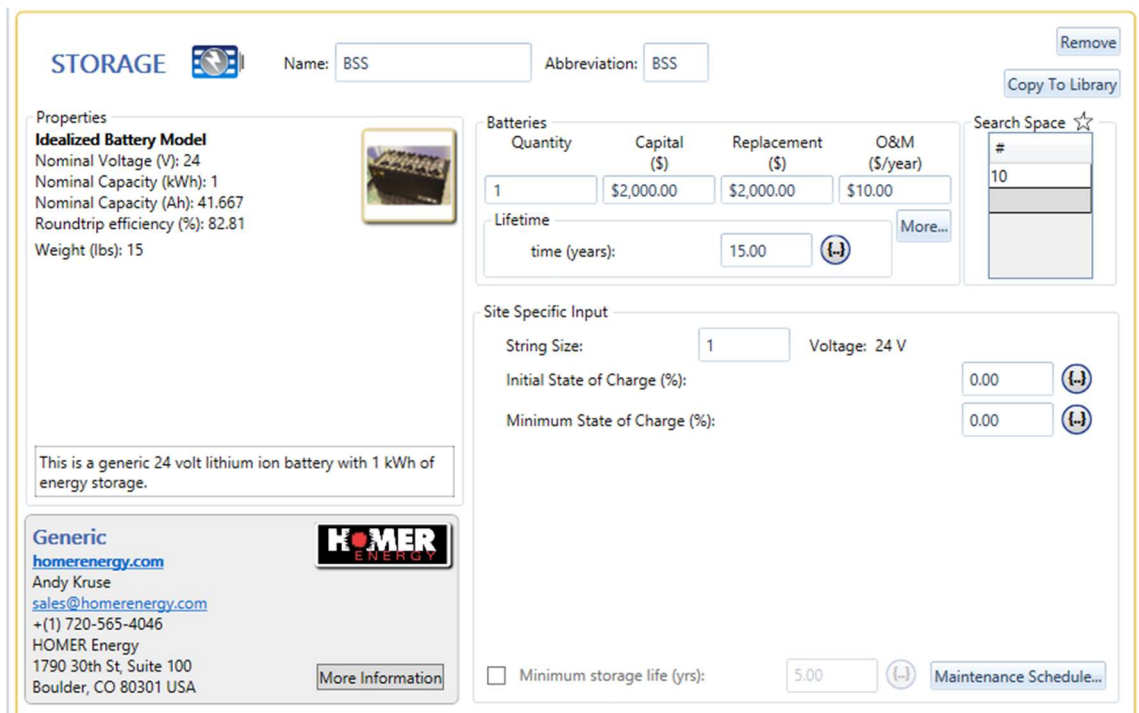


Figure F.3 – BSS input into HOMER Pro

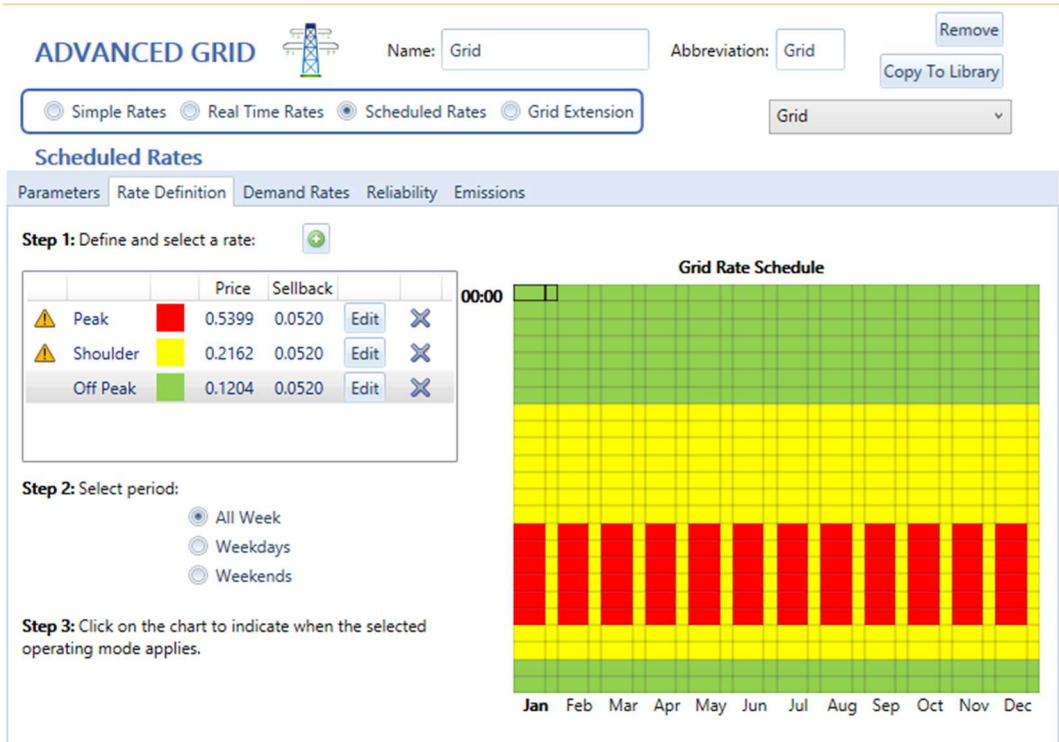


Figure F.4 – Time of Use tariff structure

## Appendix G MATLAB code

### G.1 Code for determining house models from logging

```
% Mark Thorley
% 0061029218

% House_Logging.m
% Output: Produce graphs from logging data obtained from 4 separate households.
% Called By: None
% Calls: House data.mat

clear all
clc

format long

load('House data') % Load data for each of the four houses logged.

% datetick is used to change the time step of 1/1440 (1 minute) to
% increments of time and label the axis.
figure(1)
plot(Time,House1),title('House 1 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House1)) ceil(max(House1))])
figure(2)
plot(Time,House2),title('House 2 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House2)) ceil(max(House2))])
figure(3)
plot(Time,House3),title('House 3 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House3)) ceil(max(House3))])
figure(4)
plot(Time,House4),title('House 4 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House4)) ceil(max(House4))])

figure(5)
plot(Time,House1,'r',Time,House2,'g',Time,House3,'b',Time,House4,'m'),title('All 4
Houses Average Daily Profiles'),xlabel('Time (minutes)'),ylabel('Power
(kw)'),datetick('x','HHPM')
legend('House 1','House 2','House 3','House 4')

figure(6)
subplot(4,1,1)
plot(Time,House1),title('House 1 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House1)) ceil(max(House1))])
subplot(4,1,2)
plot(Time,House2),title('House 2 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House2)) ceil(max(House2))])
subplot(4,1,3)
plot(Time,House3),title('House 3 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House3)) ceil(max(House3))])
subplot(4,1,4)
plot(Time,House4),title('House 4 Average Daily Profile'),xlabel('Time'),ylabel('Power
(kw)'),datetick('x','HHPM'),ylim([floor(min(House4)) ceil(max(House4))])

All4average=(House1+House2+House3+House4)/4;
```

```

figure(7)
plot(Time,All4average),title('All 4 Houses Combined Average Daily
Profile'),xlabel('Time'),ylabel('Power
(kW)'),datetick('x','HHPM'),ylim([floor(min(House4)) ceil(max(House4))])

```

```

House1daily=sum(House1)/60; % House 1 average daily energy usage
House2daily=sum(House2)/60; % House 2 average daily energy usage
House3daily=sum(House3)/60; % House 3 average daily energy usage
House4daily=sum(House4)/60; % House 4 average daily energy usage

```

```

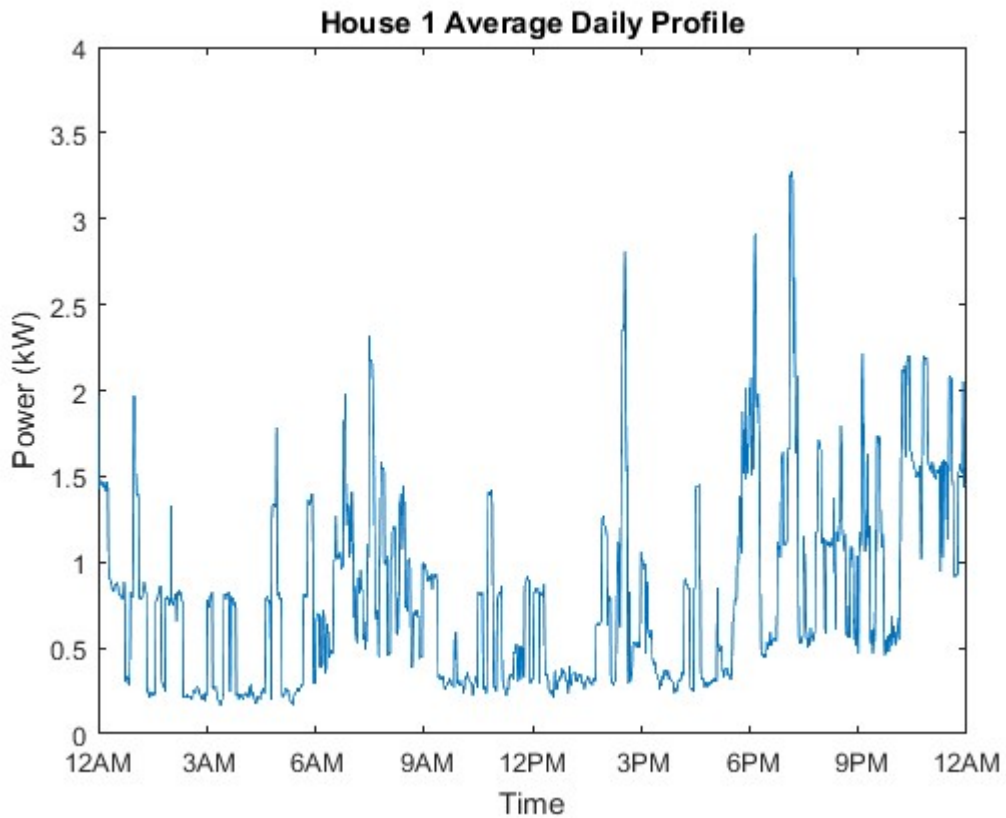
fprintf('Substation 1 average daily consumption per installation is %0.2f
kWh\n',House1daily);
fprintf('Substation 2 average daily consumption per installation is %0.2f
kWh\n',House2daily);
fprintf('Substation 3 average daily consumption per installation is %0.2f
kWh\n',House3daily);
fprintf('Substation 4 average daily consumption per installation is %0.2f
kWh\n',House4daily);

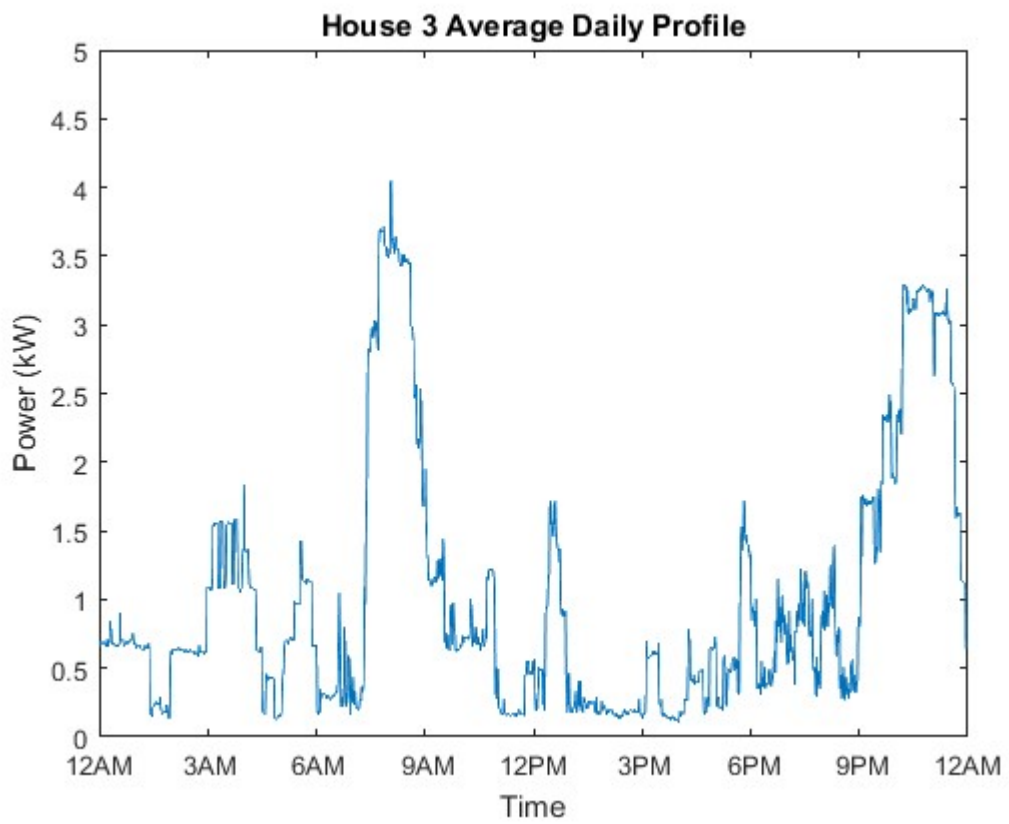
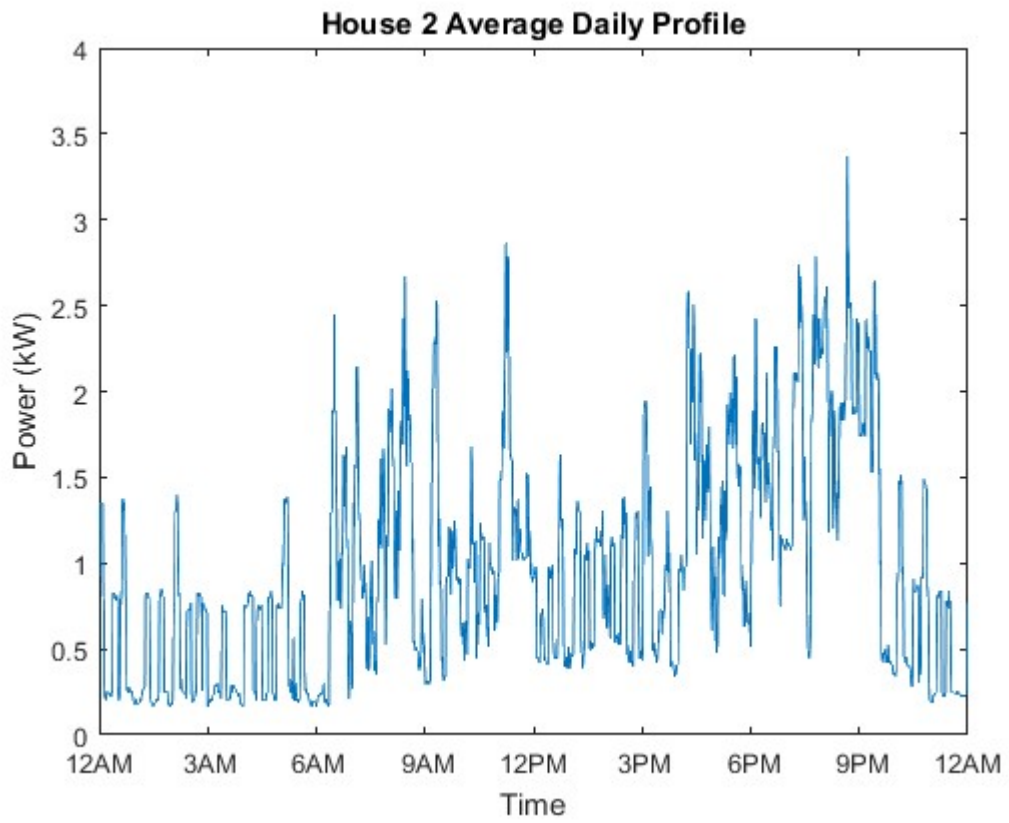
```

```

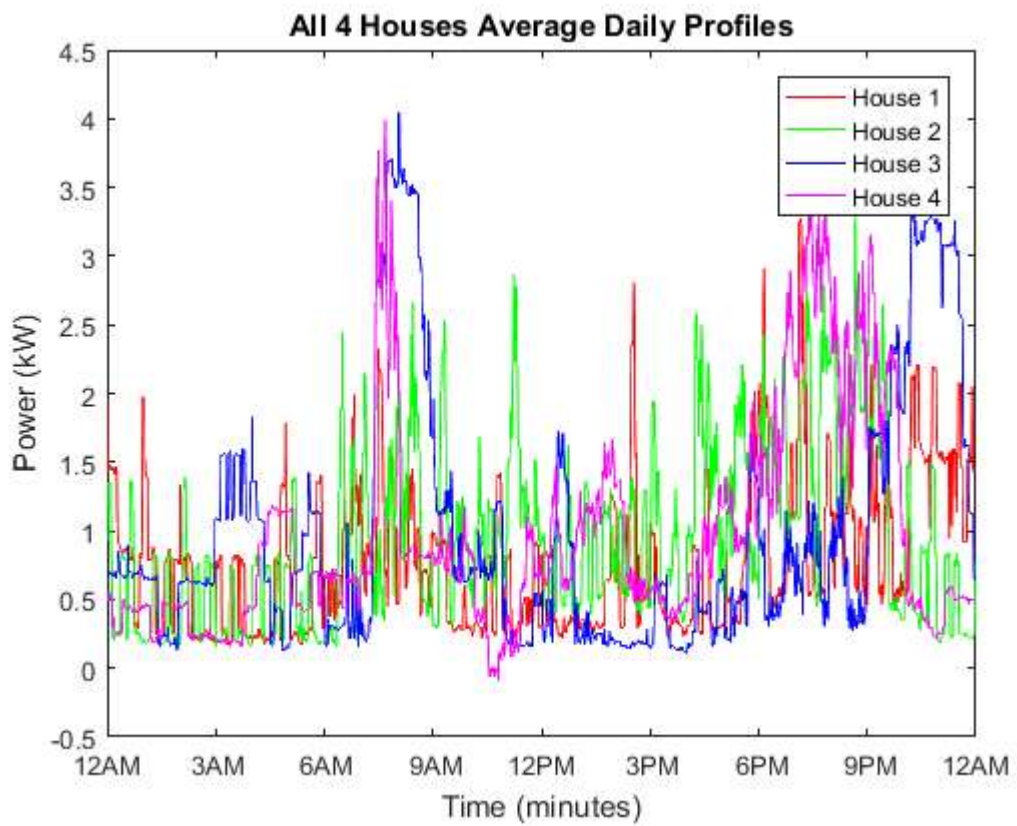
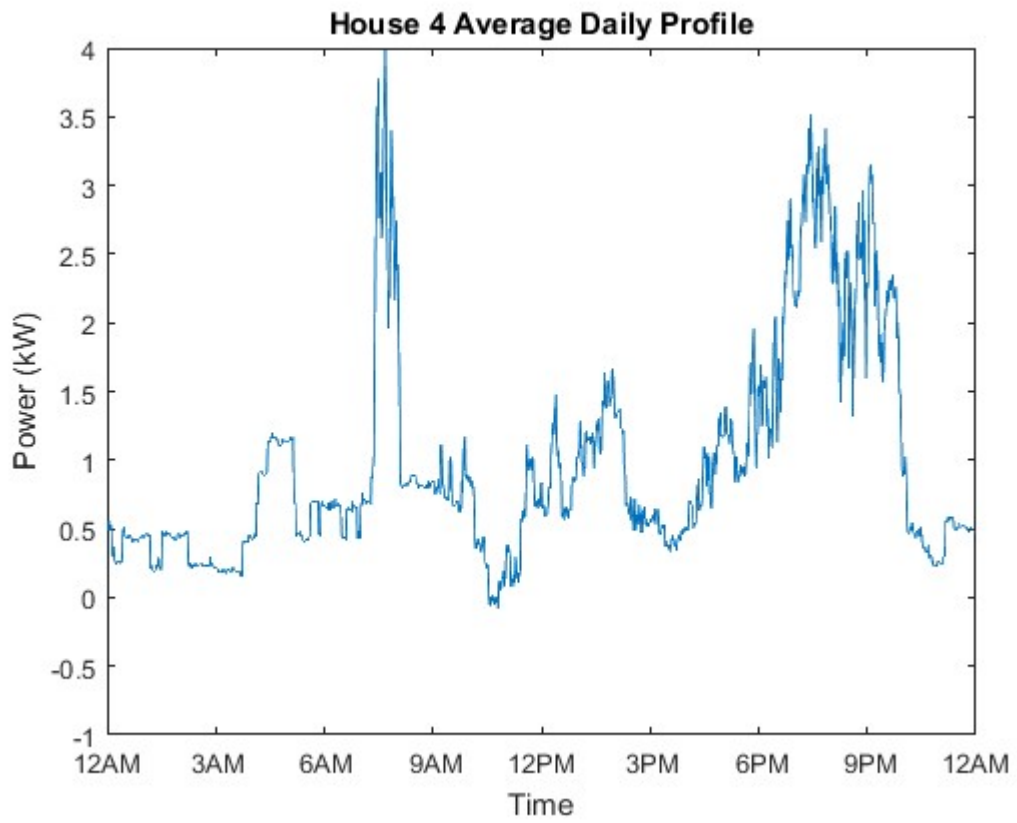
Substation 1 average daily consumption per installation is 19.09 kWh
Substation 2 average daily consumption per installation is 23.13 kWh
Substation 3 average daily consumption per installation is 24.12 kWh
Substation 4 average daily consumption per installation is 23.51 kWh

