AN OFF-GRID SOLAR SYSTEM
FOR
RURAL VILLAGE IMPLEMENTATION
IN EAST MALAYSIA

WONG SZE YIE

A dissertation submitted in partial fulfilment of the requirements for the degree of

MASTER OF ENGINEERING

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The design-and-build stages on the Long Beruang Solar Project from design phase to final implementation are reported in this thesis, with its sustainability discussed and reviewed. Long Beruang is a rural Penan village located in inland Sarawak, East Malaysia. The Long Beruang Solar Project is a 54 kWp solar power system which is implemented and monitored by the Public Works Department of Sarawak under the Stimulus Rural Electrification Projects. It is a community-based project, where villagers were fully involved in the building of power house, assembly of system components and the routine maintenance after project implementation.

Actual load profiles of the village were recorded to examine the power usage pattern: the first load profile was collected in December 2010 (eight months after the project implementation); on the other hand, the second load profile was collected in March 2012 (twenty-three months after the project implementation). It is found that in the period of fifteen months, the daily energy consumption has increased by 257% and peak load growth has increased by 223%.

The environmental and economic impact of this project is scrutinized in terms of CO₂ emissions and annual electricity payable, in comparison to two other presumed scenarios in which the village is either generated by Diesel-Generator or by grid.

This thesis also contributed to the insufficient solar radiation data available for the state of Sarawak. With this intention, this thesis proposed suitable empirical models to estimate monthly-averaged daily terrestrial solar radiation for the two towns in Sarawak: Kuching and Miri. The Angstrom-Prescott model performed best for Kuching whereas for Miri, Cloudiness model is recommended. For Long Beruang, an Angstrom-Prescott model is proposed for the current stage of this research. Additional sampling, however, maybe required to produce a model with much higher accuracy for future work.
ACKNOWLEDGEMENT

I dedicate this work to my beloved parents and my brother; for their love and care.

I would like to thank my supervisor, Dr. Almon Chai, for his encouragement and support. I am deeply grateful for the trust he has bestowed on me, and the freedom he has given me in belief that I can manage the task well.

Also, I would like to thank the officers from the Public Works Department of Sarawak, without whom I would not have the chance to be involved in such meaningful project.

Last but not least, a thousand thanks to my friends who often tracked my progress and urged me to do my work whenever I was behind time.
DISCLAIMER

Standards and criteria regarding photovoltaic (PV) installations, procedures, and approval guidelines in Malaysia have been routinely assessed by the Ministry of Energy, Green Technology and Water (KeTTHA). As such, system sizing discussed is valid and correct as of system commissioned dated 10\textsuperscript{th} April 2010.

In Malaysia, there are two standards relevant to the installation of equipment used in standalone power supply system, namely the Malaysian Standard MS/IEC 60364 for \textit{Electrical Installation of Buildings} and MS 1553:2002 for \textit{Code of Practice on Wind Loading for Building Structure}.

In Sarawak, the utility company, Sarawak Energy Berhad (SEB) adapts the Malaysian Standard MS 1837:2010 for \textit{Installation of Grid-Connected Photovoltaic (PV) System}. It is the first revision of MS 1837:2005, by the same name. MS1837 is based on various MS IEC standards for PV System, but adjusted to Malaysian condition. Therefore, some terms and definition from MS1837 will be used throughout this paper. The Institute for Sustainable Power (ISP) accredited training programmes conducted by the \textit{Universiti Teknologi MARA} (UiTM), as part of the Malaysian Building Integrated Photovoltaic (MBIPV) Project, are strictly followed by the SEB. These are 10-day training programmes covering theory; practical and exams are on design and installation of grid-connected and off-grid PV systems.