```

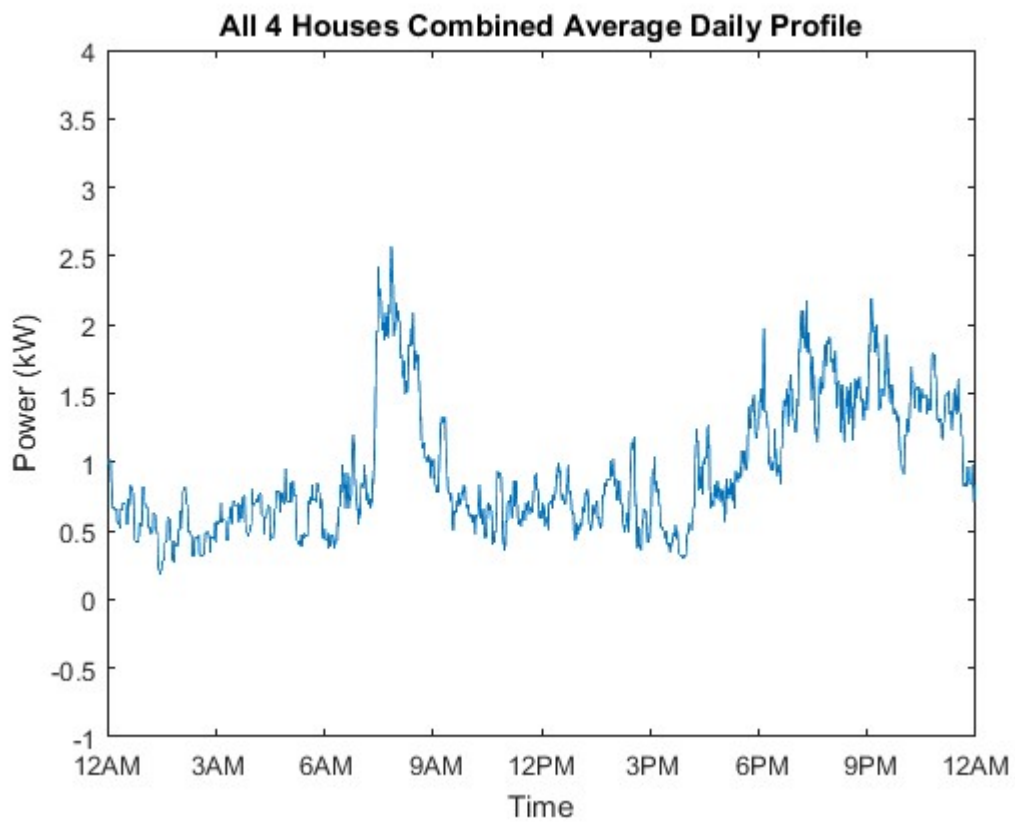
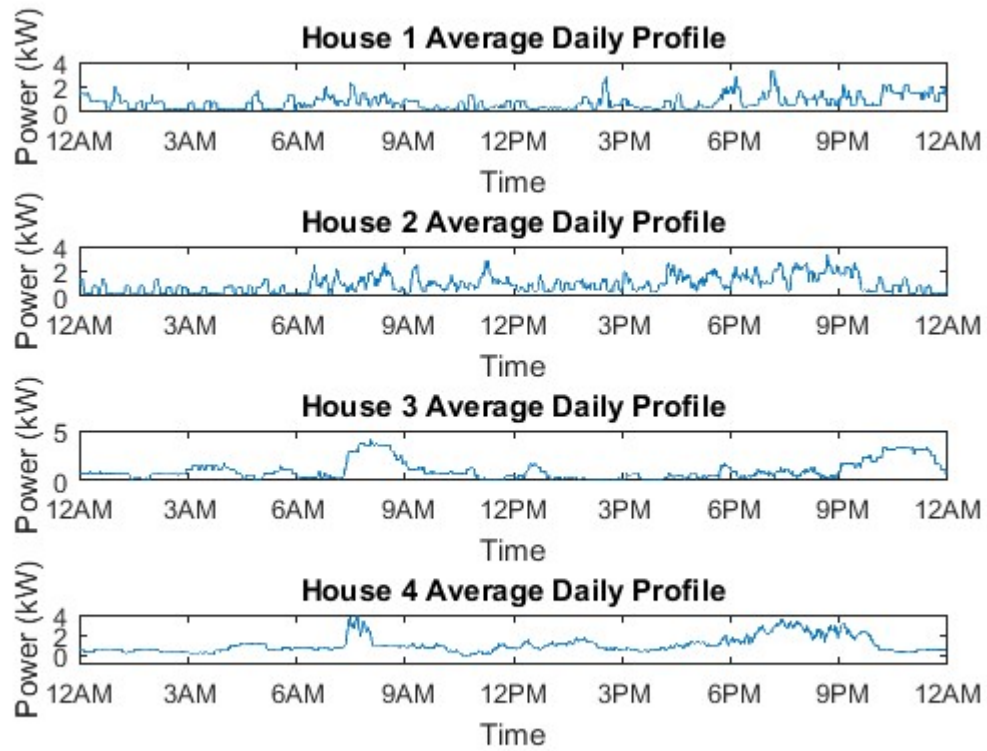












*Published with MATLAB® R2016a*

## G.2 Code for analysing distribution substation data

```
% Mark Thorley
% 0061029218

% File Name: Dist_Subst_Data_Final.m
% Output: Program to analyse the raw distribution substation data and establish
% monthly and seasonal load profiles per substation and combined.
% Called By: None
% Calls: None

clear all
close all
clc

format long g

% Days per month in 2015
Dayspermonth=[31;28;31;30;31;30;31;31;30;31;30;31];

filename='Sub1_raw.xlsx';
[Sub1values,Sub1txt,Sub1]=xlsread(filename,1);

filename='Sub2_raw.xlsx';
[Sub2values,Sub2txt,Sub2]=xlsread(filename,1);

filename='Sub3_raw.xlsx';
[Sub3values,Sub3txt,Sub3]=xlsread(filename,1);

filename='Sub4_raw.xlsx';
[Sub4values,Sub4txt,Sub4]=xlsread(filename,1);

Sub1c=44; % Number of customers off substation. 31.1kw grid connected PV installed
Sub2c=39; % Number of customers off substation. 12.5kw grid connected PV installed
Sub3c=102; % Number of customers off substation. 82.9kw grid connected PV installed
Sub4c=196; % Number of customers off substation. 83.64kw grid connected PV installed

voltage=250; % Assumed as the logging equipment does not monitor this
pf=0.9; % Residential power factor assumed to be 0.90
tenminuteinc=(0:10:1430)'; % ten minute increments of time for 1 day
lengthofincrements=length(tenminuteinc);
```

### SUB 1 ANALYSIS

```
Sub1dt=datetime(Sub1txt(2:length(Sub1txt),4),'InputFormat','uuuu-MM-dd'T'HH:mm:ss');
% Converts date format into date and time
Sub1day=datestr(Sub1dt,1); % Extracts Date
Sub1time=datestr(Sub1dt,13); % Extract Time
Sub1day=datenum(Sub1day); % Convert to serial values
Sub1time=datenum(Sub1time); % Convert to serial values
Sub1time=round((Sub1time-Sub1time(1,1))*(60*24)); % Converts to intergers in
multiples of 10
MonthlyAvg1=zeros(144,12);

% The following is looking through the data to find current readings on
```

```

% each phase at the same timestamp and adding them together to attain total
% load on the substation. The sample period and number is determined from
% the number of A phase measurements. As the device is connected across all
% three phases if it misses and A phase measurement it is assumed to have
% missed the B and C phase measurements and hence that reading is ignored.

Serial1dt=datetime(Sub1dt); % Covert date data into serial date
[Row,~]=find(Serial1dt==Serial1dt(1,1)); % Location in array of where the values
occur.
Sub1t1(1,1)=sum(Sub1values(Row)); % Total load across all three phase of
transformer at that increment
Period=length(Serial1dt(1:(Row(2,1)-1),1)); % Sample period. Finds the last value of
the A phase measurements.

for Samples=2:Period

    [Row,~]=find(Serial1dt==Serial1dt(Samples,1)); % Location in array of where the
values occur.
    Sub1t1(Samples,1)=sum(Sub1values(Row)); % Substation total load
end

% Work out Monthly average daily usage profile.

for cm=1:1:12 % For current month 1 to 12.

    if cm==1
        fdocm=1; % Set row equal to 1.
    else
        fdocm=ldocm+1; % Set row value for current month equal to last value of previous
month plus 1.
    end

    Currentday=Sub1day(fdocm,1); % Obtains first serial date of current month
    MonthD=Dayspermonth(cm,1); % Obtain days for current month

    ldocm=find(Sub1day==(Currentday+MonthD-1),1); % Last day of current month

    Monthlysamples=ldocm-fdocm+1; % Number of samples taken in the month

    for time=1:1:Lengthofincrements
        Currenttime=tenminuteinc(time,1); % Time value from increment table
        timeappears=nnz(Sub1time(fdocm:ldocm)==Currenttime); % How many times does
current time increment appear in month
        [Row,~]=find(Sub1time(fdocm:ldocm)==Currenttime); % Location in array of
where the values occur.
        MonthlyAvg1(time,cm)=0; % Set Monthly average to zero

        for v=1:length(Row)
            MonthlyAvg1(time,cm)=MonthlyAvg1(time,cm)+Sub1t1(Row(v,1),1); % Add all
current values for identified time increment in accordance with number of samples at
that time increment in the month.
        end

        MonthlyAvg1(time,cm)=MonthlyAvg1(time,cm)/timeappears; % Divide total by
numbe of occurances to get average consumption at that time increment for the month.

    end
end

```

## SUB 2 ANALYSIS

```

Sub2dt=datetime(Sub2txt(2:length(Sub2txt),4), 'InputFormat', 'uuuu-MM-dd''T''HH:mm:ss');
% Converts date format into date and time
Sub2day=datestr(Sub2dt,1); % Extracts Date
Sub2time=datestr(Sub2dt,13); % Extract Time
Sub2day=datenum(Sub2day); % Convert to serial values
Sub2time=datenum(Sub2time); % Convert to serial values
Sub2time=round((Sub2time-Sub2time(1,1))*(60*24)); % Converts to intergers in
multiples of 10
MonthlyAvg2=zeros(144,12);

% The following is looking through the data to find current readings on
% each phase at the same timestamp and adding them together to attain total
% load on the substation. The sample period and number is determined from
% the number of A phase measurements. As the device is connected across all
% three phases if it misses and A phase measurement it is assumed to have
% missed the B and C phase measurements and hence that reading is ignored.

Serial2dt=datenum(Sub2dt); % Covert date data into serial date
[Row,~]=find(Serial2dt==Serial2dt(1,1)); % Location in array of where the values
occur.
Sub2t1(1,1)=sum(Sub2values(Row)); % Total load across all three phase of
transformer at that increment
Period=length(Serial2dt(1:(Row(2,1)-1),1)); % Sample period

for Samples=2:Period
    [Row,~]=find(Serial2dt==Serial2dt(Samples,1)); % Location in array of where the
values occur.
    Sub2t1(Samples,1)=sum(Sub2values(Row)); % Substation total load
end

% Work out Monthly average daily usage profile.

for cm=1:1:12 % For current month 1 to 12.

    if cm==1
        fdocm=1; % Set row equal to 1.
    else
        fdocm=ldocm; % Set row value for current month equal to value of next month from
previous iteration.
    end

    Currentday=Sub2day(fdocm,1); % Obtains first serial date of current month
    MonthD=Dayspermonth(cm,1); % Obtain days for current month

    ldocm=find(Sub2day==(Currentday+MonthD-1),1); % Last day of current month

    Monthlysamples=ldocm-fdocm+1; % Number of samples taken in the month

    for time=1:1:Lengthofincrements
        Currenttime=tenminuteinc(time,1); % Time value from increment table
        timeappears=nnz(Sub2time(fdocm:ldocm)==Currenttime); % How many times does
current time increment appear in month
        [Row,~]=find(Sub2time(fdocm:ldocm)==Currenttime); % Location in array of
where the values occur.
        MonthlyAvg2(time,cm)=0; % Set Monthly avgerage to zero
    end
end

```

```

        for v=1:length(Row)
            MonthlyAvg2(time,cm)=MonthlyAvg2(time,cm)+Sub2t1(Row(v,1),1); % Add all
            current values for identified time increment in accordance with number of samples at
            that time increment in the month.
        end

        MonthlyAvg2(time,cm)=MonthlyAvg2(time,cm)/timeappears; % Divide total by
        numbe of occurances to get average consumption at that time increment for the month.

    end
end

```

### SUB 3 ANALYSIS

```

Sub3dt=datetime(Sub3txt(2:length(Sub3txt),4),'InputFormat','uuuu-MM-dd'T'HH:mm:ss');
% Converts date format into date and time
Sub3day=datestr(Sub3dt,1); % Extracts Date
Sub3time=datestr(Sub3dt,13); % Extract Time
Sub3day=datenum(Sub3day); % Convert to serial values
Sub3time=datenum(Sub3time); % Convert to serial values
Sub3time=round((Sub3time-Sub3time(1,1))*(60*24)); % Converts to intergers in
multiples of 10
MonthlyAvg3=zeros(144,12);

% The following is looking through the data to find current readings on
% each phase at the same timestamp and adding them together to attain total
% load on the substation. The sample period and number is determined from
% the number of A phase measurements. As the device is connected across all
% three phases if it misses and A phase measurement it is assumed to have
% missed the B and C phase measurements and hence that reading is ignored.

Serial3dt=datenum(Sub3dt); % Covert date data into serial date
[Row,~]=find(Serial3dt==Serial3dt(1,1)); % Location in array of where the values
occur.
Sub3t1(1,1)=sum(Sub3values(Row)); % Total load across all three phase of
transformer at that increment
Period=length(Serial3dt(1:(Row(2,1)-1),1)); % Sample period

for Samples=2:Period
    [Row,~]=find(Serial3dt==Serial3dt(Samples,1)); % Location in array of where the
values occur.
    Sub3t1(Samples,1)=sum(Sub3values(Row)); % Substation total load
end

% Work out Monthly average daily usage profile.

for cm=1:1:12 % For current month 1 to 12.

    if cm==1
        fdocm=1; % Set row equal to 1.
    else
        fdocm=ldocm; % Set row value for current month equal to value of next month from
previous iteration.
    end
end

```

```

Currentday=Sub3day(fdocm,1); % Obtains first serial date of current month
MonthD=Dayspermonth(cm,1); % Obtain days for current month

ldocm=find(Sub3day==(Currentday+MonthD-1),1); % Last day of current month

Monthlysamples=ldocm-fdocm+1; % Number of samples taken in the month

for time=1:1:Lengthofincrements
    Currenttime=tenminuteinc(time,1); % Time value from increment table
    timeappears=nnz(Sub3time(fdocm:ldocm)==Currenttime); % How many times does
current time increment appear in month
    [Row,~]=find(Sub3time(fdocm:ldocm)==Currenttime); % Location in array of
where the values occur.
    MonthlyAvg3(time,cm)=0; % Set Monthly averge to zero

    for v=1:length(Row)
        MonthlyAvg3(time,cm)=MonthlyAvg3(time,cm)+Sub3t1(Row(v,1),1); % Add all
current values for identified time increment in accordance with number of samples at
that time increment in the month.
    end

    MonthlyAvg3(time,cm)=MonthlyAvg3(time,cm)/timeappears; % Divide total by
numbe of occurances to get average consumption at that time increment for the month.

end
end

```

#### SUB 4 ANALYSIS

```

Sub4dt=datetime(Sub4txt(2:length(Sub4txt),4),'InputFormat','uuuu-MM-dd'T'HH:mm:ss');
% Converts date format into date and time
Sub4day=datestr(Sub4dt,1); % Extracts Date
Sub4time=datestr(Sub4dt,13); % Extract Time
Sub4day=datenum(Sub4day); % Convert to serial values
Sub4time=datenum(Sub4time); % Convert to serial values
Sub4time=round((Sub4time-Sub4time(1,1))*(60*24)); % Converts to intergers in
multiples of 10
MonthlyAvg4=zeros(144,12);

% The following is looking through the data to find current readings on
% each phase at the same timestamp and adding them together to attain total
% load on the substation. The sample period and number is determined from
% the number of A phase measurements. As the device is connected across all
% three phases if it misses and A phase measurement it is assumed to have
% missed the B and C phase measurements and hence that reading is ignored.

Serial4dt=datenum(Sub4dt); % Covert date data into serial date
[Row,~]=find(Serial4dt==Serial4dt(1,1)); % Location in array of where the values
occur.
Sub4t1(1,1)=sum(Sub4values(Row)); % Total load across all three phase of
transformer at that increment
Period=length(Serial4dt(1:(Row(2,1)-1),1)); % Sample period

for Samples=2:Period
    [Row,~]=find(Serial4dt==Serial4dt(Samples,1)); % Location in array of where the
values occur.
    Sub4t1(Samples,1)=sum(Sub4values(Row)); % Substation total load

```

```

end

% Work out Monthly average daily usage profile.

for cm=1:1:12 % For current month 1 to 12.

    if cm==1
        fdocm=1; % Set row equal to 1.
    else
        fdocm=ldocm; % Set row value for current month equal to value of next month from
previous iteration.
    end

    Currentday=Sub4day(fdocm,1); % Obtains first serial date of current month
    MonthD=Dayspermonth(cm,1); % Obtain days for current month

    ldocm=find(Sub4day==(Currentday+MonthD-1),1); % Last day of current month

    Monthlysamples=ldocm-fdocm+1; % Number of samples taken in the month

    for time=1:1:Lengthofincrements
        Currenttime=tenminuteinc(time,1); % Time value from increment table
        timeappears=nnz(Sub4time(fdocm:ldocm)==Currenttime); % How many times does
current time increment appear in month
        [Row,~]=find(Sub4time(fdocm:ldocm)==Currenttime); % Location in array of
where the values occur.
        MonthlyAvg4(time,cm)=0; % Set Monthly average to zero

        for v=1:length(Row)
            MonthlyAvg4(time,cm)=MonthlyAvg4(time,cm)+Sub4t1(Row(v,1),1); % Add all
current values for identified time increment in accordance with number of samples at
that time increment in the month.
        end

        MonthlyAvg4(time,cm)=MonthlyAvg4(time,cm)/timeappears; % Divide total by
number of occurrences to get average consumption at that time increment for the month.

    end
end

Sub1map=(MonthlyAvg1*Voltage*pf)/(Sub1c*1000); % Average daily consumption profile
per month per installation in kw
Sub2map=(MonthlyAvg2*Voltage*pf)/(Sub2c*1000); % Average daily consumption profile
per month per installation in kw
Sub3map=(MonthlyAvg3*Voltage*pf)/(Sub3c*1000); % Average daily consumption profile
per month per installation in kw
Sub4map=(MonthlyAvg4*Voltage*pf)/(Sub4c*1000); % Average daily consumption profile
per month per installation in kw

SubAvg=(Sub1map+Sub2map+Sub3map+Sub4map)/4; % Average consumption across all four
substations.

tenminuteinc=tenminuteinc/1440; % Convert intervals into the range 0 to 1.

Sub1summer=(Sub1map(:,1)+Sub1map(:,2)+Sub1map(:,12))/3; % Summer profile for substation

```

```

1
Sub2summer=(Sub2map(:,1)+Sub2map(:,2)+Sub2map(:,12))/3; % Summer profile for substation
2
Sub3summer=(Sub3map(:,1)+Sub3map(:,2)+Sub3map(:,12))/3; % Summer profile for substation
3
Sub4summer=(Sub4map(:,1)+Sub4map(:,2)+Sub4map(:,12))/3; % Summer profile for substation
4
SubAvgsummer=(SubAvg(:,1)+SubAvg(:,2)+SubAvg(:,12))/3; % Summer profile for all four
substations

Sub1autumn=(Sub1map(:,3)+Sub1map(:,4)+Sub1map(:,5))/3; % Autumn profile for substation 1
Sub2autumn=(Sub2map(:,3)+Sub2map(:,4)+Sub2map(:,5))/3; % Autumn profile for substation 2
Sub3autumn=(Sub3map(:,3)+Sub3map(:,4)+Sub3map(:,5))/3; % Autumn profile for substation 3
Sub4autumn=(Sub4map(:,3)+Sub4map(:,4)+Sub4map(:,5))/3; % Autumn profile for substation 4
SubAvgautumn=(SubAvg(:,3)+SubAvg(:,4)+SubAvg(:,5))/3; % Autumn profile for all four
substations

Sub1winter=(Sub1map(:,6)+Sub1map(:,7)+Sub1map(:,8))/3; % Winter profile for substation
1
Sub2winter=(Sub2map(:,6)+Sub2map(:,7)+Sub2map(:,8))/3; % Winter profile for substation
2
Sub3winter=(Sub3map(:,6)+Sub3map(:,7)+Sub3map(:,8))/3; % Winter profile for substation
3
Sub4winter=(Sub4map(:,6)+Sub4map(:,7)+Sub4map(:,8))/3; % Winter profile for substation
4
SubAvgwinter=(SubAvg(:,6)+SubAvg(:,7)+SubAvg(:,8))/3; % Winter profile for all four
substations

Sub1spring=(Sub1map(:,9)+Sub1map(:,10)+Sub1map(:,11))/3; % Spring profile for
substation 1
Sub2spring=(Sub2map(:,9)+Sub2map(:,10)+Sub2map(:,11))/3; % Spring profile for
substation 2
Sub3spring=(Sub3map(:,9)+Sub3map(:,10)+Sub3map(:,11))/3; % Spring profile for
substation 3
Sub4spring=(Sub4map(:,9)+Sub4map(:,10)+Sub4map(:,11))/3; % Spring profile for
substation 4
SubAvgspring=(SubAvg(:,9)+SubAvg(:,10)+SubAvg(:,11))/3; % Spring profile for all
four substations

% figure(1)
% hold on
% plot(tenminuteinc,Sub1map(:,1)),title('January Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
% plot(tenminuteinc,Sub2map(:,1))
% plot(tenminuteinc,Sub3map(:,1))
% plot(tenminuteinc,Sub4map(:,1))
% plot(tenminuteinc,SubAvg(:,1),'Linewidth',2)
% legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
% hold off
% figure(2)
% hold on
% plot(tenminuteinc,Sub1map(:,4)),title('April Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

```



```

% plot(tenminuteinc,Sub2map(:,4))
% plot(tenminuteinc,Sub3map(:,4))
% plot(tenminuteinc,Sub4map(:,4))
% plot(tenminuteinc,SubAvg(:,4),'Linewidth',2)
% legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
% hold off
% figure(3)
% hold on
% plot(tenminuteinc,Sub1map(:,7)),title('July Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
% plot(tenminuteinc,Sub2map(:,7))
% plot(tenminuteinc,Sub3map(:,7))
% plot(tenminuteinc,Sub4map(:,7))
% plot(tenminuteinc,SubAvg(:,7),'Linewidth',2)
% legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
% hold off
% figure(4)
% hold on
% plot(tenminuteinc,Sub1map(:,10)),title('October Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
% plot(tenminuteinc,Sub2map(:,10))
% plot(tenminuteinc,Sub3map(:,10))
% plot(tenminuteinc,Sub4map(:,10))
% plot(tenminuteinc,SubAvg(:,10),'Linewidth',2)
% legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
% hold off

figure(5)
hold on
plot(tenminuteinc,Sub1summer(:,1)),title('Summer Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
plot(tenminuteinc,Sub2summer(:,1))
plot(tenminuteinc,Sub3summer(:,1))
plot(tenminuteinc,Sub4summer(:,1))
plot(tenminuteinc,SubAvgsummer(:,1),'Linewidth',2)
legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
hold off
figure(6)
hold on
plot(tenminuteinc,Sub1autumn(:,1)),title('Autumn Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
plot(tenminuteinc,Sub2autumn(:,1))
plot(tenminuteinc,Sub3autumn(:,1))
plot(tenminuteinc,Sub4autumn(:,1))
plot(tenminuteinc,SubAvgautumn(:,1),'Linewidth',2)
legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
hold off
figure(7)
hold on
plot(tenminuteinc,Sub1winter(:,1)),title('Winter Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
plot(tenminuteinc,Sub2winter(:,1))
plot(tenminuteinc,Sub3winter(:,1))
plot(tenminuteinc,Sub4winter(:,1))
plot(tenminuteinc,SubAvgwinter(:,1),'Linewidth',2)
legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
hold off
figure(8)

```

```

hold on
plot(tenminuteinc,Sub1spring(:,1)),title('Spring Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
plot(tenminuteinc,Sub2spring(:,1))
plot(tenminuteinc,Sub3spring(:,1))
plot(tenminuteinc,Sub4spring(:,1))
plot(tenminuteinc,SubAvgspring(:,1),'Linewidth',2)
legend('Sub1','Sub2','Sub3','Sub4','SubAvg','Location','northwest');
hold off

figure(9)
subplot(4,1,1)
plot(tenminuteinc,SubAvgsummer),title('Summer Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
subplot(4,1,2)
plot(tenminuteinc,SubAvgautumn),title('Autumn Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
subplot(4,1,3)
plot(tenminuteinc,SubAvgwinter),title('Winter Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
subplot(4,1,4)
plot(tenminuteinc,SubAvgspring),title('Spring Daily Average Energy Usage Per
Installation'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

Sub1Daily=sum(Sub1map(:))/72; % Average daily consumption in kWhrs. 72 is 12*6. The 12
comes from 12 months and the 6 from 6*10min intervals per hour.
Sub2Daily=sum(Sub2map(:))/72; % Average daily consumption in kWhrs. 72 is 12*6. The 12
comes from 12 months and the 6 from 6*10min intervals per hour.
Sub3Daily=sum(Sub3map(:))/72; % Average daily consumption in kWhrs. 72 is 12*6. The 12
comes from 12 months and the 6 from 6*10min intervals per hour.
Sub4Daily=sum(Sub4map(:))/72; % Average daily consumption in kWhrs. 72 is 12*6. The 12
comes from 12 months and the 6 from 6*10min intervals per hour.

SummerDaily=sum(SubAvgsummer)/6; % Average daily consumption in kWhrs
AutumnDaily=sum(SubAvgautumn)/6; % Average daily consumption in kWhrs
WinterDaily=sum(SubAvgwinter)/6; % Average daily consumption in kWhrs
SpringDaily=sum(SubAvgspring)/6; % Average daily consumption in kWhrs

fprintf('Substation 1 average daily consumption per installation is %0.2f
kWh\n',Sub1Daily);
fprintf('Substation 2 average daily consumption per installation is %0.2f
kWh\n',Sub2Daily);
fprintf('Substation 3 average daily consumption per installation is %0.2f
kWh\n',Sub3Daily);
fprintf('Substation 4 average daily consumption per installation is %0.2f
kWh\n\n',Sub4Daily);

fprintf('Summer average daily consumption per installation is %0.2f kWh\n',SummerDaily);
fprintf('Autumn average daily consumption per installation is %0.2f kWh\n',AutumnDaily);
fprintf('Winter average daily consumption per installation is %0.2f kWh\n',WinterDaily);
fprintf('Spring average daily consumption per installation is %0.2f kWh\n',SpringDaily);

```

```

Substation 1 average daily consumption per installation is 22.19 kWh
Substation 2 average daily consumption per installation is 15.36 kWh
Substation 3 average daily consumption per installation is 18.94 kWh

```

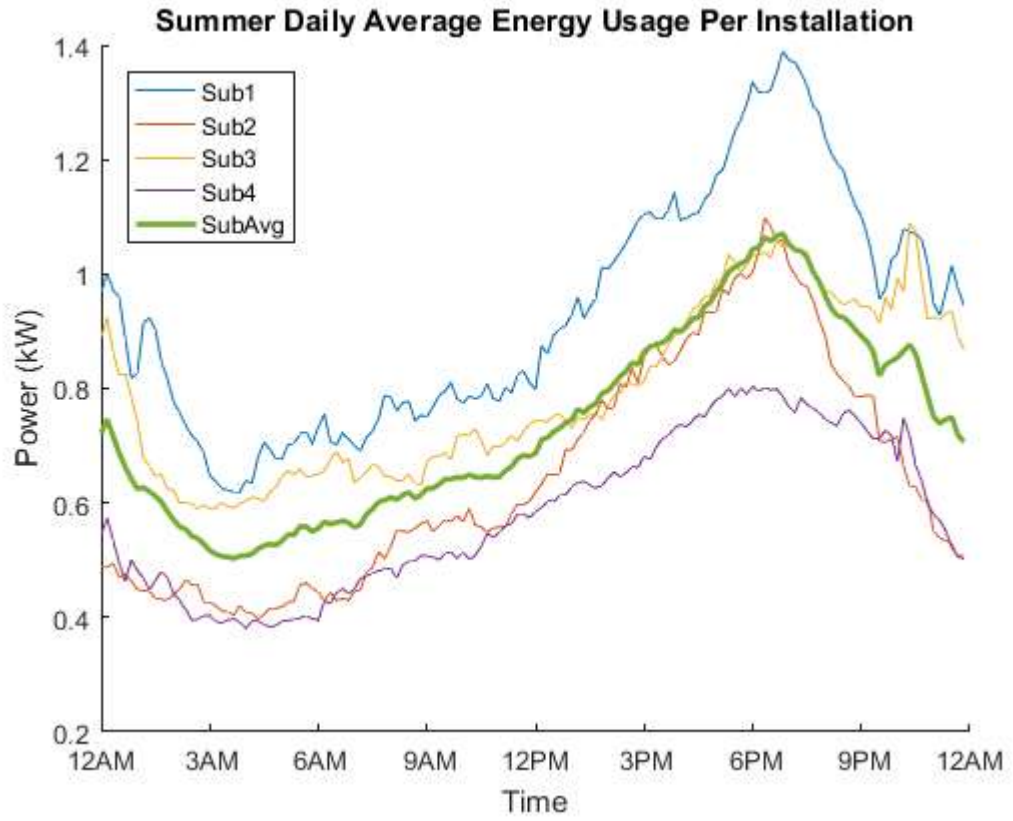
Substation 4 average daily consumption per installation is 13.86 kwh

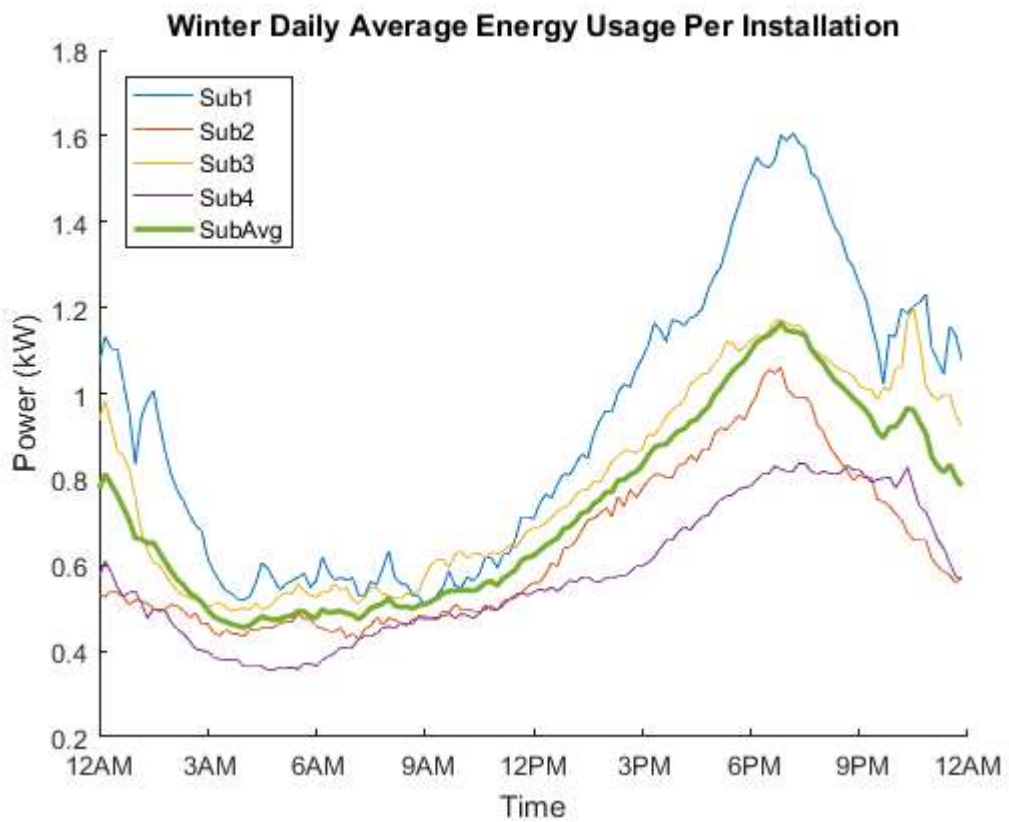
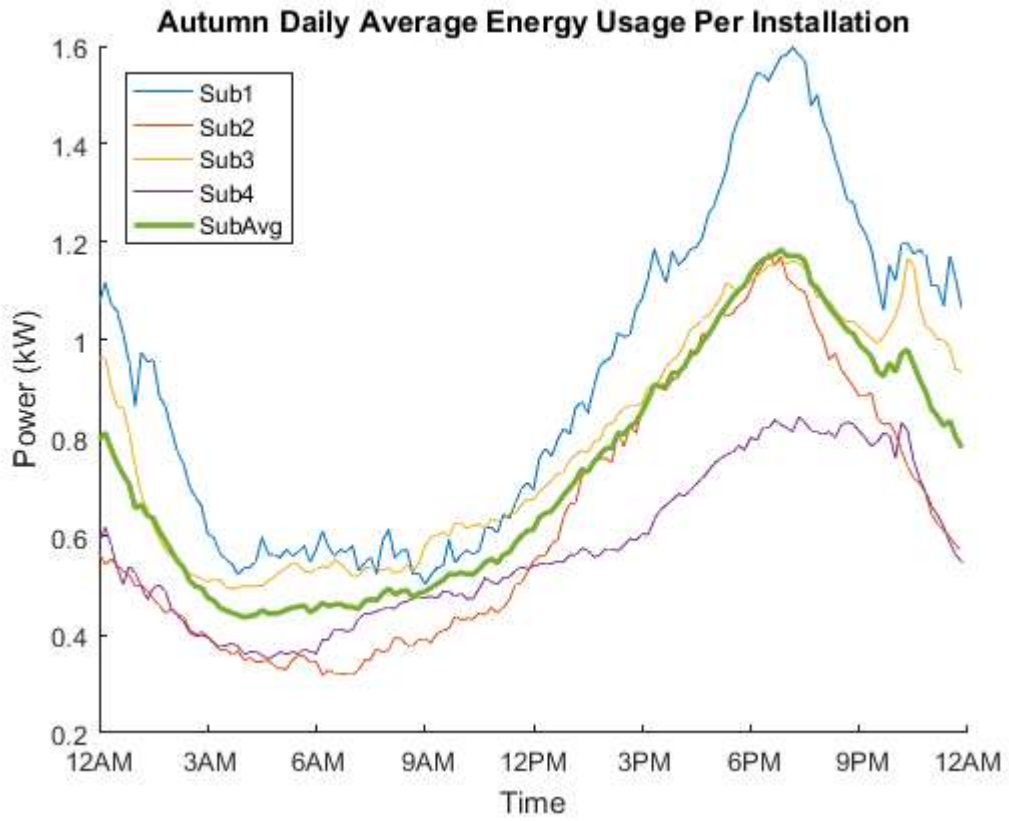
Summer average daily consumption per installation is 17.70 kwh

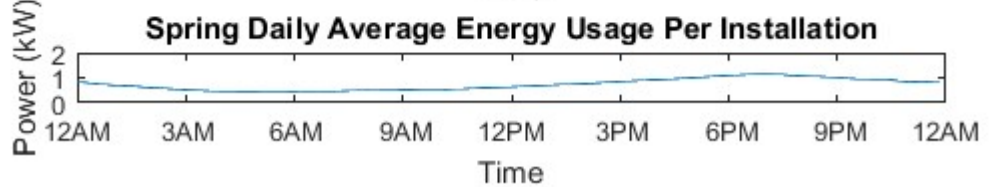
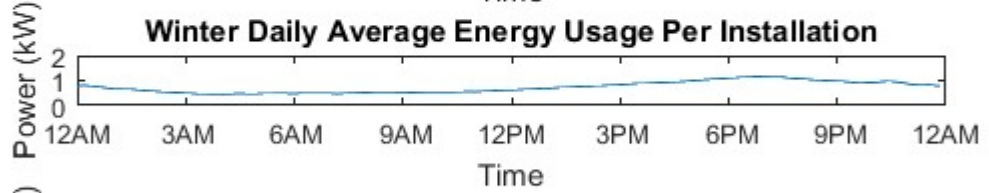
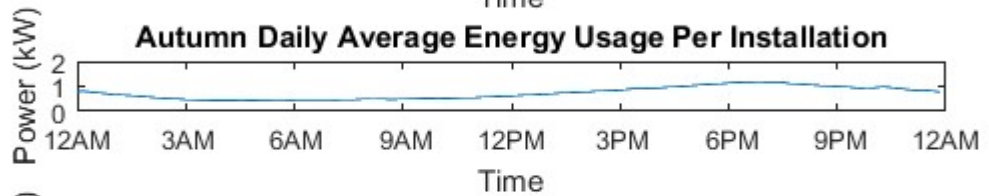
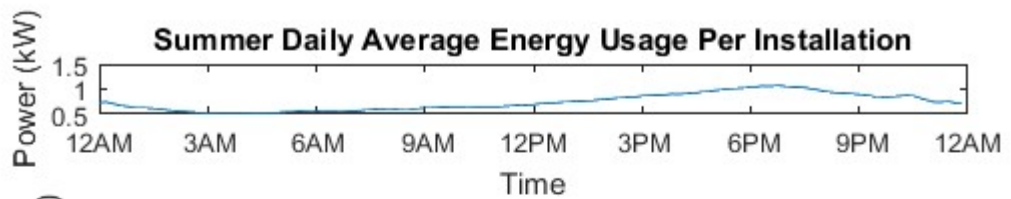
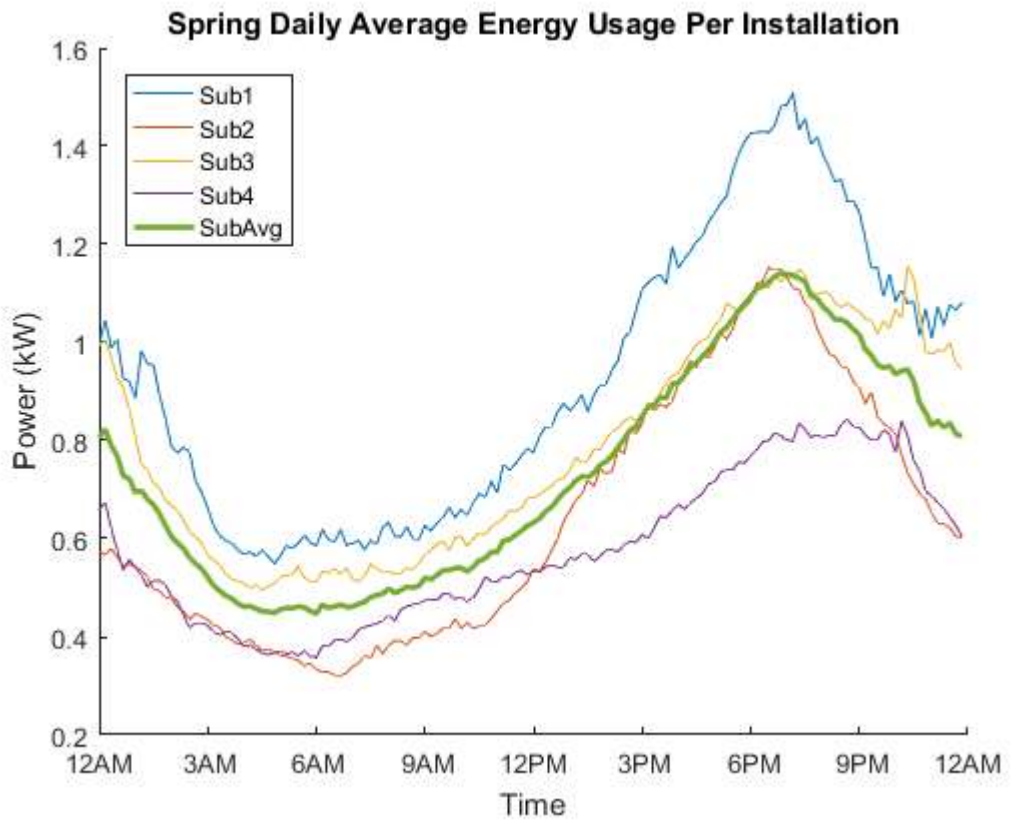
Autumn average daily consumption per installation is 17.54 kwh

Winter average daily consumption per installation is 17.53 kwh

Spring average daily consumption per installation is 17.59 kwh







*Published with MATLAB® R2016a*

### G.3 Code for House 1 model

```
% Mark Thorley
% 0061029218

% File Name: House_1_Simulation
% Output: House 1 modelled profile compared to house 1 logged profile
% Called By: None
% Calls: Simulink model - House_Model_Sim

clear all
close all
clc

simtime=1:1:86400; % Seconds in a day
%simtime=1:1:1440; % Mintues in a day
lsim=length(simtime); % Length of simulation time
load('House data') % Load data for each of the four houses logged.

c1=49.07; % 1.0mm2 cable single phase/DC voltage drop per ampere-meter
c15=31.52; % 1.5mm2 cable single phase/DC voltage drop per ampere-meter
c25=17.21; % 2.5mm2 cable single phase/DC voltage drop per ampere-meter
c4=10.67; % 4mm2 cable single phase/DC voltage drop per ampere-meter
c6=7.14; % 6mm2 cable single phase/DC voltage drop per ampere-meter
c10=4.24; % 10mm2 cable single phase/DC voltage drop per ampere-meter
c16=2.67; % 16mm2 cable single phase/DC voltage drop per ampere-meter
c25=1.70; % 25mm2 cable single phase/DC voltage drop per ampere-meter
c35=1.22; % 35mm2 cable single phase/DC voltage drop per ampere-meter
c50=0.91; % 50mm2 cable single phase/DC voltage drop per ampere-meter
c70=0.64; % 70mm2 cable single phase/DC voltage drop per ampere-meter
c95=0.48; % 95mm2 cable single phase/DC voltage drop per ampere-meter

autumnlength=92; % Season duration in days
winterlength=92; % Season duration in days
springlength=91; % Season duration in days
summerlength=90; % Season duration in days
JanFeblength=59; % January and February duration in days
Declength=31; % December duration in days

gridvoltage=230; % Fixed system voltage
voltage1set=380; % High voltage level for DC house with 2 buses.
voltage2set=24; % Low voltage level for DC house with 2 buses.

lightcablel=30; % Length of light circuits
powercablel=30; % Length of power circuits
ovencablel=30; % Length of stove and oven circuit
solarcablel=30; % Length of solar circuit - panels to inverter

pf=0.9; % Residential power factor
```

The following parameters are user definable. Once set here they will be applied to all models as appropriate.

```

% The ACDC rectifier gain block is there to represent the removal of the
% AC/DC rectifier in an appliance. This is the chosen method as
% appliances only list the total input power required. As a result the
% losses in the rectifier are calculated by multiplying the total input by
% one minus rectifier efficiency. However, to calculate the input power
% required following the removal of the rectifier a gain equal to the
% rectifier efficiency will provide the correct value.
% A value of 1 represents no conversion or change to the inputted value.
% A value of 0.95 represents a 95% efficient conversion being removed
% from the system.
% A value of 1/0.95 represent a conversion process that adds additional
% losses to the system, resulting in 105.25% consumption compared to the
% unconverted load.

Apprectifierset=0.88; % Individual appliance recitifier

% The following are used to connect the DC bus to the AC grid. Depending on
% configuration the power flow could be either direction.
Gridrectifierset=1/0.93; % Rectifier for connection from the grid. AC grid power
% supplied to DC bus. 93% efficient rectifier. The reason for 1/0.93 is
% that the rectifier results in 105.25% of the required load.
DCACinverterset=0.97; % Inverter used for connecting the DC bus to the AC
% grid.
DCDCconverterset=1/0.95; % DC/DC converter efficiency to change between
% DC voltages

Solarinverterset=0.95; % Inverter/Converter efficiency for solar connection
SolarMPPTset=0.98; % Solar MPPT/DC charger efficiency.

%
Gridrecteffx=[0;0.05;0.1;0.15;0.2;0.25;0.3;0.35;0.4;0.45;0.5;0.55;0.6;0.65;0.7;0.75;0.8;
0.85;0.9;0.95;1.0]; % Loading percentage
%
Gridrecteffx2=[0;0.92;0.945;0.95;0.956;0.955;0.954;0.952;0.95;0.948;0.9455;0.943;0.942;0
.94;0.935;0.9325;0.93;0.9275;0.9250;0.9225;0.92]; % Grid rectifier efficiency curve
based on Sunny Island 6.0H/8.0H.

```

SOLAR CONNECTION + BATTERY The following figures were obtained from the Beauru of Meterology's St Heliers weather station located just on the edge of Muswellbrook. This weather station only offers average daily global exposure per month over many years. These figures are the average of the data from 1990 to 2016.

```

AutumnSolar=4.13; % Autumn mean daily solar exposure in kwh/m2
WinterSolar=3.03; % Winter mean daily solar exposure in kwh/m2
SpringSolar=5.73; % Spring mean daily solar exposure in kwh/m2
SummerSolar=6.70; % Summer mean daily solar exposure in kwh/m2

```

```

% The following are solar figures in 1 minute increments obtained from the
% Beauru of Meterology's Wagga weather station. The data is based on 2014
% as that was the most recent year that contained 100% information. Wagga
% was the closest weather station to the geographical region in question
% that contained 1 minute solar readings for an entire year. The figures
% are in kw/sq m.
summersolar=xlsread('Solar Irradiance summary',1,'A:A');

```



```

autumnSolar=xlSread('Solar Irradiance summary',1,'B:B');
winterSolar=xlSread('Solar Irradiance summary',1,'C:C');
springSolar=xlSread('Solar Irradiance summary',1,'D:D');

% A perfect 1kw solar installation would produce 1kwh of energy per m2 of
% roof area, however, this is not the case in any installation as
% efficiency is around 22%.
% For the purpose of the model, the size of the solar array will
% be stated and this is referring to the maximum output of the PV system.
% This is relevant as this model is not concerned with PV efficiency and
% roof space just PV output. Utilising the mean daily solar exposure in
% kwh/m2 multiplied by the size of the system in kw will produce the
% average daily output.

PVsize=5000;           % PV installation size in watts
Solaroutput=0;        % Initial solar output parameter
Solarvoltage=48;      % Solar system voltage
Solarcable=c50;       % Solar cable size
Solarstrings=2;       % Number of parallel solar panel strings. This reduces current in
each cable and hence voltage drop.
Solaroutputprofile(:,1)=simtime; % Populates matrix with simtime for adding in solar
data in latter models
Solaroutputprofile(:,2)=zeros; % Create matrix column for later utilisation

Batterysize=10;       % Battery size in kilowatts. This is the usable figure.
Battini=0;%Batterysize/2; % Battery initial condition
batteff=0.91;        % Battery one way efficiency

% Appliance ratings - User defined
Fridge=129; % Main Fridge wattage
BarFridge=106; % Bar Fridge
DW=395; % Dishwasher
AC=6200; % Air Conditioner
WM=110; % Washing Machine
Dryer=2200; % Dryer
TV=209; % Plasma TV
Llights=264; % All living, kitchen, lounge, hallway etc.
Hlamps=500; % Bathroom Heat Lamps
HW=1300; % Hot water
HWB=3200; % Hot Water Boost Element
Stove_RH=825; % Stove and Rangehood. 575W is one of the small plates on medium temp,
250W for the rangehood.
OvenH=3176; % Oven when element is on
OvenL=124; % Oven when up to temperature
GameC=68; % PS3
Comp=55; % Laptop and LED screen
Baseload=125; % Constant load of standby appliances

ACduty=540; % A/C duty cycle. 9 minutes every 30 minutes = 30%
ACpulse=1800;
Ovenduty=120; % Oven duty cycle. 2 minutes every 10 minutes = 20%
Ovenpulse=600;
HWduty=480; % Hot Water duty cycle. 8 minutes every 100 minutes = 8%
HWpulse=6000;
Fridgeduty=780; % Fridge duty cycle. 7 minutes every 20 minutes = 35%
Fridgepulse=1200;