Hitherto there are no mandatory standards enforced on the installation of off-grid PV systems in Sarawak as of the system commissioned date, although designers are encouraged to follow the guidelines from ISP.
DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Sarawak, May 31, 2013

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Wong Sze Yie
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................... i
ACKNOWLEDGEMENT ......................................................................................................................... ii
DISCLAIMER ......................................................................................................................................... iii
DECLARATION ......................................................................................................................................... iv
LIST OF FIGURES ................................................................................................................................. ix
LIST OF TABLES .................................................................................................................................. xi
LIST OF ABBREVIATIONS & ACRONYMS ......................................................................................... xii

CHAPTER 1 ........................................................................................................................................... 1

1.1 INTRODUCTION ............................................................................................................................... 1
1.2 THE PROBLEM AND ITS BACKGROUND ......................................................................................... 2

1.2.1 The Village & its People ............................................................................................................. 2
1.3 STATEMENT OF THE PROBLEM .................................................................................................... 4
1.4 SIGNIFICANCE OF THE STUDY .................................................................................................... 4
1.5 SCOPE AND DELIMITATION ......................................................................................................... 4
1.6 THESIS OVERVIEW ....................................................................................................................... 6

CHAPTER 2 ........................................................................................................................................... 7

LITERATURE REVIEW ............................................................................................................................ 7

2.1 PHOTOVOLTAIC (PV) CELLS ........................................................................................................ 7
2.1.1 Brief History of Solar Cells .......................................................................................................... 8
2.1.2 Crystalline Silicon .......................................................................................................................... 9
2.1.2.1 Principles of Solar Cell Operation ........................................................................................ 9
2.1.2.2 Monocrystalline Silicon ......................................................................................................... 12
2.1.2.3 Polycrystalline Silicon ........................................................................................................... 13
2.1.3 Amorphous Silicon .................................................................................................................... 13
2.1.4 Other Materials .......................................................................................................................... 14

2.2 CHARGE REGULATOR, CONVERTER & INVERTER .................................................................... 15
2.2.1 Charge Regulator ........................................................................................................................ 15
2.2.2 DC / DC Converter ...................................................................................................................... 16
2.2.3 DC / AC Inverter ........................................................................................................................ 16

2.3 ENERGY STORAGE SYSTEM ......................................................................................................... 18
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1</td>
<td>System Overview</td>
<td>61</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Site Clearing and Power House Construction</td>
<td>63</td>
</tr>
<tr>
<td>3.3.3</td>
<td>PV Mounting Structures &amp; Modules installation</td>
<td>65</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Batteries Installation</td>
<td>66</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Inverters and VSAT Installation</td>
<td>66</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Involvement of Local Community</td>
<td>68</td>
</tr>
<tr>
<td>3.3.7</td>
<td>Testing &amp; Commissioning</td>
<td>69</td>
</tr>
<tr>
<td>4.1</td>
<td>ACTUAL LOAD PROFILE</td>
<td>70</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Load Profile in December 2010</td>
<td>70</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Load Profile in March 2010</td>
<td>72</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Section Summary</td>
<td>74</td>
</tr>
<tr>
<td>4.2</td>
<td>SOLAR RADIATION IN LONG BERRUANG</td>
<td>75</td>
</tr>
<tr>
<td>5.1</td>
<td>ENVIRONMENTAL CONSIDERATIONS</td>
<td>76</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Scenario A: Diesel-Generator</td>
<td>77</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Scenario B: Grid-Connected</td>
<td>77</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Section Summary</td>
<td>78</td>
</tr>
<tr>
<td>5.2</td>
<td>ECONOMIC ANALYSIS</td>
<td>79</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Energy Delivery Factor</td>
<td>79</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Initial Capital Cost</td>
<td>80</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Maintenance</td>
<td>80</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Energy Cost Estimates</td>
<td>81</td>
</tr>
<tr>
<td>5.2.5</td>
<td>Net Present Cost</td>
<td>82</td>
</tr>
<tr>
<td>5.2.6</td>
<td>Return of Investment</td>
<td>84</td>
</tr>
<tr>
<td>5.2.7</td>
<td>Scenario A: Diesel-Generator</td>
<td>85</td>
</tr>
<tr>
<td>5.2.8</td>
<td>Scenario B: Grid-Connected</td>
<td>87</td>
</tr>
<tr>
<td>5.2.9</td>
<td>Section Summary</td>
<td>87</td>
</tr>
<tr>
<td>5.3</td>
<td>SOCIOECONOMIC IMPACT</td>
<td>88</td>
</tr>
<tr>
<td>5.4</td>
<td>SUMMARY OF THE CHAPTER</td>
<td>88</td>
</tr>
<tr>
<td>6.1</td>
<td>SOLAR RADIATION MODELS IN SARAWAK</td>
<td>89</td>
</tr>
</tbody>
</table>
6.1 DATA & METHODOLOGY ........................................................................................................ 89
  6.1.1 Data .................................................................................................................................... 89
  6.1.2 Models .................................................................................................................................. 90
  6.1.2.1 Model based on sunshine hours: ...................................................................................... 90
  6.1.2.2 Model based on cloud cover: ............................................................................................ 90
6.2 RESULTS & DISCUSSION ...................................................................................................... 91
  6.2.1 Data .................................................................................................................................... 91
  6.2.1.1 Model based on sunshine hours: ...................................................................................... 91
  6.2.1.2 Model based on cloud cover: ............................................................................................ 92
  6.2.2 Statistical Evaluation ........................................................................................................... 92
  6.2.3 Discussion ............................................................................................................................ 94
CHAPTER 7 ...................................................................................................................................... 96
CONCLUSIONS & FUTURE WORK ............................................................................................ 96
REFERENCE
APPENDICES
LIST OF FIGURES