```



```
BFridgeduty=240; % Bar Fridge duty cycle. 4 mintues every 20 minutes = 20%
BFridgepulse=1200;
```

```
% Appliance operating times - Used defined
```

```
DWont=2200; % Dishwasher on time (hours)
Dwofft=2359; % Dishwasher off time (hours)
ACont1=0000;
ACofft1=0700;
ACont2=1600;
ACofft2=2359;
WMont=2000;
WMOfft=2130;
Dryeront=0;
Dryerofft=0;
TVont1=0600;
TVofft1=0700;
TVont2=1730;
TVofft2=2200;
Llightson1=0530;
Llightsofft1=0630;
Llightson2=1700;
Llightsofft2=2300;
Hlampsont1=0545;
Hlampsofft1=0600;
Hlampsont2=2230;
Hlampsofft2=2300;
HWBont1=0000;
HWBofft1=0100;
HWBont2=2300;
HWBofft2=2359;
Stoveont=0;%1730;
Stoveofft=0;%1800;
Ovenont=1730;
Ovenofft=1800;
GameCont=2000;
GameCofft=2300;
Compont=1930;
Compofft=2300;
```

```
% Adjusted operating times in seconds (Do not change these)
```

```
Dwon=(DWont/2400)*length(simtime);
Dwoff=(Dwofft/2400)*length(simtime);
ACon1=(ACont1/2400)*length(simtime);
ACoff1=(ACofft1/2400)*length(simtime);
ACon2=(ACont2/2400)*length(simtime);
ACoff2=(ACofft2/2400)*length(simtime);
WMon=(WMont/2400)*length(simtime);
WMOff=(WMOfft/2400)*length(simtime);
Dryeron=(Dryeront/2400)*length(simtime);
Dryeroff=(Dryerofft/2400)*length(simtime);
TVon1=(TVont1/2400)*length(simtime);
TVoff1=(TVofft1/2400)*length(simtime);
TVon2=(TVont2/2400)*length(simtime);
TVoff2=(TVofft2/2400)*length(simtime);
Llightson1=(Llightson1/2400)*length(simtime);
Llightsoff1=(Llightsofft1/2400)*length(simtime);
```

```

Llightson2=(Llightson2/2400)*length(simtime);
Llightsoff2=(Llightsoff2/2400)*length(simtime);
Hlampson1=(Hlampson1/2400)*length(simtime);
Hlampsoff1=(Hlampsoff1/2400)*length(simtime);
Hlampson2=(Hlampson2/2400)*length(simtime);
Hlampsoff2=(Hlampsoff2/2400)*length(simtime);
HWBon1=(HWBon1/2400)*length(simtime);
HWBoff1=(HWBoff1/2400)*length(simtime);
HWBon2=(HWBon2/2400)*length(simtime);
HWBoff2=(HWBoff2/2400)*length(simtime);
Stoveon=(Stoveon/2400)*length(simtime);
Stoveoff=(Stoveoff/2400)*length(simtime);
Ovenon=(Ovenon/2400)*length(simtime);
Ovenoff=(Ovenoff/2400)*length(simtime);
GameCon=(GameCon/2400)*length(simtime);
GameCoff=(GameCoff/2400)*length(simtime);
Compon=(Compon/2400)*length(simtime);
Compoff=(Compoff/2400)*length(simtime);

voltage=230;    % System supply voltage
Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1/pf;

load_system('House_Model_Sim_minute') % Load the Simulink model
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '1'); % Set A/C off as this did
not run during logging timeframe.
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime) % Run simulation for one day

figure(1)
xaxis=(simtime/length(simtime));
plot(xaxis,Energyusage),title('House 1 Modelled Daily
Profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

figure(2)
hold on
plot(xaxis,Energyusage),title('House 1 Modelled Daily Profile - Logged vs
Simulated'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
plot(Time,House1)
hold off
legend('Simulated', 'Logged')

Dailyenergy=sum(Energyusage)/3600;    % Convert to hours if simulation is in seconds
%Dailyenergy=sum(Energyusage)/60;    % Convert to hours is simulation in minutes

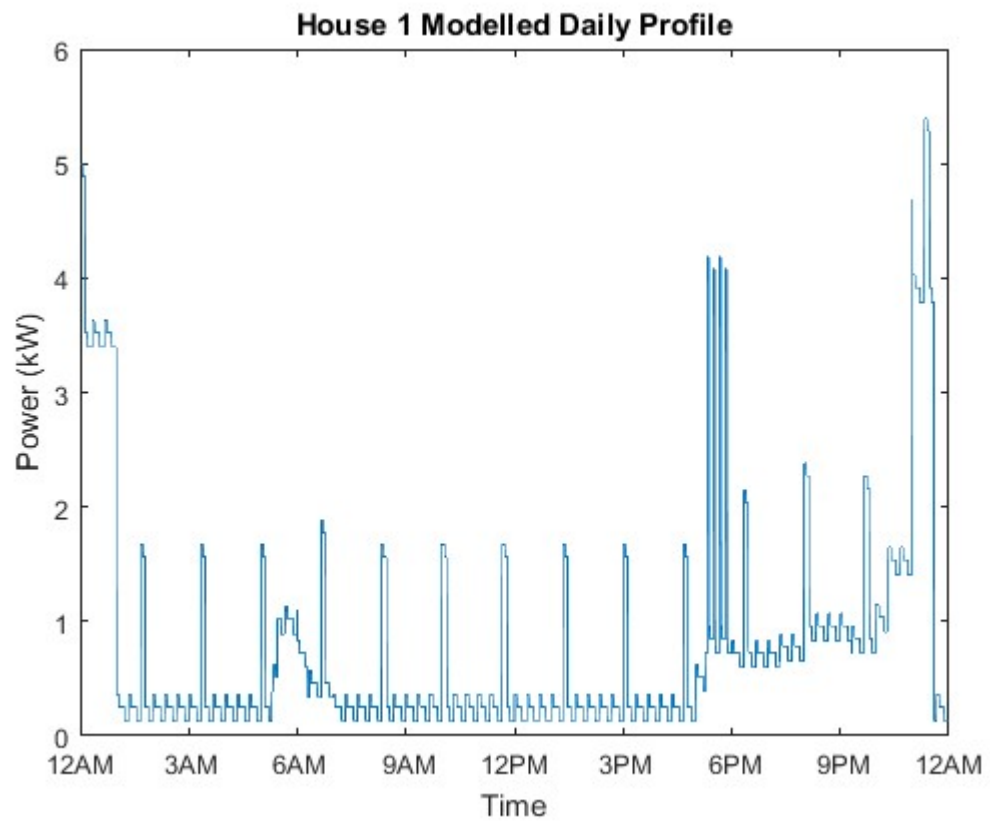
fprintf('House daily energy usage is %0.2f kWh\n',Dailyenergy);

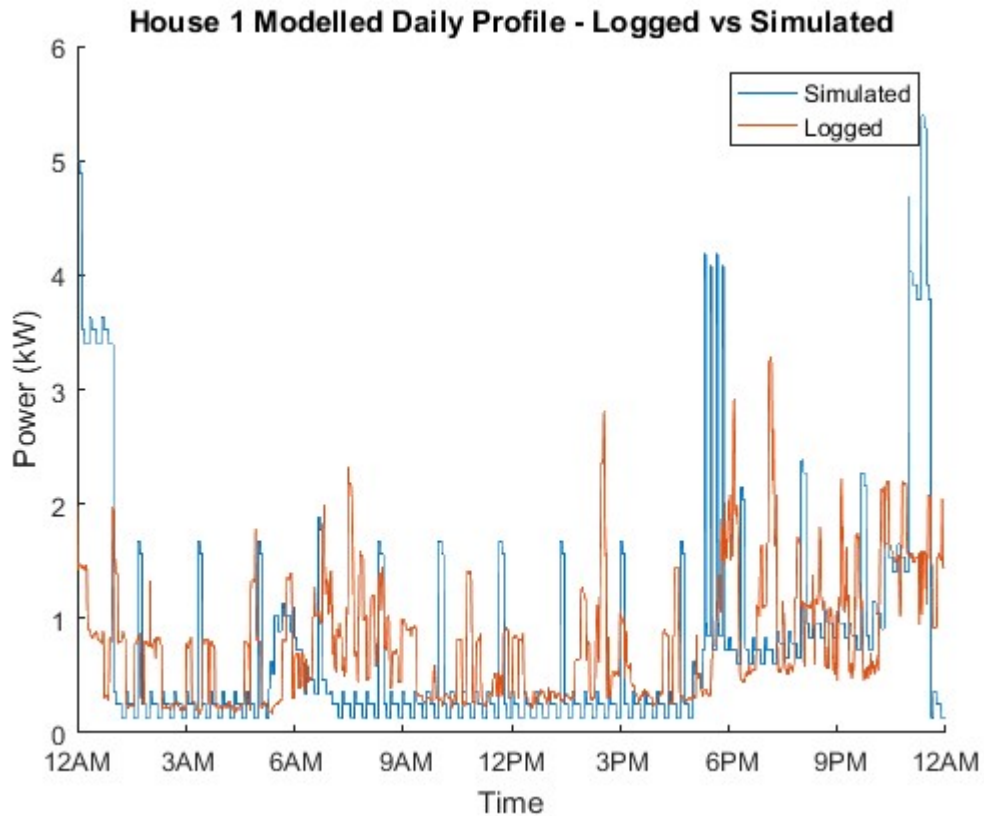
% Convert 1 second data from above into 1 minute averages

```

```
Dailyenergy_min_house1=zeros(1440,1);  
for m=0:1:1439  
    Dailyenergy_min_house1(m+1,1)=sum(Energyusage((m*60)+1:(m*60)+60))/60;  
end
```

House daily energy usage is 18.73 kwh





Removal of AC/DC rectifiers for a high level assessment of the savings offered.

```
Apprectifier=0.88;
```

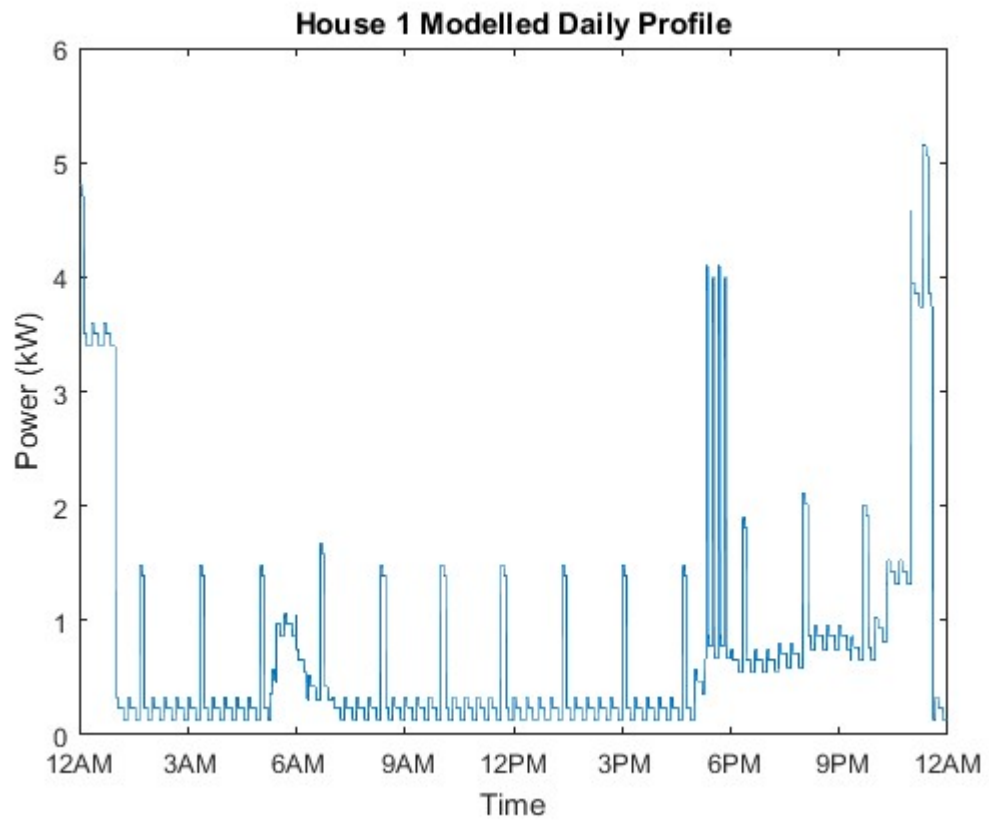
```
load_system('House_Model_Sim_minute') % Load the Simulink model
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '1'); % Set A/C off as this did
not run during logging timeframe.
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime) % Run simulation for one day
```

```
figure(3)
xaxis=(simtime/length(simtime));
plot(xaxis,Energyusage),title('House 1 Modelled Daily
Profile'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')
```

```
Dailyenergy=sum(Energyusage)/3600; % Convert to hours if simulation is in seconds
%Dailyenergy=sum(Energyusage)/60; % Convert to hours if simulation is in minutes
```

```
fprintf('House daily energy usage with AC/DC rectifiers removed is %0.2f
kWh\n',Dailyenergy);
```

House daily energy usage with AC/DC rectifiers removed is 17.60 kWh



*[Published with MATLAB® R2016a](#)*

## G.4 Code for Project model

```
% Mark Thorley
% 0061029218

% File Name: Project_model.m
% Output: Modelling AC and DC configurations and determining losses in each
%
% Called By: None
% Calls:    Simulink model - House_Model_Sim_minute
%          Simulink model - House_Model_Sim_voltageoptions_minute

clear all
close all
clc

%simtime=1:1:86400;    % Seconds in a day
simtime=1:1:1440;    % Minutes in a day
lsim=length(simtime); % Length of simulation time
divisor=60;          % Divisor to get back to kWhs. When the addition
% of 1440 minute power readings it performed it is necessary to divide by
% 60 to get the power used in a 24 hour period.

c1=49.07;           % 1.0mm2 cable single phase/DC voltage drop per ampere-meter
c15=31.52;          % 1.5mm2 cable single phase/DC voltage drop per ampere-meter
c25=17.21;          % 2.5mm2 cable single phase/DC voltage drop per ampere-meter
c4=10.67;           % 4mm2 cable single phase/DC voltage drop per ampere-meter
c6=7.14;            % 6mm2 cable single phase/DC voltage drop per ampere-meter
c10=4.24;           % 10mm2 cable single phase/DC voltage drop per ampere-meter
c16=2.67;           % 16mm2 cable single phase/DC voltage drop per ampere-meter
c25=1.70;           % 25mm2 cable single phase/DC voltage drop per ampere-meter
c35=1.22;           % 35mm2 cable single phase/DC voltage drop per ampere-meter
c50=0.91;           % 50mm2 cable single phase/DC voltage drop per ampere-meter
c70=0.64;           % 70mm2 cable single phase/DC voltage drop per ampere-meter
c95=0.48;           % 95mm2 cable single phase/DC voltage drop per ampere-meter

autumnlength=92;    % Season duration in days
winterlength=92;    % Season duration in days
springlength=91;    % Season duration in days
summerlength=90;    % Season duration in days
JanFeb=length=59;   % January and February duration in days
Dec=length=31;      % December duration in days

gridvoltage=230;    % Fixed system voltage
voltage1set=380;    % High voltage level for DC house with 2 buses.
voltage2set=24;     % Low voltage level for DC house with 2 buses.
pf=0.9;             % Power Factor

lightcablel=30;    % Length of light circuits
powercablel=30;    % Length of power circuits
ovencablel=30;     % Length of stove and oven circuit
solarcablel=30;    % Length of solar circuit - panels to inverter
```

The following parameters are user definable. Once set here they will be applied to all models as appropriate.

```

% The ACDC rectifier gain block is there to represent the removal of the
% AC/DC rectifier in an appliance. This is the chosen method as
% appliances only list the total input power required. As a result the
% losses in the rectifier are calculated by multiplying the total input by
% one minus rectifier efficiency. However, to calculate the input power
% required following the removal of the rectifier a gain equal to the
% rectifier efficiency will provide the correct value.
% A value of 1 represents no conversion or change to the inputted value.
% A value of 0.95 represents a 95% efficient conversion being removed
% from the system.
% A value of 1/0.95 represent a conversion process that adds additional
% losses to the system, resulting in 105.25% consumption compared to the
% unconverted load.
Apprectifierset=0.88; % Individual appliance recitifier

% The following are used to connect the DC bus to the AC grid. Depending on
% configuration the power flow could be either direction.
Gridrectifierset=1/0.93; % Rectifier for connection from the grid. AC grid power
% supplied to DC bus. 93% efficient rectifier. The reason for 1/0.93 is
% that the rectifier results in 105.25% of the required load.
DCACinverterset=0.97; % Inverter used for connecting the DC bus to the AC
% grid.
DCDCconverterset=1/0.95; % DC/DC converter efficiency to change between
% DC voltages

Solarinverterset=0.95; % Inverter/Converter efficiency for solar connection
SolarMPPTset=0.98; % Solar MPPT/DC charger efficiency.
Battconvdac=1/0.97; % DC/AC inverter efficiency for discharge of battery
Battconvdcdc=1/0.95; % DC/DC converter efficiency for discharge of battery
Battchargecorr=SolarMPPTset/Solarinverterset; % Converts 95% efficiency back to 98%
efficiency for battery charging.

%
Gridrecteffx=[0;0.05;0.1;0.15;0.2;0.25;0.3;0.35;0.4;0.45;0.5;0.55;0.6;0.65;0.7;0.75;0.8;
0.85;0.9;0.95;1.0]; % Loading percentage
%
Gridrecteffx2=[0;0.92;0.945;0.95;0.956;0.955;0.954;0.952;0.95;0.948;0.9455;0.943;0.942;0
.94;0.935;0.9325;0.93;0.9275;0.9250;0.9225;0.92]; % Grid rectifier efficiency curve
based on Sunny Island 6.0H/8.0H.

```

SOLAR CONNECTION + BATTERY The following figures were obtained from the Bureau of Meteorology's St Heliers weather station located just on the edge of Muswellbrook. This weather station only offers average daily global exposure per month over many years. These figures are the average of the data from 1990 to 2016.

```

Autumnsolar=4.13; % Autumn mean daily solar exposure in kwh/m2
wintersolar=3.03; % Winter mean daily solar exposure in kwh/m2
SpringSolar=5.73; % Spring mean daily solar exposure in kwh/m2
Summersolar=6.70; % Summer mean daily solar exposure in kwh/m2
Annualsolar=(Autumnsolar+wintersolar+SpringSolar+Summersolar)/4;

```

```

% The following are solar figures in 1 minute increments obtained from the
% Bureau of Meteorology's wagga weather station. The data is based on 2014
% as that was the most recent year that contained 100% information. wagga
% was the closest weather station to the geographical region in question

```

```

% that contained 1 minute solar readings for an entire year. The figures
% are in kw/sq m.
summersolar=xlsread('Solar Irradiance summary',1,'A:A');
autumnSolar=xlsread('Solar Irradiance summary',1,'B:B');
wintersolar=xlsread('Solar Irradiance summary',1,'C:C');
springsolar=xlsread('Solar Irradiance summary',1,'D:D');
annualsolar=(summersolar+autumnSolar+wintersolar+springsolar)/4;

% A perfect 1kw solar installation would produce 1kw of energy per m2 of
% roof area, however, this is not the case in any installation as
% efficiency is around 22%.
% For the purpose of the model, the size of the solar array will
% be stated and this is referring to the maximum output of the PV system.
% This is relevant as this model is not concerned with PV efficiency and
% roof space just PV output. Utilising the mean daily solar exposure in
% kwh/m2 multiplied by the size of the system in kw will produce the
% average daily output.

PVsize=5000;      % PV installation size in watts
solaroutput=0;   % Initial solar output parameter
solarvoltage=240; % Solar system voltage
solarcable=c16;  % Solar cable size
solarstrings=1;  % Number of parallel solar panel strings. This reduces current in
each cable and hence voltage drop.
solaroutputprofile(:,1)=simtime; % Populates matrix with simtime for adding in solar
data in later models
solaroutputprofile(:,2)=zeros;    % Create matrix column for later utilisation

Batterysize=10; % Battery size in kilowatts. This is the usable figure.
Battini=0;      % Battery initial condition
batteff=0.91;   % Battery one way efficiency

% Appliance ratings - Obtained from either the energy star website or real
% measurements. All values are user definable.

Fridge=111;     % Main Fridge wattage
BarFridge=79;   % Bar Fridge
DW=315;         % Dishwasher
AC=2100;        % Air Conditioner - DC drive
WM=110;         % Washing Machine - cold wash
Dryer=1026;     % Heat Pump Dryer
TV=80;          % Plasma TV
Llights=264;    % All living, kitchen, lounge, hallway etc.
Hlamps=500;     % Bathroom Heat Lamps
HW=1300;        % Hot water
HWB=3200;       % Hot Water Boost Element
Stove_RH=825;   % Stove and Rangehood. 575W is one of the small plates on medium temp,
250W for the rangehood.
OvenH=3176;     % Oven when element is on
OvenL=124;      % Oven when up to temperature
GameC=68;       % PS3
Comp=55;        % Laptop and LED screen
BaseLoad=125;   % Constant load of standby appliances and constantly on appliances such
as the alarm and router.

ACduty=9;       % A/C duty cycle. 9 minutes every 30 minutes = 30%
ACpulse=30;
Ovenduty=2;     % Oven duty cycle. 2 minutes every 10 minutes = 20%

```



```

Ovenpulse=10;
HWduty=8;      % Hot water duty cycle. 8 minutes every 100 minutes = 8%
HPulse=100;
Fridgeduty=7 ; % Fridge duty cycle. 7 minutes every 20 minutes = 35%
Fridgepulse=20;
BFridgeduty=4; % Bar Fridge duty cycle. 4 minutes every 20 minutes = 20%
BFridgepulse=20;

```

### AUTUMN Appliance operating times - Used defined

```

Dwont=2200;    % Dishwasher on time (hours)
Dwofft=2359;  % Dishwasher off time (hours)
ACont1=0000;  % Air Conditioner on time (hours)
ACofft1=0000; % Air Conditioner off time (hours)
ACont2=1800;  % Air Conditioner on time (hours)
ACofft2=2200; % Air Conditioner off time (hours)
WMont=2000;   % Washing Machine on time (hours)
WMOfft=2130;  % Washing Machine off time (hours)
Dryeront=0;   % Dryer on time (hours)
Dryerofft=0;  % Dryer off time (hours)
TVont1=0600;  % TV on time (hours)
TVofft1=0700; % TV off time (hours)
TVont2=1730;  % TV on time (hours)
TVofft2=2200; % TV off time (hours)
Llightsont1=0530; % Lights on time (hours)
Llightsofft1=0630; % Lights off time (hours)
Llightsont2=1800; % Lights on time (hours)
Llightsofft2=2300; % Lights off time (hours)
Hlampsont1=0545; % Heat Lamps on time (hours)
Hlampofft1=0600; % Heat Lamps off time (hours)
Hlampsont2=2245; % Heat Lamps on time (hours)
Hlampofft2=2300; % Heat Lamps off time (hours)
HWBont1=0000;   % Hot Water Booster on time (hours)
HWBofft1=0100;  % Hot Water Booster off time (hours)
HWBont2=2300;   % Hot Water Booster on time (hours)
HWBofft2=2359;  % Hot Water Booster off time (hours)
Stoveont=1730;  % Stove on time (hours)
Stoveofft=1800; % Stove off time (hours)
Ovenont=1730;  % Oven on time (hours)
Ovenofft=1800; % Oven off time (hours)
GameCont=2000; % Game Console on time (hours)
GameCofft=2300; % Game Console off time (hours)
Compont=1930;  % Computer on time (hours)
Compofft=2300; % Computer off time (hours)

% Adjusted operating times by converting to seconds (Do not change these).
Dwon=(Dwont/2400)*1sim;
Dwoff=(Dwofft/2400)*1sim;
ACon1=(ACont1/2400)*1sim;
ACoff1=(ACofft1/2400)*1sim;
ACon2=(ACont2/2400)*1sim;
ACoff2=(ACofft2/2400)*1sim;
WMon=(WMont/2400)*1sim;
WMOff=(WMOfft/2400)*1sim;
Dryeron=(Dryeront/2400)*1sim;
Dryeroff=(Dryerofft/2400)*1sim;

```

```

TVon1=(TVont1/2400)*1sim;
TVoff1=(TVofft1/2400)*1sim;
TVon2=(TVont2/2400)*1sim;
TVoff2=(TVofft2/2400)*1sim;
Llightson1=(Llightson1/2400)*1sim;
Llightsoff1=(Llightsofft1/2400)*1sim;
Llightson2=(Llightson2/2400)*1sim;
Llightsoff2=(Llightsofft2/2400)*1sim;
Hlampson1=(Hlampson1/2400)*1sim;
Hlampsoff1=(Hlampsofft1/2400)*1sim;
Hlampson2=(Hlampson2/2400)*1sim;
Hlampsoff2=(Hlampsofft2/2400)*1sim;
HWBon1=(HWBont1/2400)*1sim;
HWBoff1=(HWBofft1/2400)*1sim;
HWBon2=(HWBont2/2400)*1sim;
HWBoff2=(HWBofft2/2400)*1sim;
Stoveon=(Stoveont/2400)*1sim;
Stoveoff=(Stoveofft/2400)*1sim;
Ovenon=(Ovenont/2400)*1sim;
Ovenoff=(Ovenofft/2400)*1sim;
GameCon=(GameCont/2400)*1sim;
GameCoff=(GameCofft/2400)*1sim;
Compon=(Compont/2400)*1sim;
Compoff=(Compofft/2400)*1sim;

```

Configuration 1 AC supplied house operating with DC internal appliances. This is the base case and is assumed to be the current status of the house.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1/pf;

load_system('House_Model_Sim_minute') % Load the Simulink model
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime) % Run simulation for one day

% xaxis=(simtime/length(simtime));
% figure(1)
% plot(xaxis,Energyusage),title('Model 1 - AC house with DC internal appliances autumn
daily profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM1_Energyusage=Energyusage;
AM1_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
AM1_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
AM1_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
AM1_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
AM1_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This

```

```

includes cables losses and appliance AC/DC rectifier losses.
fprintf('Model 1 - AC house with DC internal appliances autumn daily energy usage is
%0.2f kWh\n',AM1_Dailyenergy);

% Repeat the daily profile figures for all of autumn
AM1energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    AM1energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

AM1_HWu=(sum(HWusage)/60)/1000;    % Daily hot water usage in kwh
AM1_ACu=(sum(ACusage)/60)/1000;    % Daily air conditioner usage in kwh
AM1_Cooku=(sum(Cookusage)/60)/1000; % Daily cooking appliance use in kwh
AM1_Lightu=(sum(Lightusage)/60)/1000; % Daily light usage in kwh
AM1_WGu=(sum(WGusage)/60)/1000;    % Daily white goods usage in kwh
AM1_Appu=(sum(Appusage)/60)/1000;  % Daily appliance usage in kwh
AM1_Baseu=BaseLoad*24/1000;        % Daily base load usage in kwh

AM1_Loadtotal=AM1_HWu+AM1_ACu+AM1_Cooku+AM1_Lightu+AM1_WGu+AM1_Appu+AM1_Baseu;

```

Configuration 2 Remove appliance AC/DC rectifiers. High level result as this assumes complete DC supply and common DC bus voltage in the house.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(2)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily profile (high
level)'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM2_Dailyenergy=sum(Energyusage)/60;    % Total daily energy usage.
AM2_Gridcons=sum(Gridusage)/60;    % Sum of positive values (energy from the grid)
AM2_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5)/60)/1000;    % Power lost in cables
AM2_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
AM2_ACDCsav=AM1_Dailyenergy-AM2_Dailyenergy;    % Appliance ACDC rectifier saving
compared to Model 1
fprintf('Model 2 - Daily autumn energy usage with appliance AC/DC rectifiers removed is
%0.2f kWh. This assumes complete DC supply and common DC voltage.\n',AM2_Dailyenergy);

% Repeat the daily profile figures for all of autumn
AM2energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1

```

```

AM3energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
end

```

Configuration 3 Remove appliance AC/DC rectifiers, resulting in a reduction in baseload by 50W. This reduction is due to eliminating standby current.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(3)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM3_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
AM3_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
AM3_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
AM3_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
AM3_ACDCsav=AM1_Dailyenergy-AM3_Dailyenergy; % Appliance ACDC rectifier saving
compared to Model 1
%AM3_Homer_Load=sum(Total_Load)/60; % Total load for use in Homer Energy on DC bus.
This includes cables losses and the removal of AC/DC rectifiers.
%fprintf('Model 3 - Daily autumn energy usage with appliance AC/DC rectifiers removed,
resulting in reduced standby current, is %0.2f kWh\n',AM3_Dailyenergy);

% Repeat the daily profile figures for all of autumn
AM3energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    AM3energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 4 Install central AC/DC rectifier to supply the DC home from the AC grid.

```

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;

```

```

Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(4)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM4_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
AM4_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
AM4_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
AM4_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
AM4_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
%fprintf('Model 4 - Daily autumn energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed is %0.2f kWh\n',AM4_Dailyenergy);
%
% % Repeat the daily profile figures for all of autumn
% AM4energy_min=zeros(autumnlength*1440,1);
% for y=0:1:autumnlength-1
% AM4energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 5 Install two DC buses. A 380V bus and a 24V bus, both supplied from the AC grid.

```

voltage1=voltage1set;
voltage2=voltage2set;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCconverterset;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '1'); % Set
solar off
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

```

```

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM5_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
AM5_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
AM5_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
AM5_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
AM5_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter losses
AM5_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-AM5_DCloss_v2;
% Load consumption
AM5_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.

%fprintf('Model 5 - Daily autumn energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed with a 380V and 24V buses is %.2f
kwh\n',AM5_Dailyenergy);

% Repeat the daily profile figures for all of spring
AM5energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    AM5energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 6 Full AC house with DC internal appliances. Install Solar onto single bus model. No profile just average daily contribution. ie: Total consumption minus total generation.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset;
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutput=PVsize*Autumnsolar/24; % Sets kwh figure for use over entire 24 hour
period.
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '1'); % Set Solar total as active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Profile with block solar
applied'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM6_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
AM6_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
AM6_SILoss=sum(SILoss)/60; % Solar inverter loss

```

```

AM6_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
%fprintf('Model 6 - Daily autumn energy usage for AC house with solar PV installed is
%0.2f kWh. This is based on total consumption minus total generation, it does not factor
in time of day.\n',AM6_Dailyenergy);

% % Repeat the daily profile figures for all of autumn
% AM6energy_min=zeros(autumnlength*1440,1);
% for y=0:1:autumnlength-1
%     AM6energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 7 Install Solar following autumn profile onto single bus model. Solar generation follows irradiance data obtained from BOM. Solar inverter is considered the central connection between solar and house/grid.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % DC/AC inverter to connect solar to grid/installation
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*autumnsolar; % Sets value for solar generation based on
average irradiance level.
powerfactor=1/pf;

Load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% solarplot=Solaroutputprofile(:,2)/1000;
% xaxis=(simtime/length(simtime));
% figure(106)
% plot(xaxis,solarplot),title('Autumn solar generation in one minute
increments'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
%
% xaxis=(simtime/length(simtime));
% figure(6)
% plot(xaxis,Energyusage),title('Model 7 - Daily autumn energy usage for AC house with
solar installed'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
%
% figure(107)
% subplot(2,1,1)
% plot(xaxis,solarplot),title('Daily autumn solar generation in one minute
increments'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
% subplot(2,1,2)
% plot(xaxis,Energyusage),title('Model 7 - Daily autumn energy usage for AC house with
solar installed'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

```

```

AM7_Energyusage=Energyusage;
AM7_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
AM7_Solarexp=(sum(Solarexport)*-1)/60; % Sum of negative values (energy exported to the
grid)
AM7_Solarcons=AM7_Solargen-AM7_Solarexp; % Solar energy consumed by installation,
including all losses.
AM7_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
AM7_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the grid)
AM7_Dailyenergycons=AM7_Solarcons+AM7_Gridcons; % Consumption by installation
AM7_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
AM7_Grloss=sum(GRloss)/60; % Grid rectifier loss
AM7_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
AM7_SIlloss=sum(SIlloss)/60; % Energy lost in solar inverter
AM7_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
%fprintf('Model 7 - Daily autumn energy usage for AC house with solar installed is %0.2f
kWh.\n',AM7_Dailyenergycons);

%% Repeat the daily profile figures for all of autumn
% AM7energy_min=zeros(autumnlength*1440,1);
% for y=0:1:autumnlength-1
% AM7energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 8 Install two buses. A 380V bus and a 24V bus. Solar connected to 380V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCinverterset;
Solarinverter=SolarMPPTset; % DC/DC converter / MPPT
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)

```



```

% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

AM8_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
AM8_Solarexp=(sum(Solarexport)*-1)/60; % Sum of negative values (energy exported to the
grid)
AM8_Solarcons=AM8_Solargen-AM8_Solarexp;
AM8_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the grid)
AM8_Dailyenergycons=AM8_Solarcons+AM8_Gridcons;
AM8_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
AM8_GRloss=sum(GRloss)/60; % Grid rectifier loss
AM8_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
AM8_SILoss=sum(SILoss)/60; % Solar inverter loss
AM8_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter on v2 loss
AM8_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-AM8_DCloss_v2;
% Load consumption
%AM8_Homer_Load=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.
%fprintf('Model 8 - Daily autumn energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',AM8_Dailyenergycons);

% Repeat the daily profile figures for all of autumn
AM8energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    AM8energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 9 Install solar and battery storage on single bus model.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset;
Battconv=Battconvdcac; % Battery discharge inverter
Battcc=Battchargecorr;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*autumnsolar;
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '0'); % Set Grid connection to off
set_param('House_Model_Sim_minute/Battery switch', 'sw', '0'); % Set battery on
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

AM9_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
AM9_Solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to the

```

```

grid)
AM9_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
AM9_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
AM9_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy into battery after
efficiency and converter losses.
AM9_Battcons=Battini+(max(Battusage))/60; % Energy used from battery,
including losses
AM9_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
AM9_GRloss=sum(GRloss2)/60; % Grid rectifier loss
AM9_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
AM9_SIlloss=sum(SIlloss)/60; % Solar inverter loss
AM9_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
AM9_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
AM9_Solarcons=AM9_Solargen-AM9_Solarexp; % Solar energy consumed by model
AM9_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
AM9_SOC=Battsoc; % Battery state of charge
AM9_Dailyenergycons=AM9_Solarcons+AM9_Gridcons;
%fprintf('Model 9 - Daily autumn energy usage for AC house with solar PV + batteries
installed is %0.2f kWh.\n',AM9_Dailyenergycons);

% % Repeat the daily profile figures for all of autumn
% AM9energy_min=zeros(autumnlength*1440,1);
% for y=0:1:autumnlength-1
% AM9energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 10 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 380V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset; % 93% efficient grid connected DC
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCinverterset;
Solarinverter=SolarMPPTset; % MPPT
Battconv=Battconvdc; % Battery discharge converter
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on

```

```

sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM10_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
AM10_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
AM10_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
AM10_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
AM10_Solarexp=(sum(Solarexp2)*-1)/60; % Sum of negative values (energy exported to
the grid)
AM10_Solarcons=AM10_Solargen-AM10_Solarexp;
AM10_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
AM10_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
AM10_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
AM10_SILoss=sum(SILoss)/60; % Solar inverter loss
AM10_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter loss on v2
AM10_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
AM10_BattchargeLoss=sum(BattchargeLoss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
AM10_Loadcons=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
AM10_DCloss_v2; % Load consumption
AM10_HomerLoad=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.
AM10_SOC=Battsoc; % Battery state of charge
AM10_Dailyenergycons=AM10_Solarcons+AM10_Gridcons;
%fprintf('Model 10 - Daily autumn energy usage for DC house (2 voltages) with solar PV
and batteries installed is %0.2f kWh.\n',AM10_Dailyenergycons);

% Repeat the daily profile figures for all of autumn
AM10energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    AM10energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end
end

```

Configuration 11 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 24V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset; % 93% efficient grid connected DC
DCACinverter=DCACinverterset;
DCDCconverter_v1=DCDCconverterset;
DCDCconverter_v2=1;
Solarinverter=SolarMPPTset;
Battconv=1; % No battery discharge converter as it is at the same voltage as DC bus.
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on

```

```

set_param('House_Model_Sim_voltgeoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltgeoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltgeoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltgeoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltgeoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

AM11_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
AM11_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
AM11_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
AM11_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
AM11_Solarexp=(sum(Solarexp2)*-1)/60; % Sum of negative values (energy exported to
the grid)
AM11_Solarcons=AM11_Solargen-AM11_Solarexp;
AM11_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
AM11_GRloss=sum(GRloss2)/60; % Grid rectifier loss
AM11_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
AM11_SIlloss=sum(SIlloss)/60; % Solar inverter loss
AM11_DCloss_v1=sum(DCloss_v1)/60; % DC/DC converter loss
AM11_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
AM11_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
AM11_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
AM11_DCloss_v1; % Load consumption
AM11_HomerLoad=sum(Total_Load)/60; % Total load including Cable loasses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 24V bus.
AM11_SOC=Battsoc; % Battery state of charge
AM11_Dailyenergycons=AM11_Solarcons+AM11_Gridcons;
%fprintf('Model 11 - Daily autumn energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',AM11_Dailyenergycons);

% Repeat the daily profile figures for all of autumn
AM11energy_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    AM11energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

fprintf('\n')

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% WINTER
ACDCrectifier=1; % Individual appliance recitifier
Gridrectifier=1; % Rectifier for connection from the grid
DCACinverter=1; % Inverter used for connecting to the grid
DCDCconverter=1; % DC/DC converter to change voltages

```

```

Baseload=125; % Constant load of standby appliances
ACduty=9; % A/C duty cycle. 9 minutes every 30 minutes = 30%
Ovenduty=2; % Oven duty cycle. 2 minutes every 10 minutes = 20%
HWduty=10; % Hot water duty cycle. 10 minutes every 100 minutes = 10%
Fridgeduty=7; % Fridge duty cycle. 7 minutes every 20 minutes = 35%
BFridgeduty=4; % Bar Fridge duty cycle. 4 minutes every 20 minutes = 20%

```

```
% Appliance operating times - Used defined
```

```

DWont=2200; % Dishwasher on time (hours)
Dwoffft=2359; % Dishwasher off time (hours)
ACont1=0000; % Air Conditioner on time (hours)
ACoffft1=0700; % Air Conditioner off time (hours)
ACont2=1700; % Air Conditioner on time (hours)
ACoffft2=2359; % Air Conditioner off time (hours)
WMont=2000; % Washing Machine on time (hours)
WMOfft=2130; % Washing Machine off time (hours)
Dryeront=0; % Dryer on time (hours)
Dryerofft=0; % Dryer off time (hours)
TVont1=0600; % TV on time (hours)
TVoffft1=0700; % TV off time (hours)
TVont2=1730; % TV on time (hours)
TVoffft2=2200; % TV off time (hours)
Llightsont1=0530; % Lights on time (hours)
Llightsofft1=0630; % Lights off time (hours)
Llightsont2=1700; % Lights on time (hours)
Llightsofft2=2300; % Lights off time (hours)
Hlampsont1=0545; % Heat Lamps on time (hours)
Hlampofft1=0600; % Heat Lamps off time (hours)
Hlampsont2=2230; % Heat Lamps on time (hours)
Hlampofft2=2300; % Heat Lamps off time (hours)
HWBont1=0000; % Hot Water Booster on time (hours)
HWBofft1=0100; % Hot Water Booster off time (hours)
HWBont2=2300; % Hot Water Booster on time (hours)
HWBofft2=2359; % Hot Water Booster off time (hours)
Stoveont=1730; % Stove on time (hours)
Stoveofft=1800; % Stove off time (hours)
Ovenont=1730; % Oven on time (hours)
Ovenofft=1800; % Oven off time (hours)
GameCont=2000; % Game Console on time (hours)
GameCofft=2300; % Game Console off time (hours)
Compont=1930; % Computer on time (hours)
Compofft=2300; % Computer off time (hours)

```

```
% Adjusted operating times by converting to seconds (Do not change these).
```

```

Dwon=(DWont/2400)*1sim;
Dwoff=(Dwoffft/2400)*1sim;
ACon1=(ACont1/2400)*1sim;
ACoff1=(ACoffft1/2400)*1sim;
ACon2=(ACont2/2400)*1sim;
ACoff2=(ACoffft2/2400)*1sim;
WMon=(WMont/2400)*1sim;
WMOff=(WMOfft/2400)*1sim;
Dryeron=(Dryeront/2400)*1sim;
Dryeroff=(Dryerofft/2400)*1sim;
TVon1=(TVont1/2400)*1sim;
TVoff1=(TVoffft1/2400)*1sim;
TVon2=(TVont2/2400)*1sim;

```

```

TVoff2=(TVofft2/2400)*1sim;
Lightson1=(Lightson1/2400)*1sim;
Lightsoff1=(Lightsofft1/2400)*1sim;
Lightson2=(Lightson2/2400)*1sim;
Lightsoff2=(Lightsofft2/2400)*1sim;
Hlampson1=(Hlampson1/2400)*1sim;
Hlampsoff1=(Hlampsofft1/2400)*1sim;
Hlampson2=(Hlampson2/2400)*1sim;
Hlampsoff2=(Hlampsofft2/2400)*1sim;
HWBon1=(HWBon1/2400)*1sim;
HWBoff1=(HWBofft1/2400)*1sim;
HWBon2=(HWBon2/2400)*1sim;
HWBoff2=(HWBofft2/2400)*1sim;
Stoveon=(Stoveont/2400)*1sim;
Stoveoff=(Stoveofft/2400)*1sim;
Ovenon=(Ovenont/2400)*1sim;
Ovenoff=(Ovenofft/2400)*1sim;
GameCon=(GameCont/2400)*1sim;
GameCoff=(GameCofft/2400)*1sim;
Compon=(Compont/2400)*1sim;
Compoff=(Compofft/2400)*1sim;

```

Configuration 1 AC supplied house operating with DC internal appliances. This is the base case and is assumed to be the current status of the house.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1/pf;

load_system('House_Model_Sim_minute') % Load the Simulink model
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime) % Run simulation for one day

% xaxis=(simtime/length(simtime));
% figure(1)
% plot(xaxis,Energyusage),title('Simple AC house with DC internal appliances winter
daily profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM1_Energyusage=Energyusage;
WM1_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
WM1_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
WM1_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
WM1_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
WM1_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.
%fprintf('Model 1 - AC house with DC internal appliances winter daily energy usage is
%0.2f kWh\n',WM1_Dailyenergy);

```

```

% Repeat the daily profile figures for all of winter
WM1energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM1energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

WM1_HWu=(sum(HWusage)/60)/1000;    % Daily hot water usage in kwh
WM1_ACu=(sum(ACusage)/60)/1000;    % Daily air conditioner usage in kwh
WM1_Cooku=(sum(Cookusage)/60)/1000; % Daily cooking appliance use in kwh
WM1_Lightu=(sum(Lightusage)/60)/1000; % Daily light usage in kwh
WM1_WGu=(sum(WGusage)/60)/1000;    % Daily white goods usage in kwh
WM1_Appu=(sum(Appusage)/60)/1000;  % Daily appliance usage in kwh
WM1_Baseu=BaseLoad*24/1000;        % Daily base load usage in kwh

WM1_Loadtotal=WM1_HWu+WM1_ACu+WM1_Cooku+WM1_Lightu+WM1_WGu+WM1_Appu+WM1_Baseu;

```

Configuration 2 Remove appliance AC/DC rectifiers. High level result as this assumes complete DC supply and common DC bus voltage in the house.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(2)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily profile (high
level)'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM2_Dailyenergy=sum(Energyusage)/60;    % Total daily energy usage.
WM2_Gridcons=sum(Gridusage)/60;    % Sum of positive values (energy from the grid)
WM2_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5)/60)/1000;    % Power lost in cables
WM2_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
WM2_ACDCsav=WM1_Dailyenergy-WM2_Dailyenergy;    % Appliance ACDC rectifier saving
compared to Model 1
%fprintf('Model 2 - Daily winter energy usage with appliance AC/DC rectifiers removed is
%0.2f kwh. This assumes complete DC supply and common DC voltage.\n',WM2_Dailyenergy);

% Repeat the daily profile figures for all of winter
WM2energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM2energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
end

```

Configuration 3 Remove appliance AC/DC rectifiers, resulting in a reduction in baseload by 50W. This reduction is due to eliminating standby current.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(3)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM3_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
WM3_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
WM3_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
WM3_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
WM3_ACDCsav=WM1_Dailyenergy-WM3_Dailyenergy; % Appliance ACDC rectifier saving
compared to Model 1
%WM3_Homer_Load=sum(Total_Load)/60; % Total load for use in Homer Energy on DC bus.
This includes cables losses and the removal of AC/DC rectifiers.
%fprintf('Model 3 - Daily winter energy usage with appliance AC/DC rectifiers removed,
resulting in reduced standby current, is %0.2f kWh\n',WM3_Dailyenergy);

% Repeat the daily profile figures for all of winter
WM3energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM3energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end
end

```

Configuration 4 Install central AC/DC rectifier to supply the DC home from the AC grid.