Figure 1.1 - Geographical location of Long Beruang (Image courtesy of Google) .............................................. 3
Figure 1.2 – Scope of work ............................................................................................................................... 5
Figure 2.1 – Solar cells, made from monocrystalline, polycrystalline and amorphous silicon.............................. 8
Figure 2.2 - (a) Silicon crystal lattice; (b) electrons and holes ........................................................................ 9
Figure 2.3 – A p-n junction ............................................................................................................................. 11
Figure 2.4 - The voltage-current characteristic of a silicon diode. ................................................................ 11
Figure 2.5 – The equivalent circuit of an ideal solar cell. ................................................................................. 11
Figure 2.6 - Quantum effects in solar cell....................................................................................................... 12
Figure 2.7 - (a) Shunt regulator; (b) Series regulator ....................................................................................... 17
Figure 2.8 - Circuit diagram of the (a) buck converter (b) boost converter ..................................................... 17
Figure 2.9 - Four categories of batteries ....................................................................................................... 20
Figure 2.10 - Electrochemical operation of a cell during discharge ................................................................. 22
Figure 2.11 - Electrochemical operation of a cell during charging ................................................................. 22
Figure 2.12 - The photovoltaic modules connection ....................................................................................... 28
Figure 2.13 - PV system supplying DC loads without backup supply ............................................................ 29
Figure 2.14 - Series Configuration .................................................................................................................. 30
Figure 2.15 - Switched Configuration ............................................................................................................ 31
Figure 2.16 - Parallel Configuration ............................................................................................................... 31
Figure 2.17 - AC-connected Parallel Configuration ....................................................................................... 31
Figure 3.1 – Village Layout Plan ..................................................................................................................... 50
Figure 3.2 - Plant Layout Plan. ....................................................................................................................... 61
Figure 3.3 - Solar array mounting structures .................................................................................................. 61
Figure 3.4 - Power House. .............................................................................................................................. 62
Figure 3.5 - Layout of power house (interior) .................................................................................................. 62
Figure 3.6 - System block diagram. ................................................................................................................ 63
Figure 3.7 - Power house under construction ............................................................................................... 64
Figure 3.8 - Marking and preparing stumps for PV array poles. .................................................................... 64
Figure 3.9 - Constructing footings for the poles .............................................................................................. 65
Figure 3.10 - Erecting PV mounting structure ............................................................................................... 65
Figure 3.11 - Modules were mounted directly mounted on the structures after unloading at 8 p.m. .......... 65
Figure 3.12 - Testing of batteries ................................................................................................................... 66
Figure 3.13 – Installed battery banks and battery fuse boxes ........................................................................ 66
Figure 3.14 – Grid-tied inverters for AC coupling between solar modules and AC grid ................................ 66
Figure 3.15 - Bi-directional inverters connecting AC grid and batteries ......................................................... 67
Figure 3.16 – Installation of BOS ................................................................................................................... 67
Figure 3.17 - Installation of VSAT communication system ............................................................................. 67
Figure 3.18 - (a) Anemometer; (b) Solar radiation sensor ............................................................................... 68
Figure 3.19 - C-band VSAT ........................................................................................................................... 68
Figure 3.20 - Soil from borrow pit for the foundation and fencing structures .................................................. 68
Figure 3.21 - Stones and Gravels collected from nearby river ....................................................................... 68
Figure 3.22 - The Penan ‘Gotong-Royong’ team. ......................................................................................... 69
Figure 4.1 – Daily load profile in December 2010; (a) Difference in power consumption in weekdays and weekend ................................................................................................................ 71
Figure 4.2 - Average daily load profile in December 2010 .............................................................................. 71
Figure 4.3 - Comparison of average daily current pattern for Year 2010 and 2012; (a) Difference in average current usage at daytime and night-time in Year 2012; (b) Difference in average current usage at daytime and night-time in Year 2010 ............................................................................................... 72
Figure 4.4 - Daily load profile in March 2012 ................................................................. 74
Figure 4.5 - Monthly Averaged Daily Solar Irradiation ............................................... 75
Figure 5.1 – Initial Capital Cost ...................................................................................... 80
LIST OF TABLES