```

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

```



```

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(4)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM4_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
WM4_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
WM4_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
WM4_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
WM4_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
%fprintf('Model 4 - Daily winter energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed is %0.2f kWh\n',WM4_Dailyenergy);
%
% % Repeat the daily profile figures for all of winter
% WM4energy_min=zeros(winterlength*1440,1);
% for y=0:1:winterlength-1
% WM4energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 5 Install DC two buses. A 380V bus and a 24V bus, both supplied from the AC grid.

```

voltage1=voltage1set;
voltage2=voltage2set;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCconverterset;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '1'); % Set
solar off
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily

```

```

profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM5_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
WM5_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
WM5_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
WM5_GRloss=sum(GRloss)/60; % Grid rectifier loss
WM5_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter losses
WM5_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-WM5_DCloss_v2;
% Load consumption
WM5_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.

%fprintf('Model 5 - Daily winter energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed with a 380V and 24V buses is %.2f
kwh\n',WM5_Dailyenergy);

% Repeat the daily profile figures for all of spring
WM5energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM5energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 6 Full AC house with DC internal appliances. Install Solar onto single bus model. No profile just average daily contribution. ie: Total consumption minus total generation.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset;
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutput=PVsize*wintersolar/24; % Sets kwh figure for use over entire 24 hour
period.
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '1'); % Set Solar total as active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Profile with block solar
applied'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM6_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
WM6_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
WM6_SIloss=sum(SIloss)/60; % Solar inverter loss
WM6_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
%fprintf('Model 6 - Daily winter energy usage for AC house with solar PV installed is

```

```

%0.2f kWh. This is based on total consumption minus total generation, it does not factor
in time of day.\n',WM6_Dailyenergy);

%% Repeat the daily profile figures for all of winter
% WM6energy_min=zeros(winterlength*1440,1);
% for y=0:1:winterlength-1
%     WM6energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 7 Install Solar following winter profile onto single bus model. Solar generation follows irradiance data obtained from BOM. Solar inverter is considered the central connection between solar and house/grid.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % DC/AC inverter to connect solar to grid/installation
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*wintersolar; % Sets value for solar generation based on
average irradiance level.
powerfactor=1/pf;

Load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM7_Energyusage=Energyusage;
WM7_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
WM7_Solarexp=(sum(Solarexport)*-1)/60; % Sum of negative values (energy exported to
the grid)
WM7_Solarcons=WM7_Solargen-WM7_Solarexp; % Solar energy consumed by installation
WM7_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
WM7_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the
grid)
WM7_Dailyenergycons=WM7_Solarcons+WM7_Gridcons; % Consumption by installation
WM7_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
WM7_GRloss=sum(GRloss)/60; % Grid rectifier loss
WM7_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
WM7_SIloss=sum(SIloss)/60; % Energy lost in solar inverter
WM7_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption

```

```

%fprintf('Model 7 - Daily winter energy usage for AC house with solar PV installed is
%0.2f kWh.\n',WM7_Dailyenergycons);

% % Repeat the daily profile figures for all of winter
% WM7energy_min=zeros(winterlength*1440,1);
% for y=0:1:winterlength-1
%     WM7energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 8 Install two buses. A 380V bus and a 24V bus. Solar connected to 380V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCinverterset;
Solarinverter=SolarMPPTset; % DC/DC converter / MPPT
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

WM8_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
WM8_Solarexp=(sum(Solarexp)*-1)/60; % Sum of negative values (energy exported to the
grid)
WM8_Solarcons=WM8_Solargen-WM8_Solarexp;
WM8_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the grid)
WM8_Dailyenergycons=WM8_Solarcons+WM8_Gridcons;
WM8_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
WM8_GRloss=sum(GRloss)/60; % Grid rectifier loss
WM8_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
WM8_SIloss=sum(SIloss)/60; % Solar inverter loss
WM8_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter on v2 loss
WM8_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-WM8_DCloss_v2;
% Load consumption
%WM8_Homer_Load=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.

```

```

%fprintf('Model 8 - Daily winter energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',WM8_Dailyenergycons);

% Repeat the daily profile figures for all of winter
WM8energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM8energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

### Configuration 9 Install solar and battery storage on single bus model.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % Treated as DC/AC inverter + battery charger efficiency
Battconv=Battconvdcac;
Battcc=Battchargecorr;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*wintersolar;
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '0'); % Set Grid connection to off
set_param('House_Model_Sim_minute/Battery switch', 'sw', '0'); % Set battery on
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

WM9_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
WM9_Solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to the
grid)
WM9_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
WM9_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
WM9_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
WM9_Battcons=Battini+(max(Battusage))/60; % Energy used from battery
WM9_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
WM9_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
WM9_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
WM9_SILoss=sum(SILoss)/60; % Solar inverter loss
WM9_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
WM9_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
WM9_Solarcons=WM9_Solargen-WM9_Solarexp; % Solar energy consumed by installation
WM9_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
WM9_SOC=Battsoc; % Battery state of charge

```

```

WM9_Dailyenergycons=WM9_Solarcons+WM9_Gridcons;
%fprintf('Model 9 - Daily winter energy usage for AC house with solar PV + batteries
installed is %0.2f kWh.\n',WM9_Dailyenergycons);

% % Repeat the daily profile figures for all of winter
% WM9energy_min=zeros(winterlength*1440,1);
% for y=0:1:winterlength-1
%     WM9energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 10 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 380V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCinverterset;
Solarinverter=SolarMPPTset;
Battconv=Battconvdc;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

Load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM10_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
WM10_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
WM10_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
WM10_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
WM10_Solarexp=(sum(Solareport2)*-1)/60; % Sum of negative values (energy exported to
the grid)
WM10_Solarcons=WM10_Solargen-WM10_Solarexp;
WM10_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7))/60/1000; % Power lost in cables
WM10_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
WM10_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
WM10_SILoss=sum(SILoss)/60; % Solar inverter loss
WM10_DCloss_v2=sum(DCloss_v2)/60; % DC/DC conveter loos on v2
WM10_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one

```

```

way batt efficiency + converter.
WM10_Battchargetloss=sum(Battchargetloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
WM10_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
WM10_DCloss_v2; % Load consumption
WM10_HomerLoad=sum(Total_Load)/60; % Total load including Cable loasses and DC/DC
converter. For attaching to DC bus in Homer energy. COmmon 380V bus.
WM10_SOC=Battsoc; % Battery state of charge
WM10_Dailyenergycons=WM10_Solarcons+WM10_Gridcons;
%fprintf('Model 10 - Daily winter energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',WM10_Dailyenergycons);

% Repeat the daily profile figures for all of winter
WM10energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM10energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 11 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 24V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=DCDCconverterset;
DCDCconverter_v2=1;
Solarinverter=SolarMPPTset;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

WM11_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
WM11_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
WM11_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
WM11_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
WM11_Solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to

```

```

the grid)
WM11_Solarcons=WM11_Solargen-WM11_Solarexp;
WM11_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
WM11_GRloss=sum(GRloss2)/60; % Grid rectifier loss
WM11_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
WM11_SIloss=sum(SIloss)/60; % Solar inverter loss
WM11_DCloss_v1=sum(DCloss_v1)/60; % DC/DC converter loss
WM11_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
WM11_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
WM11_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
WM11_DCloss_v1; % Load consumption
WM11_HomerLoad=sum(Total_Load)/60; % Total load including Cable loasses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 24V bus.
WM11_SOC=Battsoc; % Battery state of charge
WM11_Dailyenergycons=WM11_Solarcons+WM11_Gridcons;
%fprintf('Model 11 - Daily winter energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',WM11_Dailyenergycons);

% Repeat the daily profile figures for all of winter
WM11energy_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WM11energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

fprintf('\n')

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% SPRING

```

```

ACDCrectifier=1; % Individual appliance recitifier
Gridrectifier=1; % Rectifier for connection from the grid
DCACinverter=1; % Inverter used for connecting to the grid
DCDCconverter=1; % DC/DC converter to change voltages
Baseload=125; % Constant load of standby appliances
ACduty=9; % A/C duty cycle. 9 mintures every 30 minutes = 30%
Ovenduty=2; % Oven duty cycle. 2 minutes every 10 minutes = 20%
HWduty=8; % Hot water duty cycle. 8 mintues every 100 minutes = 8%
Fridgeduty=7 ; % Fridge duty cycle. 7 minutes every 20 minutes = 35%
BFridgeduty=4; % Bar Fridge duty cycle. 4 mintues every 20 minutes = 20%

```

```

% Appliance operating times - Used defined

```

```

DWont=2200; % Dishwasher on time (hours)
DWOft=2359; % Dishwasher off time (hours)
ACont1=0000; % Air Conditioner on time (hours)
ACoft1=0000; % Air Conditioner off time (hours)
ACont2=1700; % Air Conditioner on time (hours)
ACoft2=2200; % Air Conditioner off time (hours)
WMont=2000; % Washing Machine on time (hours)
WMOft=2130; % Washing Machine off time (hours)
Dryeront=0; % Dryer on time (hours)
Dryerofft=0; % Dryer off time (hours)
TVont1=0600; % TV on time (hours)

```



```

TVofft1=0700; % TV off time (hours)
TVont2=1730; % TV on time (hours)
TVofft2=2200; % TV off time (hours)
Llightsont1=0530; % Lights on time (hours)
Llightsofft1=0630; % Lights off time (hours)
Llightsont2=1800; % Lights on time (hours)
Llightsofft2=2300; % Lights off time (hours)
Hlampsont1=0545; % Heat Lamps on time (hours)
Hlampofft1=0600; % Heat Lamps off time (hours)
Hlampsont2=2245; % Heat Lamps on time (hours)
Hlampofft2=2300; % Heat Lamps off time (hours)
HWBont1=0000; % Hot Water Booster on time (hours)
HWBofft1=0100; % Hot Water Booster off time (hours)
HWBont2=2300; % Hot Water Booster on time (hours)
HWBofft2=2359; % Hot Water Booster off time (hours)
Stoveont=1730; % Stove on time (hours)
Stoveofft=1800; % Stove off time (hours)
Ovenont=1730; % Oven on time (hours)
Ovenofft=1800; % Oven off time (hours)
GameCont=2000; % Game Console on time (hours)
GameCofft=2300; % Game Console off time (hours)
Compont=1930; % Computer on time (hours)
Compofft=2300; % Computer off time (hours)

% Adjusted operating times by converting to seconds (Do not change these).
Dwon=(Dwont/2400)*1sim;
Dwoff=(Dwofft/2400)*1sim;
ACon1=(ACont1/2400)*1sim;
ACoff1=(ACofft1/2400)*1sim;
ACon2=(ACont2/2400)*1sim;
ACoff2=(ACofft2/2400)*1sim;
WMon=(WMont/2400)*1sim;
WMOff=(WMOfft/2400)*1sim;
Dryeron=(Dryeront/2400)*1sim;
Dryeroff=(Dryerofft/2400)*1sim;
TVon1=(TVont1/2400)*1sim;
TVoff1=(TVofft1/2400)*1sim;
TVon2=(TVont2/2400)*1sim;
TVoff2=(TVofft2/2400)*1sim;
Llightson1=(Llightsont1/2400)*1sim;
Llightsoff1=(Llightsofft1/2400)*1sim;
Llightson2=(Llightsont2/2400)*1sim;
Llightsoff2=(Llightsofft2/2400)*1sim;
Hlampson1=(Hlampsont1/2400)*1sim;
Hlampsoff1=(Hlampofft1/2400)*1sim;
Hlampson2=(Hlampsont2/2400)*1sim;
Hlampsoff2=(Hlampofft2/2400)*1sim;
HWBon1=(HWBont1/2400)*1sim;
HWBoff1=(HWBofft1/2400)*1sim;
HWBon2=(HWBont2/2400)*1sim;
HWBoff2=(HWBofft2/2400)*1sim;
Stoveon=(Stoveont/2400)*1sim;
Stoveoff=(Stoveofft/2400)*1sim;
Ovenon=(Ovenont/2400)*1sim;
Ovenoff=(Ovenofft/2400)*1sim;
GameCon=(GameCont/2400)*1sim;
GameCoff=(GameCofft/2400)*1sim;

```

```
Compon=(Compont/2400)*1sim;
Compoff=(Compofft/2400)*1sim;
```

Configuration 1 AC supplied house operating with DC internal appliances. This is the base case and is assumed to be the current status of the house.

```
Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1/pf;

load_system('House_Model_Sim_minute') % Load the Simulink model
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime) % Run simulation for one day

% xaxis=(simtime/length(simtime));
% figure(1)
% plot(xaxis,Energyusage),title('Simple AC house with DC internal appliances spring
daily profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM1_Energyusage=Energyusage;
SM1_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SM1_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
SM1_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
SM1_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
SM1_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.
fprintf('Model 1 - AC house with DC internal appliances spring daily energy usage is
%0.2f kWh\n',SM1_Dailyenergy);

% Repeat the daily profile figures for all of spring
SM1energy_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SM1energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

SM1_HWu=(sum(HWusage)/60)/1000; % Daily hot water usage in kwh
SM1_ACu=(sum(ACusage)/60)/1000; % Daily air conditioner usage in kwh
SM1_Cooku=(sum(Cookusage)/60)/1000; % Daily cooking appliance use in kwh
SM1_Lightu=(sum(Lightusage)/60)/1000; % Daily light usage in kwh
SM1_WGu=(sum(WGusage)/60)/1000; % Daily white goods usage in kwh
SM1_Appu=(sum(Appusage)/60)/1000; % Daily appliance usage in kwh
SM1_Baseu=BaseLoad*24/1000; % Daily base load usage in kwh

SM1_Loadtotal=SM1_HWu+SM1_ACu+SM1_Cooku+SM1_Lightu+SM1_WGu+SM1_Appu+SM1_Baseu;
```

Configuration 2 Remove appliance AC/DC rectifiers. High level result as this assumes complete DC supply and common DC bus voltage in the house.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(2)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily profile (high
level)'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM2_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SM2_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
SM2_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5)/60)/1000; % Power lost in cables
SM2_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
SM2_ACDCsav=SM1_Dailyenergy-SM2_Dailyenergy; % Appliance ACDC rectifier saving
compared to Model 1
fprintf('Model 2 - Daily spring energy usage with appliance AC/DC rectifiers removed is
%0.2f kWh. This assumes complete DC supply and common DC voltage.\n',SM2_Dailyenergy);

% Repeat the daily profile figures for all of spring
SM2energy_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SM2energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
end

```

Configuration 3 Remove appliance AC/DC rectifiers, resulting in a reduction in baseload by 50W. This reduction is due to eliminating standby current.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off

```

```

set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(3)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM3_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SM3_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
SM3_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
SM3_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
SM3_ACDCsav=SM1_Dailyenergy-SM3_Dailyenergy; % Appliance ACDC rectifier saving
compared to Model 1
%SM3_Homer_Load=sum(Total_Load)/60; % Total load for use in Homer Energy on DC bus.
This includes cables losses and the removal of AC/DC rectifiers.
%fprintf('Model 3 - Daily spring energy usage with appliance AC/DC rectifiers removed,
resulting in reduced standby current, is %0.2f kWh\n',SM3_Dailyenergy);

% Repeat the daily profile figures for all of spring
SM3energy_min=zeros(springleth*1440,1);
for y=0:1:springleth-1
    SM3energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 4 Install central AC/DC rectifier to supply the DC home from the AC grid.

```

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(4)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM4_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SM4_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
SM4_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
SM4_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
SM4_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load

```

```

consumption
%fprintf('Model 4 - Daily spring energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed is %0.2f kWh\n',SM4_Dailyenergy);
%
%% Repeat the daily profile figures for all of spring
% SM4energy_min=zeros(springleth*1440,1);
% for y=0:1:springleth-1
%     SM4energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 5 Install DC two buses. A 380V bus and a 24V bus, both supplied from the AC grid.

```

voltage1=voltage1set;
voltage2=voltage2set;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCconverterset;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

Load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '1'); % Set
solar off
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM5_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SM5_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
SM5_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
SM5_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
SM5_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter losses
SM5_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-SM5_DCloss_v2;
% Load consumption
SM5_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.

%fprintf('Model 5 - Daily spring energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed with a 380V and 24V buses is %0.2f
kWh\n',SM5_Dailyenergy);

%% Repeat the daily profile figures for all of spring

```

```

SM5energy_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SM5energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 6 Full AC house with DC internal appliances. Install Solar onto single bus model. No profile just average daily contribution. ie: Total consumption minus total generation.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset;
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutput=PVsize*Springsolar/24; % Sets kwh figure for use over entire 24 hour
period.
powerfactor=1/pf;

Load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '1'); % Set Solar total as active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Profile with block solar
applied'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM6_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SM6_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
SM6_SIloss=sum(SIloss)/60; % Solar inverter loss
SM6_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
%fprintf('Model 6 - Daily spring energy usage for AC house with solar PV installed is
%0.2f kWh. This is based on total consumption minus total generation, it does not factor
in time of day.\n',SM6_Dailyenergy);

% % Repeat the daily profile figures for all of spring
% SM6energy_min=zeros(springlength*1440,1);
% for y=0:1:springlength-1
%     SM6energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 7 Install Solar following spring profile onto single bus model. Solar generation follows irradiance data obtained from BOM. Solar inverter is considered the central connection between solar and house/grid.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % DC/AC inverter to connect solar to grid/installation
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*springsolar; % Sets value for solar generation based on
average irradiance level.
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

SM7_Energyusage=Energyusage;
SM7_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
SM7_Solarexp=(sum(Solareport)*-1)/60; % Sum of negative values (energy exported to
the grid)
SM7_Solarcons=SM7_Solargen-SM7_Solarexp; % Solar energy consumed by installation
SM7_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
SM7_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the
grid)
SM7_Dailyenergycons=SM7_Solarcons+SM7_Gridcons; % Consumption by installation
SM7_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
SM7_GRloss=sum(GRloss)/60; % Grid rectifier loss
SM7_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
SM7_SIloss=sum(SIloss)/60; % Energy lost in solar inverter
SM7_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
fprintf('Model 7 - Daily spring energy usage for AC house with solar PV installed is
%0.2f kWh.\n',SM7_Dailyenergycons);

% % Repeat the daily profile figures for all of spring
% SM7energy_min=zeros(springlength*1440,1);
% for y=0:1:springlength-1
% SM7energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 8 Install two buses. A 380V bus and a 24V bus. Solar connected to 380V bus.

```

voltage1=380;
voltage2=24;

```

```

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCconverterset;
Solarinverter=SolarMPPTset; % DC/DC converter / MPPT
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHMM')

SM8_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
SM8_Solarexp=(sum(Solarexport)*-1)/60; % Sum of negative values (energy exported to the
grid)
SM8_Solarcons=SM8_Solargen-SM8_Solarexp;
SM8_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the grid)
SM8_Dailyenergycons=SM8_Solarcons+SM8_Gridcons;
SM8_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7))/60/1000; % Power lost in cables
SM8_GRloss=sum(GRloss)/60; % Grid rectifier loss
SM8_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
SM8_SIlloss=sum(SIlloss)/60; % Solar inverter loss
SM8_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter on v2 loss
SM8_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-SM8_DCloss_v2;
% Load consumption
%SM8_Homer_Load=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.
%fprintf('Model 8 - Daily spring energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',SM8_Dailyenergycons);

% Repeat the daily profile figures for all of spring
SM8energy_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SM8energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 9 Install solar and battery storage on single bus model.

```

Apprectifier=1;
Gridrectifier=1;

```



```

DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % Treated as DC/AC inverter + battery charger efficiency
Battconv=Battconvdcac;
Battcc=Battchargecorr;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*springsolar;
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '0'); % Set Grid connection to off
set_param('House_Model_Sim_minute/Battery switch', 'sw', '0'); % Set battery on
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

SM9_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
SM9_Solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to the
grid)
SM9_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
SM9_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
SM9_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
SM9_Battcons=Battini+(max(Battusage))/60; % Energy used from battery
SM9_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
SM9_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
SM9_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
SM9_SILoss=sum(SILoss)/60; % Solar inverter loss
SM9_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
SM9_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
SM9_Solarcons=SM9_Solargen-SM9_Solarexp; % Solar energy consumed by model
SM9_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
SM9_SOC=Battsoc; % Battery state of charge
SM9_Dailyenergycons=SM9_Solarcons+SM9_Gridcons;
%fprintf('Model 9 - Daily spring energy usage for AC house with solar PV + batteries
installed is %0.2f kWh.\n',SM9_Dailyenergycons);

% % Repeat the daily profile figures for all of spring
% SM9energy_min=zeros(springlength*1440,1);
% for y=0:1:springlength-1
% SM9energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 10 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 380V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCconverterset;
Solarinverter=SolarMPPTset;
Battconv=Battconvdc;
Battcc=1;
Baseload=75;    % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM10_solargen=(sum(Gen_Solar))/60;    % Solar energy generated
SM10_Gridcons=(sum(Gridusage2))/60;    % Sum of positive values (energy from the grid)
SM10_Battchar=(Battini+(min(Battcharging)/60))*(-1);    % Energy used to charge battery
SM10_Battcons=Battini+(max(Battusage))/60;    % Energy used from battery
SM10_solarexp=(sum(Solarexport2)*-1)/60;    % Sum of negative values (energy exported to
the grid)
SM10_solarcons=SM10_solargen-SM10_solarexp;
SM10_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7))/60)/1000;    % Power lost in cables
SM10_Gridloss=sum(Gridloss2)/60;    % Grid rectifier loss
SM10_DCACloss=sum(DCACloss2)/60;    % DC/AC inverter loss
SM10_SILoss=sum(SILoss)/60;    % Solar inverter loss
SM10_DCloss_v2=sum(DCloss_v2)/60;    % DC/DC converter loss on v2
SM10_Battuseloss=sum(Battuseloss)/60;    % Loss from discharge of battery, includes one
way batt efficiency + converter.
SM10_BattchargeLoss=sum(BattchargeLoss)/60;    % Loss from charge of battery. This is the
one way batt efficiency.
SM10_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
SM10_DCloss_v2;    % Load consumption
SM10_HomerLoad=sum(Total_Load)/60;    % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.
SM10_SOC=Battsoc;    % Battery state of charge
SM10_Dailyenergycons=SM10_solarcons+SM10_Gridcons;
%fprintf('Model 10 - Daily spring energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',SM10_Dailyenergycons);

% Repeat the daily profile figures for all of spring

```

```

SM10energy_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SM10energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 11 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 24V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=DCDCconverterset;
DCDCconverter_v2=1;
Solarinverter=SolarMPPTset;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

Load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SM11_solargen=(sum(Gen_Solar))/60; % Solar energy generated
SM11_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
SM11_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
SM11_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
SM11_solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to
the grid)
SM11_solarcons=SM11_solargen-SM11_solarexp;
SM11_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
SM11_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
SM11_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
SM11_SILoss=sum(SILoss)/60; % Solar inverter loss
SM11_DCloss_v1=sum(DCloss_v1)/60; % DC/DC converter loss
SM11_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
SM11_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
SM11_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
SM11_DCloss_v1; % Load consumption

```

```

SM11_HomerLoad=sum(Total_Load)/60; % Total load including Cable loasses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 24V bus.
SM11_SOC=Battsoc; % Battery state of charge
SM11_Dailyenergycons=SM11_Solarcons+SM11_Gridcons;
%fprintf('Model 11 - Daily spring energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',SM11_Dailyenergycons);

% Repeat the daily profile figures for all of spring
SM11energy_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SM11energy_min(y*1440+1:(y+1)*1440)=Total_Load(:);
end

fprintf('\n')

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% SUMMER

```

```

ACDCrectifier=1; % Individual appliance recitifier
Gridrectifier=1; % Rectifier for connection from the grid
DCACinverter=1; % Inverter used for connecting to the grid
DCDCconverter=1; % DC/DC converter to change voltages
Baseload=125; % Constant load of standby appliances
ACduty=9; % A/C duty cycle. 9 mintures every 30 minutes = 30%
Ovenduty=2; % Oven duty cycle. 2 minutes every 10 minutes = 20%
HWduty=6; % Hot water duty cycle. 6 mintues every 100 minutes = 6%
Fridgeduty=7 ; % Fridge duty cycle. 7 minutes every 20 minutes = 35%
BFridgeduty=4; % Bar Fridge duty cycle. 4 mintues every 20 minutes = 20%

```

```

% Appliance operating times - Used defined

```

```

DWont=2200; % Dishwasher on time (hours)
Dwofft=2359; % Dishwasher off time (hours)
ACont1=0000; % Air Conditioner on time (hours)
ACofft1=0700; % Air Conditioner off time (hours)
ACont2=1700; % Air Conditioner on time (hours)
ACofft2=2359; % Air Conditioner off time (hours)
WMont=2000; % Washing Machine on time (hours)
WMOfft=2130; % Washing Machine off time (hours)
Dryeront=0; % Dryer on time (hours)
Dryerofft=0; % Dryer off time (hours)
TVont1=0600; % TV on time (hours)
TVofft1=0700; % TV off time (hours)
TVont2=1730; % TV on time (hours)
TVofft2=2200; % TV off time (hours)
Llightsont1=0530; % Lights on time (hours)
Llightsofft1=0630; % Lights off time (hours)
Llightsont2=1900; % Lights on time (hours)
Llightsofft2=2300; % Lights off time (hours)
Hlampsont1=0000; % Heat Lamps on time (hours)
Hlampsofft1=0000; % Heat Lamps off time (hours)
Hlampsont2=0000; % Heat Lamps on time (hours)
Hlampsofft2=0000; % Heat Lamps off time (hours)
HWBont1=0000; % Hot Water Booster on time (hours)
HWBofft1=0100; % Hot Water Booster off time (hours)

```

```

HWBont2=2300;      % Hot Water Booster on time (hours)
HWBofft2=2359;    % Hot Water Booster off time (hours)
Stoveont=1730;    % Stove on time (hours)
Stoveofft=1800;   % Stove off time (hours)
Ovenont=1745;     % Oven on time (hours)
Ovenofft=1800;    % Oven off time (hours)
GameCont=2000;    % Game Console on time (hours)
GameCofft=2300;   % Game Console off time (hours)
Compont=1930;     % Computer on time (hours)
Compofft=2300;    % Computer off time (hours)

% Adjusted operating times by converting to seconds (Do not change these).
Dwon=(Dwont/2400)*1sim;
Dwoff=(Dwofft/2400)*1sim;
ACon1=(ACont1/2400)*1sim;
ACoff1=(ACofft1/2400)*1sim;
ACon2=(ACont2/2400)*1sim;
ACoff2=(ACofft2/2400)*1sim;
WMon=(WMont/2400)*1sim;
WMOff=(WMOfft/2400)*1sim;
Dryeron=(Dryeront/2400)*1sim;
Dryeroff=(Dryerofft/2400)*1sim;
TVon1=(TVont1/2400)*1sim;
TVoff1=(TVofft1/2400)*1sim;
TVon2=(TVont2/2400)*1sim;
TVoff2=(TVofft2/2400)*1sim;
Llightson1=(Llightson1/2400)*1sim;
Llightsoff1=(Llightsofft1/2400)*1sim;
Llightson2=(Llightson2/2400)*1sim;
Llightsoff2=(Llightsofft2/2400)*1sim;
Hlampson1=(Hlampson1/2400)*1sim;
Hlampsoff1=(Hlampsofft1/2400)*1sim;
Hlampson2=(Hlampson2/2400)*1sim;
Hlampsoff2=(Hlampsofft2/2400)*1sim;
HWBon1=(HWBont1/2400)*1sim;
HWBoff1=(HWBofft1/2400)*1sim;
HWBon2=(HWBont2/2400)*1sim;
HWBoff2=(HWBofft2/2400)*1sim;
Stoveon=(Stoveont/2400)*1sim;
Stoveoff=(Stoveofft/2400)*1sim;
Ovenon=(Ovenont/2400)*1sim;
Ovenoff=(Ovenofft/2400)*1sim;
GameCon=(GameCont/2400)*1sim;
GameCoff=(GameCofft/2400)*1sim;
Compon=(Compont/2400)*1sim;
Compoff=(Compofft/2400)*1sim;

```

Configuration 1 AC supplied house operating with DC internal appliances. This is the base case and is assumed to be the current status of the house.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;

```

```

Battconv=1;
Battcc=1;
powerfactor=1/pf;

load_system('House_Model_Sim_minute') % Load the Simulink model
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime) % Run simulation for one day

% xaxis=(simtime/length(simtime));
% figure(1)
% plot(xaxis,Energyusage),title('Simple AC house with DC internal appliances summer
daily profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum1_Energyusage=Energyusage;
Sum1_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
Sum1_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
Sum1_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
Sum1_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
Sum1_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.
fprintf('Model 1 - AC house with DC internal appliances summer daily energy usage is
%0.2f kWh\n',Sum1_Dailyenergy);

% Repeat the daily profile figures for January and February
Sum1energy_min_JanFeb=zeros(JanFeblength*1440,1);
for y=0:1:JanFeblength-1
    Sum1energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
Sum1energy_min_Dec=zeros(Declength*1440,1);
for y=0:1:Declength-1
    Sum1energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

Sum1_HWu=(sum(HWusage)/60)/1000; % Daily hot water usage in kwh
Sum1_ACu=(sum(ACusage)/60)/1000; % Daily air conditioner usage in kwh
Sum1_Cooku=(sum(Cookusage)/60)/1000; % Daily cooking appliance use in kwh
Sum1_Lightu=(sum(Lightusage)/60)/1000; % Daily light usage in kwh
Sum1_WGu=(sum(WGusage)/60)/1000; % Daily white goods usage in kwh
Sum1_Appu=(sum(Appusage)/60)/1000; % Daily appliance usage in kwh
Sum1_Baseu=BaseLoad*24/1000; % Daily base load usage in kwh

Sum1_Loadtotal=Sum1_HWu+Sum1_ACu+Sum1_Cooku+Sum1_Lightu+Sum1_WGu+Sum1_Appu+Sum1_Baseu;

```

Configuration 2 Remove appliance AC/DC rectifiers. High level result as this assumes complete DC supply and common DC bus voltage in the house.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;

```

```

Solarinverter=1;
Battconv=1;
Battcc=1;
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(2)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily profile (high
level)'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum2_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
Sum2_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
Sum2_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5)/60)/1000; % Power lost in cables
Sum2_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
Sum2_ACDCsav=Sum1_Dailyenergy-Sum2_Dailyenergy; % Appliance ACDC rectifier saving
compared to Model 1
%fprintf('Model 2 - Daily summer energy usage with appliance AC/DC rectifiers removed is
%0.2f kWh. This assumes complete DC supply and common DC voltage.\n',Sum2_Dailyenergy);

% Repeat the daily profile figures for January and February
Sum2energy_min_JanFeb=zeros(JanFeblength*1440,1);
for y=0:1:JanFeblength-1
    Sum2energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
Sum2energy_min_Dec=zeros(Declength*1440,1);
for y=0:1:Declength-1
    Sum2energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 3 Remove appliance AC/DC rectifiers, resulting in a reduction in baseload by 50W. This reduction is due to eliminating standby current.

```

Apprectifier=Apprectifierset;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

```

```

% xaxis=(simtime/length(simtime));
% figure(3)
% plot(xaxis,Energyusage),title('AC/DC appliance rectifiers removed daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum3_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
Sum3_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
Sum3_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
Sum3_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
Sum3_ACDCsav=Sum1_Dailyenergy-Sum3_Dailyenergy; % Appliance ACDC rectifier saving
compared to Model 1
%Sum3_Homer_Load=sum(Total_Load)/60; % Total load for use in Homer Energy on DC bus.
This includes cables losses and the removal of AC/DC rectifiers.
%fprintf('Model 3 - Daily summer energy usage with appliance AC/DC rectifiers removed,
resulting in reduced standby current, is %0.2f kWh\n',Sum3_Dailyenergy);

% Repeat the daily profile figures for January and February
Sum3energy_min_JanFeb=zeros(JanFeblength*1440,1);
for y=0:1:JanFeblength-1
    Sum3energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
Sum3energy_min_Dec=zeros(Declength*1440,1);
for y=0:1:Declength-1
    Sum3energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 4 Install central AC/DC rectifier to supply the DC home from the AC grid.

```

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.
powerfactor=1;

set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '1'); % Set Solar off
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(4)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum4_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.

```



```

Sum4_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
Sum4_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
Sum4_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
Sum4_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
fprintf('Model 4 - Daily summer energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed is %0.2f kWh\n',Sum4_Dailyenergy);
%
% % Repeat the daily profile figures for all of summer
% Sum4energy_min=zeros(summerlength*1440,1);
% for y=0:1:summerlength-1
%     Sum4energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 5 Install DC two buses. A 380V bus and a 24V bus, both supplied from the AC grid.

```

voltage1=voltage1set;
voltage2=voltage2set;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCconverterset;
Solarinverter=1;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '1'); % Set
solar off
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum5_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
Sum5_Gridcons=sum(Gridusage)/60; % Sum of positive values (energy from the grid)
Sum5_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
Sum5_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
Sum5_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter losses
Sum5_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
Sum5_DCloss_v2; % Load consumption
Sum5_HomerLoad=sum(Total_Load)/60; % Total load for use in Homer Energy on AC bus. This
includes cables losses and appliance AC/DC rectifier losses.
fprintf('Model 5 - Daily summer energy usage with appliance AC/DC rectifiers removed
and central AC/DC rectifier installed with a 380V and 24V buses is %0.2f

```

```

kwh\n',SuM5_Dailyenergy);

% Repeat the daily profile figures for January and February
SuM5energy_min_JanFeb=zeros(JanFeblength*1440,1);
for y=0:1:JanFeblength-1
    SuM5energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
SuM5energy_min_Dec=zeros(Declength*1440,1);
for y=0:1:Declength-1
    SuM5energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 6 Full AC house with DC internal appliances. Install Solar onto single bus model. No profile just average daily contribution. ie: Total consumption minus total generation.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset;
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutput=PVsize*Summersolar/24; % Sets kwh figure for use over entire 24 hour
period.
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '1'); % Set Solar total as active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Profile with block solar
applied'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

SuM6_Dailyenergy=sum(Energyusage)/60; % Total daily energy usage.
SuM6_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
SuM6_SIloss=sum(SIloss)/60; % Solar inverter loss
SuM6_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
fprintf('Model 6 - Daily summer energy usage for AC house with solar PV installed is
%0.2f kwh. This is based on total consumption minus total generation, it does not factor
in time of day.\n',SuM6_Dailyenergy);

% % Repeat the daily profile figures for all of summer
% SuM6energy_min=zeros(summerlength*1440,1);
% for y=0:1:summerlength-1

```

```

% Sum6energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 7 Install Solar following summer profile onto single bus model. Solar generation follows irradiance data obtained from BOM. Solar inverter is considered the central connection between solar and house/grid.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % DC/AC inverter to connect solar to grid/installation
Battconv=1;
Battcc=1;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*summersolar; % Sets value for solar generation based on
average irradiance level.
powerfactor=1/pf;

Load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '1'); % Set Grid connection to on
set_param('House_Model_Sim_minute/Battery switch', 'sw', '1'); % Set battery off
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum7_Energyusage=Energyusage;
Sum7_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
Sum7_Solarexp=(sum(Solarexport)*-1)/60; % Sum of negative values (energy exported to
the grid)
Sum7_Solarcons=Sum7_Solargen-Sum7_Solarexp; % solar energy consumed by installation
Sum7_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
Sum7_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the
grid)
Sum7_Dailyenergycons=Sum7_Solarcons+Sum7_Gridcons; % Consumption by installation
Sum7_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Energy lost in cables
Sum7_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
Sum7_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
Sum7_SILoss=sum(SILoss)/60; % Energy lost in solar inverter
Sum7_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
fprintf('Model 7 - Daily summer energy usage for AC house with solar PV installed is
%0.2f kWh.\n',Sum7_Dailyenergycons);

% % Repeat the daily profile figures for all of summer
% Sum7energy_min=zeros(summerlength*1440,1);
% for y=0:1:summerlength-1

```

```
% Sum7energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end
```

Configuration 8 Install two buses. A 380V bus and a 24V bus. Solar connected to 380V bus.

```
voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCinverterset;
Solarinverter=SolarMPPTset; % DC/DC converter / MPPT
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '1'); % Set Grid
connection to on
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '1'); % Set
battery off
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum8_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
Sum8_Solarexp=(sum(Solarexpert)*-1)/60; % Sum of negative values (energy exported to the
grid)
Sum8_Solarcons=Sum8_Solargen-Sum8_Solarexp;
Sum8_Gridcons=(sum(Gridusage))/60; % Sum of positive values (energy from the grid)
Sum8_Dailyenergycons=Sum8_Solarcons+Sum8_Gridcons;
Sum8_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7))/60)/1000; % Power lost in cables
Sum8_Gridloss=sum(Gridloss)/60; % Grid rectifier loss
Sum8_DCACloss=sum(DCACloss)/60; % DC/AC inverter loss
Sum8_SILoss=sum(SILoss)/60; % Solar inverter loss
Sum8_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter on v2 loss
Sum8_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
Sum8_DCloss_v2; % Load consumption
%Sum8_Homer_Load=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.
%fprintf('Model 8 - Daily summer energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',Sum8_Dailyenergycons);

% Repeat the daily profile figures for January and February
Sum8energy_min_JanFeb=zeros(summerlength*1440,1);
for y=0:1:59-1
```

```

Sum8energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
Sum8energy_min_Dec=zeros(summerlength*1440,1);
for y=0:1:31-1
    Sum8energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 9 Install solar and battery storage on single bus model.

```

Apprectifier=1;
Gridrectifier=1;
DCACinverter=1;
DCDCconverter_v1=1;
DCDCconverter_v2=1;
Solarinverter=Solarinverterset; % Treated as DC/AC inverter + battery charger efficiency
Battconv=Battconvdcac;
Battcc=Battchargecorr;
Baseload=125;
Solaroutputprofile(:,2)=PVsize*summersolar;
powerfactor=1/pf;

load_system('House_Model_Sim_minute')
set_param('House_Model_Sim_minute/AirCon Switch', 'sw', '0'); % Set A/C on
set_param('House_Model_Sim_minute/Solar switch', 'sw', '0'); % Set Solar on
set_param('House_Model_Sim_minute/Solar type', 'sw', '0'); % Set Solar profile as
active
set_param('House_Model_Sim_minute/Grid switch', 'sw', '0'); % Set Grid connection to off
set_param('House_Model_Sim_minute/Battery switch', 'sw', '0'); % Set battery on
sim('House_Model_Sim_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(100)
% plot(xaxis,Energyusage),title('Profile with minute solar
data'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

Sum9_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
Sum9_Solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to
the grid)
Sum9_Solarcableloss=(sum(CL6)/60)/1000; % Energy lost in cables between panels and
inverter.
Sum9_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
Sum9_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
Sum9_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
Sum9_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000; % Power lost in cables
Sum9_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
Sum9_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
Sum9_SILoss=sum(SILoss)/60; % Solar inverter loss
Sum9_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
Sum9_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
Sum9_Solarcons=Sum9_Solargen-Sum9_Solarexp; % Solar energy consumed by the installation
Sum9_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5)/60)/1000); % Load
consumption
Sum9_SOC=Battsoc; % Battery state of charge

```

```

Sum9_Dailyenergycons=Sum9_Solarcons+Sum9_Gridcons;
%fprintf('Model 9 - Daily summer energy usage for AC house with solar PV + batteries
installed is %0.2f kWh.\n',Sum9_Dailyenergycons);

% % Repeat the daily profile figures for all of summer
% Sum9energy_min=zeros(summerlength*1440,1);
% for y=0:1:summerlength-1
%     Sum9energy_min(y*1440+1:(y+1)*1440)=Energyusage(:);
% end

```

Configuration 10 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 380V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=1;
DCDCconverter_v2=DCDCinverterset;
Solarinverter=SolarMPPTset;
Battconv=Battconvdc;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

Load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

Sum10_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
Sum10_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
Sum10_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
Sum10_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
Sum10_Solarexp=(sum(Solareport2)*-1)/60; % Sum of negative values (energy exported to
the grid)
Sum10_Solarcons=Sum10_Solargen-Sum10_Solarexp;
Sum10_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7))/60)/1000; % Power lost in cables
Sum10_Gridloss=sum(Gridloss2)/60; % Grid rectifier loss
Sum10_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
Sum10_SILoss=sum(SILoss)/60; % Solar inverter loss
Sum10_DCloss_v2=sum(DCloss_v2)/60; % DC/DC converter loss on v2
Sum10_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one

```

```

way batt efficiency + converter.
Sum10_BattchargeLoss=sum(BattchargeLoss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
Sum10_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
Sum10_DCloss_v2; % Load consumption
Sum10_HomerLoad=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 380V bus.
Sum10_SOC=Battsoc; % Battery state of charge
Sum10_Dailyenergycons=Sum10_Solarcons+Sum10_Gridcons;
%fprintf('Model 10 - Daily summer energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',Sum10_Dailyenergycons);

% Repeat the daily profile figures for January and February
Sum10energy_min_JanFeb=zeros(JanFebLength*1440,1);
for y=0:1:JanFebLength-1
    Sum10energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
Sum10energy_min_Dec=zeros(DecLength*1440,1);
for y=0:1:DecLength-1
    Sum10energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

```

Configuration 11 Install two buses. A 380V bus and a 24V bus. Solar + batteries connected to 24V bus.

```

voltage1=380;
voltage2=24;

Apprectifier=Apprectifierset;
Gridrectifier=Gridrectifierset;
DCACinverter=DCACinverterset;
DCDCconverter_v1=DCDCconverterset;
DCDCconverter_v2=1;
Solarinverter=SolarMPPTset;
Battconv=1;
Battcc=1;
Baseload=75; % Reduced baseload due to no standby losses from rectifiers.

load_system('House_Model_Sim_voltageoptions_minute')
set_param('House_Model_Sim_voltageoptions_minute/380V DC/AirCon Switch', 'sw', '0'); %
Set A/C on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar switch', 'sw', '0'); % Set
solar on
set_param('House_Model_Sim_voltageoptions_minute/Solar/Solar type', 'sw', '0'); % Set
Solar profile as active
set_param('House_Model_Sim_voltageoptions_minute/Grid switch', 'sw', '0'); % Set Grid
connection to off
set_param('House_Model_Sim_voltageoptions_minute/Battery switch', 'sw', '0'); % Set
battery on
sim('House_Model_Sim_voltageoptions_minute',simtime)

% xaxis=(simtime/length(simtime));
% figure(5)
% plot(xaxis,Energyusage),title('Central AC/DC rectifier with a 380V and 24V bus daily
profile'),xlabel('Time'),ylabel('Power (kW)'),datetick('x','HHPM')

```

```

Sum11_Solargen=(sum(Gen_Solar))/60; % Solar energy generated
Sum11_Gridcons=(sum(Gridusage2))/60; % Sum of positive values (energy from the grid)
Sum11_Battchar=(Battini+(min(Battcharging)/60))*(-1); % Energy used to charge battery
Sum11_Battcons=Battini+((max(Battusage))/60); % Energy used from battery
Sum11_Solarexp=(sum(Solarexport2)*-1)/60; % Sum of negative values (energy exported to
the grid)
Sum11_Solarcons=Sum11_Solargen-Sum11_Solarexp;
Sum11_Cableloss=(sum(CL1+CL2+CL3+CL4+CL5+CL6+CL7)/60)/1000; % Power lost in cables
Sum11_GRloss=sum(GRloss2)/60; % Grid rectifier loss
Sum11_DCACloss=sum(DCACloss2)/60; % DC/AC inverter loss
Sum11_SIloss=sum(SIloss)/60; % Solar inverter loss
Sum11_DCloss_v1=sum(DCloss_v1)/60; % DC/DC converter loss
Sum11_Battuseloss=sum(Battuseloss)/60; % Loss from discharge of battery, includes one
way batt efficiency + converter.
Sum11_Battchargeloss=sum(Battchargeloss)/60; % Loss from charge of battery. This is the
one way batt efficiency.
Sum11_Loadcon=(sum(Total_Load)/60)-(sum((CL1+CL2+CL3+CL4+CL5+CL6)/60)/1000)-
Sum11_DCloss_v1; % Load consumption
Sum11_HomerLoad=sum(Total_Load)/60; % Total load including Cable losses and DC/DC
converter. For attaching to DC bus in Homer energy. Common 24V bus.
Sum11_SOC=Battsoc; % Battery state of charge
Sum11_Dailyenergycons=Sum11_Solarcons+Sum11_Gridcons;
fprintf('Model 11 - Daily summer energy usage for DC house (2 voltages) with solar PV
installed is %0.2f kWh.\n',Sum11_Dailyenergycons);

% Repeat the daily profile figures for January and February
Sum11energy_min_JanFeb=zeros(JanFeblength*1440,1);
for y=0:1:JanFeblength-1
    Sum11energy_min_JanFeb(y*1440+1:(y+1)*1440)=Total_Load(:);
end

% Repeat the daily profile figures for December
Sum11energy_min_Dec=zeros(Declength*1440,1);
for y=0:1:Declength-1
    Sum11energy_min_Dec(y*1440+1:(y+1)*1440)=Total_Load(:);
end

fprintf('\n')

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

% SUMMARY

```

```

% Each column is a separate model. Each row represents a specific value. The
% rows are as follows:

```

```

% Daily energy consumption (net total)

```

```

% Load consumption

```

```

% Grid consumption

```

```

% Battery consumption

```

```

% Battery charging

```

```

% Solar generating

```

```

% Solar consumption

```

```

% Solar export

```

```

% Grid rectifier loss

```

```

% DC/AC inverter loss

```



```

% DC/DC loss_v1
% DC/DC loss_v2
% Solar inverter loss
% Batt discharge loss
% Batt charge loss
% Cable loss

warning('off','MATLAB:xlswrite:AddSheet'); % Turns off warning that is displayed when
adding worksheets to excel file.