Table 1 – System Equipment/Instrument .................................................................................................. 51
Table 2 - Estimation of daily energy consumption. .................................................................................... 52
Table 3 - Battery Temperature Correction Factor. .................................................................................... 53
Table 4 - Surge Demand for inductive and non-inductive load ................................................................. 54
Table 5 - Daily energy consumption and peak load in December 2010 ..................................................... 71
Table 6 - Comparison of average daily energy consumption and peak load in 2010 and 2012 .................... 74
Table 7 - Comparison of Diesel-Generator and grid-connected scenarios in terms of CO\textsubscript{2} emission. 78
Table 8 - Calculation of Net Present Cost of 20 years of project lifetime. .................................................. 84
Table 9 - SEB Tariff for Domestic Usage .................................................................................................. 87
Table 10 - Overview of the project financial value. .................................................................................. 87
Table 11 - Comparison of Diesel-Generator and grid-connected scenarios in financial terms................. 88
Table 12 - Performance of different scenarios of power generation in terms of CO\textsubscript{2} emission and unit cost of energy ......................................................................................................................... 88
Table 13 - Statistical justification of the models for Kuching. ................................................................. 93
Table 14 - Statistical justification of the models for Miri. ................................................................. 93
Table 15 - Statistical justification of the models for Long Beruang ............................................................ 94
Table 16 - Overall atmospheric transmissions under clear skies for Kuching and Miri. ............................ 95
# LIST OF ABBREVIATIONS & ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>AGM</td>
<td>Absorbed glass mat</td>
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<td>ALT</td>
<td>Solar altitude angle</td>
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<td>a-Si</td>
<td>Amorphous silicon</td>
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<td>AST</td>
<td>Apparent solar time</td>
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<tr>
<td>AZM</td>
<td>Solar azimuth angle</td>
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<td>BioGen</td>
<td>Biomass-based Power Generation and Cogeneration Project</td>
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<td>BOS</td>
<td>Balance-of-system</td>
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<td>CDM</td>
<td>Clean Development Mechanism</td>
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<td>CdTe</td>
<td>Cadmium Telluride</td>
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<td>CETREE</td>
<td>Centre for Education and Training in Renewable Energy and Energy Efficiency</td>
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<td>CIS</td>
<td>Copper Indium Diselenide</td>
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<td>COD</td>
<td>Commercial Operation Date</td>
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<td>DANIDA</td>
<td>Danish International Development Agency</td>
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<td>DC</td>
<td>Direct current</td>
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<td>DEC</td>
<td>Solar declination angle</td>
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<td>DOD</td>
<td>Depth-of-discharge</td>
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<td>DSCs</td>
<td>Dye-sensitized cells</td>
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<td>EDF</td>
<td>Energy Delivery Factor</td>
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<td>EE</td>
<td>Energy efficiency</td>
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<td>e.m.f.</td>
<td>Electromotive force</td>
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<td>EOT</td>
<td>Equation of time</td>
</tr>
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<td>EVA</td>
<td>Ethylene Vinyl Acetate</td>