Autumnsum(:,1)=[AM1_Dailyenergy, AM1_Loadcon,AM1_Gridcons,0,0,0,0,0,0,0,0,0,0,0,0,
AM1_Cableloss];
Autumnsum(:,2)=[AM2_Dailyenergy, AM2_Loadcon,AM2_Gridcons,0,0,0,0,0,0,0,0,0,0,0,0,
AM2_Cableloss];
Autumnsum(:,3)=[AM3_Dailyenergy, AM3_Loadcon,AM3_Gridcons,0,0,0,0,0,0,0,0,0,0,0,0,
AM3_Cableloss];
Autumnsum(:,4)=[AM4_Dailyenergy, AM4_Loadcon,AM4_Gridcons,0,0,0,0,0,
AM4_Gridloss,0,0,0,0,0,0, AM4_Cableloss];
Autumnsum(:,5)=[AM5_Dailyenergy, AM5_Loadcon,AM5_Gridcons,0,0,0,0,0,
AM5_Gridloss,0,0,AM5_DCloss_v2,0,0,0, AM5_Cableloss];
Autumnsum(:,6)=[AM6_Dailyenergy, AM6_Loadcon,0,0,0,0,0,0,0,0,0,0,0, AM6_Gridloss,0,0,
AM6_Cableloss];
Autumnsum(:,7)=[AM7_Dailyenergycons, AM7_Loadcon, AM7_Gridcons,0,0, AM7_Solargen,
AM7_Solarcons, AM7_Solarexp,AM7_Gridloss, AM7_DCACloss,0,0, AM7_Gridloss,0,0,
AM7_Cableloss];
Autumnsum(:,8)=[AM8_Dailyenergycons, AM8_Loadcon, AM8_Gridcons,0,0, AM8_Solargen,
AM8_Solarcons, AM8_Solarexp, AM8_Gridloss, AM8_DCACloss,0,AM8_DCloss_v2, AM8_Gridloss,0,0,
AM8_Cableloss];
Autumnsum(:,9)=[AM9_Dailyenergycons, AM9_Loadcon, AM9_Gridcons, AM9_Battcons,
AM9_Battchar, AM9_Solargen, AM9_Solarcons, AM9_Solarexp, AM9_Gridloss, AM9_DCACloss,0,0,
AM9_Gridloss,AM9_Battuseloss,AM9_Battchargeloss, AM9_Cableloss];
Autumnsum(:,10)=[AM10_Dailyenergycons, AM10_Loadcon, AM10_Gridcons,
AM10_Battcons,AM10_Battchar, AM10_Solargen, AM10_Solarcons, AM10_Solarexp, AM10_Gridloss,
AM10_DCACloss,0,AM10_DCloss_v2, AM10_Gridloss,AM10_Battuseloss,AM10_Battchargeloss,
AM10_Cableloss];
Autumnsum(:,11)=[AM11_Dailyenergycons, AM11_Loadcon, AM11_Gridcons, AM11_Battcons,
AM11_Battchar, AM11_Solargen, AM11_Solarcons, AM11_Solarexp, AM11_Gridloss, AM11_DCACloss,
AM11_DCloss_v1,0, AM11_Gridloss,AM11_Battuseloss,AM11_Battchargeloss, AM11_Cableloss];

wintersum(:,1)=[WM1_Dailyenergy, WM1_Loadcon,WM1_Gridcons,0,0,0,0,0,0,0,0,0,0,0,0,0,
WM1_Cableloss];
wintersum(:,2)=[WM2_Dailyenergy, WM2_Loadcon,WM2_Gridcons,0,0,0,0,0,0,0,0,0,0,0,0,0,
WM2_Cableloss];
wintersum(:,3)=[WM3_Dailyenergy, WM3_Loadcon,WM3_Gridcons,0,0,0,0,0,0,0,0,0,0,0,0,0,
WM3_Cableloss];
wintersum(:,4)=[WM4_Dailyenergy, WM4_Loadcon,WM4_Gridcons,0,0,0,0,0,
WM4_Gridloss,0,0,0,0,0,0, WM4_Cableloss];
wintersum(:,5)=[WM5_Dailyenergy, WM5_Loadcon,WM5_Gridcons,0,0,0,0,0, WM5_Gridloss,0,0,
WM5_DCloss_v2,0,0,0, WM5_Cableloss];
wintersum(:,6)=[WM6_Dailyenergy, WM6_Loadcon,0,0,0,0,0,0,0,0,0,0,0, WM6_Gridloss,0,0,
WM6_Cableloss];
wintersum(:,7)=[WM7_Dailyenergycons, WM7_Loadcon, WM7_Gridcons,0,0, WM7_Solargen,
WM7_Solarcons, WM7_Solarexp,WM7_Gridloss, WM7_DCACloss,0,0, WM7_Gridloss,0,0,
WM7_Cableloss];
wintersum(:,8)=[WM8_Dailyenergycons, WM8_Loadcon, WM8_Gridcons,0,0, WM8_Solargen,
WM8_Solarcons, WM8_Solarexp, WM8_Gridloss, WM8_DCACloss,0, WM8_DCloss_v2, WM8_Gridloss,0,0,
WM8_Cableloss];
wintersum(:,9)=[WM9_Dailyenergycons, WM9_Loadcon, WM9_Gridcons, WM9_Battcons,

```



```

Sum9_Battchar, Sum9_Solargen, Sum9_Solarcons, Sum9_Solarexp, Sum9_GRloss,
Sum9_DCACloss,0,0, Sum9_SIloss,Sum9_Battuseloss,Sum9_Battchargeloss, Sum9_Cableloss];
Summersum(:,10)=[Sum10_Dailyenergycons, Sum10_Loadcon, Sum10_Gridcons,
Sum10_Battcons,Sum10_Battchar, Sum10_Solargen, Sum10_Solarcons, Sum10_Solarexp,
Sum10_GRloss, Sum10_DCACloss,0, Sum10_DCloss_v2,
Sum10_SIloss,Sum10_Battuseloss,Sum10_Battchargeloss, Sum10_Cableloss];
Summersum(:,11)=[Sum11_Dailyenergycons, Sum11_Loadcon, Sum11_Gridcons, Sum11_Battcons,
Sum11_Battchar, Sum11_Solargen, Sum11_Solarcons, Sum11_Solarexp, Sum11_GRloss,
Sum11_DCACloss, Sum11_DCloss_v1,0, Sum11_SIloss,Sum11_Battuseloss,Sum11_Battchargeloss,
Sum11_Cableloss];

Yearlyaverage=(Autumnsum+Wintersum+Springsum+Summersum)/4;

Autumn_summary=array2table(Autumnsum,'VariableNames',{'Model_1','Model_2','Model_3','Mod
el_4','Model_5','Model_6','Model_7','Model_8','Model_9','Model_10','Model_11'},'RowNames
',{'Daily energy consumption (net total)','Load consumption','Grid consumption','Battery
consumption','Battery charging','Solar generating','Solar consumption','Solar
export','Grid rectifier loss','DC/AC inverter loss','DC/DC loss_v1','DC/DC
loss_v2','Solar inverter loss','Batt discharge loss','Batt charge loss','Cable loss'});
Winter_summary=array2table(Wintersum,'VariableNames',{'Model_1','Model_2','Model_3','Mod
el_4','Model_5','Model_6','Model_7','Model_8','Model_9','Model_10','Model_11'},'RowNames
',{'Daily energy consumption (net total)','Load consumption','Grid consumption','Battery
consumption','Battery charging','Solar generating','Solar consumption','Solar
export','Grid rectifier loss','DC/AC inverter loss','DC/DC loss_v1','DC/DC
loss_v2','Solar inverter loss','Batt discharge loss','Batt charge loss','Cable loss'});
Spring_summary=array2table(Springsum,'VariableNames',{'Model_1','Model_2','Model_3','Mod
el_4','Model_5','Model_6','Model_7','Model_8','Model_9','Model_10','Model_11'},'RowNames
',{'Daily energy consumption (net total)','Load consumption','Grid consumption','Battery
consumption','Battery charging','Solar generating','Solar consumption','Solar
export','Grid rectifier loss','DC/AC inverter loss','DC/DC loss_v1','DC/DC
loss_v2','Solar inverter loss','Batt discharge loss','Batt charge loss','Cable loss'});
Summer_summary=array2table(Summersum,'VariableNames',{'Model_1','Model_2','Model_3','Mod
el_4','Model_5','Model_6','Model_7','Model_8','Model_9','Model_10','Model_11'},'RowNames
',{'Daily energy consumption (net total)','Load consumption','Grid consumption','Battery
consumption','Battery charging','Solar generating','Solar consumption','Solar
export','Grid rectifier loss','DC/AC inverter loss','DC/DC loss_v1','DC/DC
loss_v2','Solar inverter loss','Batt discharge loss','Batt charge loss','Cable loss'});
Yearly_summary=array2table(Yearlyaverage,'VariableNames',{'Model_1','Model_2','Model_3',
'Model_4','Model_5','Model_6','Model_7','Model_8','Model_9','Model_10','Model_11'},'RowN
ames',{'Daily energy consumption (net total)','Load consumption','Grid
consumption','Battery consumption','Battery charging','Solar generating','Solar
consumption','Solar export','Grid rectifier loss','DC/AC inverter loss','DC/DC
loss_v1','DC/DC loss_v2','Solar inverter loss','Batt discharge loss','Batt charge
loss','Cable loss'})

writetable(Autumn_summary,'Results_Summary.xlsx','Sheet',2,'WriteRowNames',true);
writetable(Winter_summary,'Results_Summary.xlsx','Sheet',3,'WriteRowNames',true);
writetable(Spring_summary,'Results_Summary.xlsx','Sheet',4,'WriteRowNames',true);
writetable(Summer_summary,'Results_Summary.xlsx','Sheet',5,'WriteRowNames',true);
writetable(Yearly_summary,'Results_Summary.xlsx','Sheet',6,'WriteRowNames',true);

M1_Energyusage=(AM1_Energyusage+WM1_Energyusage+SM1_Energyusage+SuM1_Energyusage)/4;
M7_Energyusage=(AM7_Energyusage+WM7_Energyusage+SM7_Energyusage+SuM7_Energyusage)/4;

M1_HomerLoad=(AM1_HomerLoad+WM1_HomerLoad+SM1_HomerLoad+SuM1_HomerLoad)/4;
M5_HomerLoad=(AM5_HomerLoad+WM5_HomerLoad+SM5_HomerLoad+SuM5_HomerLoad)/4;
M10_HomerLoad=(AM10_HomerLoad+WM10_HomerLoad+SM10_HomerLoad+SuM10_HomerLoad)/4;
M11_HomerLoad=(AM11_HomerLoad+WM11_HomerLoad+SM11_HomerLoad+SuM11_HomerLoad)/4;

```

```

xaxis=(simtime/length(simtime));
figure(1)
plot(xaxis,M1_Energyusage),title('Config. 1 - AC house with DC internal appliances daily
profile'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

solaroutputprofile(:,2)=Pvsize*annualsolar;
solarplot=solaroutputprofile(:,2)/1000;
xaxis=(simtime/length(simtime));

figure(5)
subplot(3,1,1)
plot(xaxis,solarplot),title('Daily average solar generation in one minute
increments'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
subplot(3,1,2)
plot(xaxis,M1_Energyusage),title('Config. 1 - Daily average energy usage for AC
house'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')
subplot(3,1,3)
plot(xaxis,M7_Energyusage),title('Config. 7 - Daily average energy usage for AC house
with solar installed'),xlabel('Time'),ylabel('Power (kw)'),datetick('x','HHPM')

M1_HWu=(AM1_HWu+WM1_HWu+SM1_HWu+SuM1_HWu)/4; % Daily hot water usage in kwh
M1_ACu=(AM1_ACu+WM1_ACu+SM1_ACu+SuM1_ACu)/4; % Daily air conditioner usage in kwh
M1_Cooku=(AM1_Cooku+WM1_Cooku+SM1_Cooku+SuM1_Cooku)/4; % Daily cooking appliance use in
kwh
M1_Lightu=(AM1_Lightu+WM1_Lightu+SM1_Lightu+SuM1_Lightu)/4; % Daily light usage in kwh
M1_WGu=(AM1_WGu+WM1_WGu+SM1_WGu+SuM1_WGu)/4; % Daily white goods usage in kwh
M1_Appu=(AM1_Appu+WM1_Appu+SM1_Appu+SuM1_Appu)/4; % Daily appliance usage in kwh
M1_Baseu=(AM1_Baseu+WM1_Baseu+SM1_Baseu+SuM1_Baseu)/4; % Daily base load usage in kwh

M1_total=M1_HWu+M1_ACu+M1_Cooku+M1_Lightu+M1_WGu+M1_Appu+M1_Baseu;

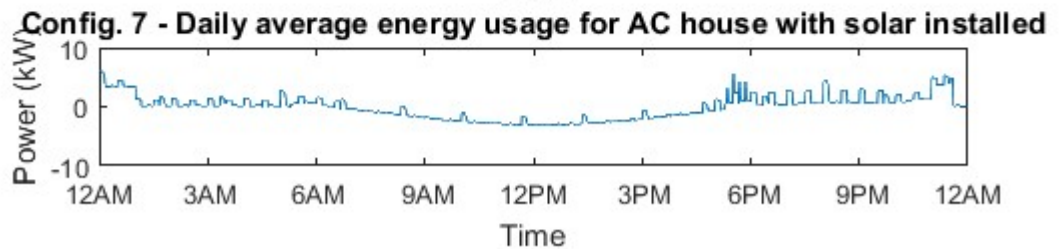
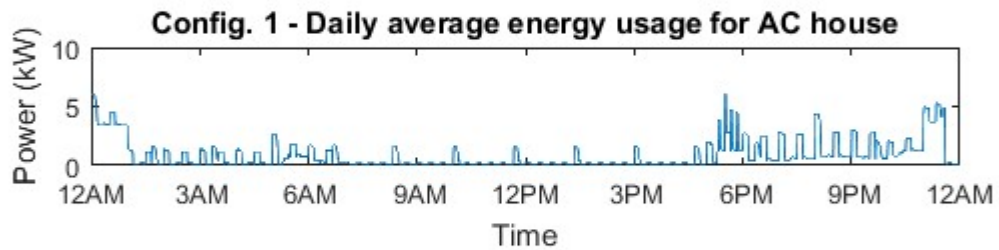
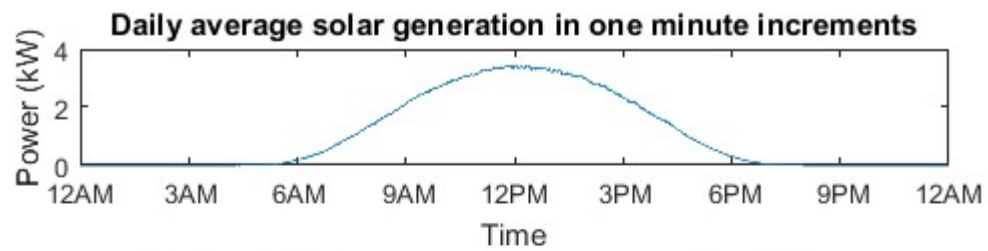
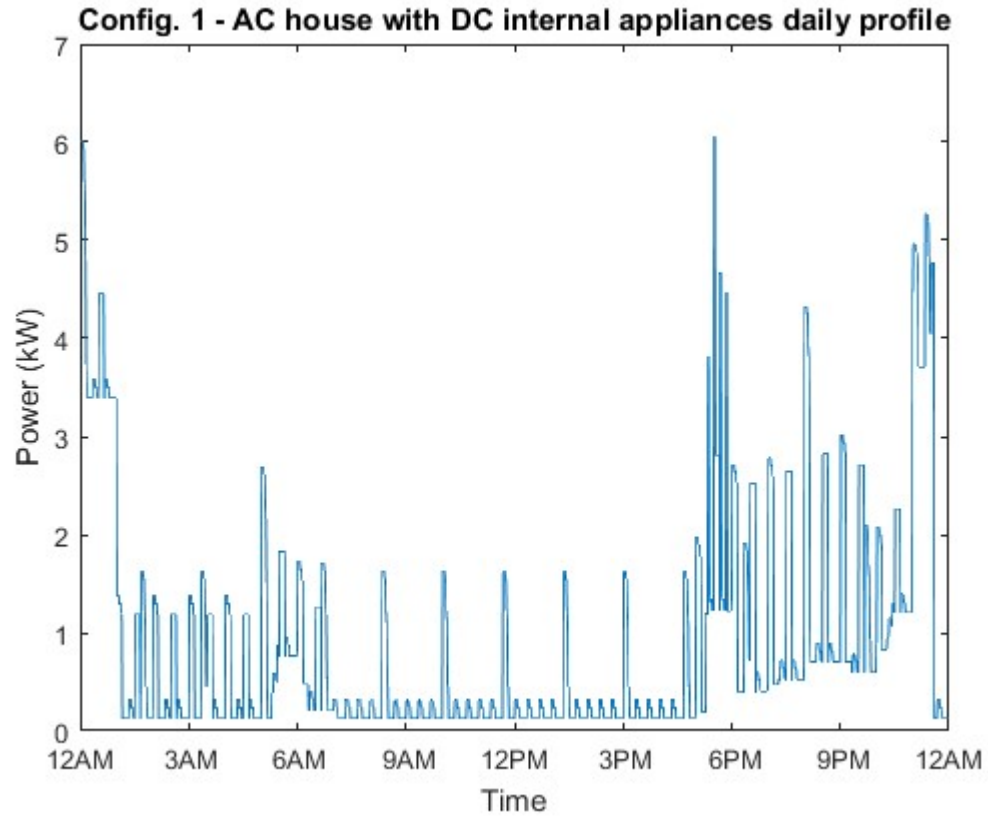
M1_pie=[M1_HWu M1_ACu M1_Cooku M1_Lightu M1_WGu M1_Appu M1_Baseu];
figure(50)
pie(M1_pie),title('Config. 1 - Residential end use per day from MATLAB model');
pielabels={'Hot Water','A/C','Cooking appliances','Lights','White Goods','Appliances',
'Base load'};
legend(pielabels,'Location','southoutside','Orientation','vertical');

```

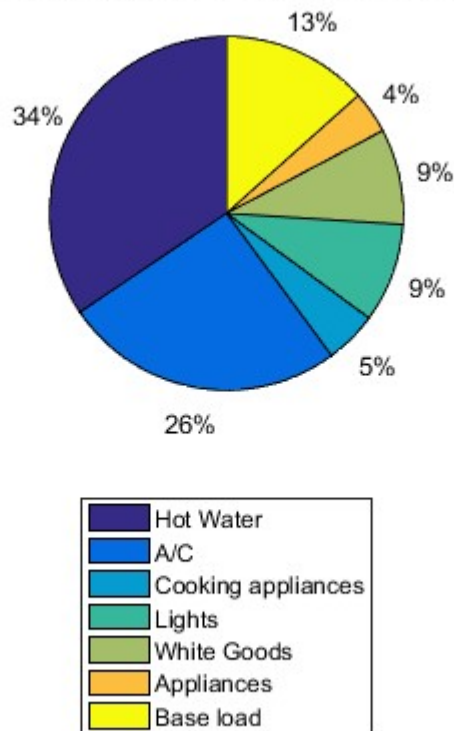
Yearly\_summary =

		Model_1	Model_2
Model_3	Model_4	Model_5	Model_6
Model_7	Model_8	Model_9	Model_10
Model_11			
Daily energy consumption (net total)		22.6403003378883	21.0650578883151
19.864543746421	21.3597244585173	22.2585100859874	-0.587058560284773
23.9844655538648	23.2780221121601	25.7543257139605	24.5723652968271
24.5453879300079			
Load consumption		22.4151666666667	20.8816926666665
19.6816926666665	19.6816926666665	19.6816926666667	22.4151666666667

22.4151666666667	19.6816926666667	22.4151666666667	19.6816926666667
19.6816926666668			
Grid consumption		22.6403003378883	21.0650578883151
19.864543746421	21.3597244585173	22.2585100859874	0
19.1438832447782	19.0948742812838	10.3139597802555	9.69738753448452
9.6880920259253			
Battery consumption		0	0
0	0	0	0
0	9.9292234264613	10.0310693097828	10.04573679052
Battery charging		0	0
0	0	0	0
0	9.92922342646133	10.0310693097827	10.0457367905201
Solar generating		0	0
0	0	0	24.9884690449522
24.9884690449522	24.9884690449522	24.9884690449522	24.9884690449522
Solar consumption		0	0
0	0	0	4.84058230908659
4.18314783087628	15.440365933705	14.8749777623425	14.8572959040826
Solar export		0	0
0	0	0	20.1478867358656
20.8053212140759	9.54810311124718	10.1134912826097	10.1311731408696
Grid rectifier loss		0	0
0	1.49518071209623	1.55809570601912	0
1.33664119968986	0	0.678817127413917	0.67816644181477
DC/AC inverter loss		0	0
0	0	0	0
0.64346354270338	0	0.312788390183805	0.313335251779473
DC/DC loss_v1		0	0
0	0	0	0
0	0	0	0.746453933124458
DC/DC loss_v2		0	0
0	0	0.32588948253019	0
0.32588948253019	0	0.32588948253019	0
Solar inverter loss		0	0
0	0	0	1.22249257358808
0.49777481745212	1.2444370436303	0.49777481745212	0.49777481745212
Batt discharge loss		0	0
0	0	0	0
0	1.16847112578101	1.36458700357352	0.906304026434685
Batt charge loss		0	0
0	0	0	0
0	0.648733899230056	0.991405216547902	0.992529319907303
Cable loss		0.225133671221593	0.183365221648615
0.18285107975447	0.18285107975447	0.692832230771612	0.262782199460522
0.324861843567834	0.792560403117854	0.324861843567834	0.792560403117854
0.792560403117854			



**Config. 1 - Residential end use per day from MATLAB model**



% Outputs of AC and DC consumption for use in the HOMER Energy models.

```
M1_Totallyear_min=[SuM1energy_min_JanFeb;AM1energy_min;WM1energy_min;SM1energy_min;SuM1energy_min_Dec]; % Yearly consumption by the minute.
```

```
M2_Totallyear_min=[SuM2energy_min_JanFeb;AM2energy_min;WM2energy_min;SM2energy_min;SuM2energy_min_Dec]; % Yearly consumption by the minute.
```

```
M3_Totallyear_min=[SuM3energy_min_JanFeb;AM3energy_min;WM3energy_min;SM3energy_min;SuM3energy_min_Dec]; % Yearly consumption by the minute.
```

```
M5_Totallyear_min=[SuM5energy_min_JanFeb;AM5energy_min;WM5energy_min;SM5energy_min;SuM5energy_min_Dec]; % Yearly consumption by the minute.
```

```
M10_Totallyear_min=[SuM10energy_min_JanFeb;AM10energy_min;WM10energy_min;SM10energy_min;SuM10energy_min_Dec]; % Yearly consumption by the minute.
```

```
M11_Totallyear_min=[SuM11energy_min_JanFeb;AM11energy_min;WM11energy_min;SM11energy_min;SuM11energy_min_Dec]; % Yearly consumption by the minute.
```

```
% xlswrite('M1_Totallyear_min.xlsx',M1_Totallyear_min);
```

```
% xlswrite('M3_Totallyear_min.xlsx',M3_Totallyear_min);
```

```
csvwrite('AC_Totallyear_min.csv',M1_Totallyear_min);
```

```
csvwrite('DC_Totallyear_min.csv',M2_Totallyear_min);
```

```
csvwrite('DCreduced_Totallyear_min.csv',M3_Totallyear_min);
```

```
csvwrite('DC_Totallyear_380min.csv',M5_Totallyear_min);
```

```
csvwrite('DC_Totallyear_380_v2min.csv',M10_Totallyear_min);
```

```
csvwrite('DC_Totallyear_24min.csv',M11_Totallyear_min);
```

```
% Calculate yearly PV output based on seasons.
```

```
% Repeat the daily solar profile for autumn
```

```

APV_min=zeros(autumnlength*1440,1);
for y=0:1:autumnlength-1
    APV_min(y*1440+1:(y+1)*1440)=autumnsolar(:);
end
% Repeat the daily solar profile for winter
WPV_min=zeros(winterlength*1440,1);
for y=0:1:winterlength-1
    WPV_min(y*1440+1:(y+1)*1440)=wintersolar(:);
end
% Repeat the daily solar profile for spring
SPV_min=zeros(springlength*1440,1);
for y=0:1:springlength-1
    SPV_min(y*1440+1:(y+1)*1440)=springsolar(:);
end
% Repeat the daily solar profile for summer Jan_Feb
JanFebPV_min=zeros(JanFeblength*1440,1);
for y=0:1:JanFeblength-1
    JanFebPV_min(y*1440+1:(y+1)*1440)=summersolar(:);
end
% Repeat the daily solar profile for summer Dec
DecPV_min=zeros(Declength*1440,1);
for y=0:1:Declength-1
    DecPV_min(y*1440+1:(y+1)*1440)=summersolar(:);
end
TotalPVout=[JanFebPV_min;APV_min;WPV_min;SPV_min;DecPV_min];
csvwrite('TotalPV.csv',TotalPVout);

```

*[Published with MATLAB® R2016a](#)*



## Appendix H CD with model files

The attached CD has a copy of the MATLAB codes, Simulink models and HOMER Pro models to allow replication of the project results.

The Simulink models were too large to include in the dissertation. For reference a PDF copy has been included on the CD.

To execute the models, the folders will need to be copied to a local computer drive, as some of the MATLAB codes output results that need to be written to a location.

A number of excel workbooks were utilised to combine and compare the results and also to create many of the graphs shown in the dissertation. These have not been included as they rely on references to other files and when moved between folders can have some errors. If they are required, please contact the author.