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<td>Abbreviation</td>
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<tr>
<td>FiT</td>
<td>Feed-in Tariff</td>
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<td>GaAs</td>
<td>Gallium Arsenide</td>
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<td>GBI</td>
<td>Green Building Index</td>
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<td>GEF</td>
<td>Global Environmental Facility</td>
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<td>GHG</td>
<td>Green House Gas</td>
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<td>ICC</td>
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</tr>
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<td>ICT</td>
<td>Information and Communication Technology</td>
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<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<td>IGBT</td>
<td>Insulated gate bipolar transistor</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>ISP</td>
<td>Institute for Sustainable Power</td>
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<td>ITA</td>
<td>Investment Tax Allowance</td>
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<td>JKKK</td>
<td>Jawatankuasa Kemajuan dan Keselamatan Kampung (Committee of Village Development and Security)</td>
</tr>
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<td>JKR</td>
<td>Jabatan Kerja Raya (Public Work of Department)</td>
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<td>KeTTHA</td>
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</tr>
<tr>
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<td>Low Energy Building</td>
</tr>
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<td>MBIPV</td>
<td>Malaysia Building Integrated Photovoltaic Project</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal oxide semiconductor field effect transistor</td>
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<td>MPPT</td>
<td>Maximum power point tracking</td>
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<td>MS</td>
<td>Malaysian Standard</td>
</tr>
<tr>
<td>NPC</td>
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</tr>
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<td>OMC</td>
<td>Operating and Maintenance Costs</td>
</tr>
<tr>
<td>PAM</td>
<td>Pertubuhan Akitek Malaysia (Malaysian Institute of Architects)</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton exchange membrane fuel cells</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>PFM</td>
<td>Pulse frequency modulation</td>
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<td>PS</td>
<td>Pioneer Status</td>
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<td>PTM</td>
<td><em>Pusat Tenaga Malaysia</em> (Malaysia Energy Centre, now known as the Malaysia Green Technology Corporation)</td>
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<td>PWM</td>
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<td>RE</td>
<td>Renewable energy</td>
</tr>
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<td>REPPA</td>
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</tr>
<tr>
<td>ROI</td>
<td>Return of Investment</td>
</tr>
<tr>
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<td>Special Committee of Renewable Energy</td>
</tr>
<tr>
<td>SEB</td>
<td>Sarawak Energy Berhad</td>
</tr>
<tr>
<td>SEDA</td>
<td>Sustainable Energy Development Authority</td>
</tr>
<tr>
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<td>Stationary energy storage</td>
</tr>
<tr>
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<td><em>Sidang Injil Borneo</em> (Borneo Evangelical Church)</td>
</tr>
<tr>
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<td>Standards and Industrial Research Institute of Malaysia</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Small Renewable Energy Programme</td>
</tr>
<tr>
<td>UCE</td>
<td>Unit Cost of Energy</td>
</tr>
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<td>UiTM</td>
<td><em>Universiti Teknologi MARA</em> (MARA University of Technology)</td>
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<td>UPS</td>
<td>Uninterruptible power supply</td>
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<td>UV</td>
<td>Ultraviolet</td>
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<td>VRLA</td>
<td>Valve-regulated lead-acid</td>
</tr>
<tr>
<td>VSAT</td>
<td>Very Small Aperture Terminal</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

Over the years, there had been a boost in the development of renewable energy in order to meet the growing worldwide energy demand, while addressing the rising concern on climate change. In line with global trends as well as to improve standard of living, the Malaysian Government aims to provide electricity to homes, villages and indigenous communities, beyond the operational areas of local authorities. Rural electrification in the state of Sarawak was initiated in the Ninth Malaysia Plan (2006-2010), comprising grid-extension as well as stand-alone generators and use of alternative energy such as solar installations (solar home system) or hybrid systems (use of solar power and diesel generator set).

1.2 THE PROBLEM AND ITS BACKGROUND

Long Beruang is a Penan settlement located at 3° 17’ 02.5” north latitude, 115° 25’ 34.7” east longitude; 598 metres above sea level. It belongs to Ulu Baram, a remote area in the Miri division of Sarawak. Its geographical location is illustrated in Fig. 1.1. Located in an off-grid rural area, the village of Long Beruang had no electricity supply from the utility and had no other mean of access to electricity before the installation of solar power system.

In order to bring electricity to the village, a Community-Based (Gotong-Royong in Malay) standalone solar power system project was proposed, implemented and monitored by the Public Works Department of Sarawak (Jabatan Kerja Raya, or JKR) under the Stimulus Rural Electrification Projects. A 54 kWp solar plant was set up and the villagers enjoy the privilege of free electricity ever since. The villagers were involved in the construction and system installation. Training on end-user’s operation and maintenance were provided to reduce their dependency on the governing body.
1.2.1 The Village & its People

The *Penan* people belong to one of the sixteen ethnic groups in Sarawak. They are widely regarded as the forest experts due to their exceptional capability of exploring and probing in the jungle without prior knowledge of the landscape. Practising nomadic lifestyle in the forest, the Penans are natural hunters and gatherers. In general, the men are about five and a half feet tall while the women are about two inches shorter. The Penans have relatively fair skin complexion; they also possess somewhat broader figures and are sturdier than the other inland tribes; hence, they are much favoured for manual labour work, especially when it involves goods delivery into the interior jungle where no vehicles can reach.

The name *Long Beruang* means “rapid stream” in the Penan language. In most of the inland Sarawakian languages, the word *Long* denotes “river or stream”; the word *Beruang* denotes “rapid or fast” in the Penan language.

Long Beruang houses 55 doors, 68 families, around 301 people (170 men and 131 women). Majority of the men work in the timber camps or nearby towns, some of them will take minor contract jobs from the government from time to time, for instance road construction. Although women folks mostly stay at home to take care of their families, a number of young girls have left home to work in nearby towns. The village is headed by a *Ketua Kampung* (village head), who will correspond to a *Penghulu* (headman). A *Penghulu* is the head of a few villages and it is a fixed position assigned by the government. In Sarawak, villages fall under the administration of *Daerah Kecil* (sub-district), which is administered by *Daerah* (district). A district is a subdivision of a *Bahagian* (division) of a state. A *Ketua Kampung* is the chairperson of *Jawatankuasa Kemajuan dan Keselamatan Kampung* (Committee of Village Development and Security), the grassroots level government body which is responsible to oversee the management and development of the village (Ahmad 1987). The committee usually hold a meeting once in a month, and the committee members will receive allowance for their contribution.
The Long Beruang Penan society was semi-nomadic a decade ago. Their living lifestyle has not transformed much since; some of the villagers are still hunters and food gatherers although they have settled at Long Beruang. Under the government scheme, the villagers are beginning to involve in agriculture. Some of them have their own lands where they plant paddy and garden vegetables. The most common of all is cucumber, which is presented on the dining table every day!

There is only one pre-school in Long Beruang. Children have to go to Bario, about five days’ walk distance, to receive primary education at Sekolah Kebangsaan Bario and secondary education at Sekolah Menengah Kebangsaan Bario. They stay in the hostel and only come home during school holidays. The government has arranged transportation between villages to schools on fixed schedule. Other than that, students can sometimes take for a ride in the pickup truck from logging camp workers. The dominant religion in Long Beruang is Christianity, and villagers are followers of the Borneo Evangelical Church, or SIB (Sidang Injil Borneo in Malay), which is very influential in inland Sarawak such as Ulu Baram and the Kelabit highland.

The village does not have any clinical service. The only clinic in the vicinity is in Long Banga, a nearby village at about four hours’ walking distance. Long Banga also has an airport, thus it serves as a vital pit stop for people travelling in Ulu Baram. Nonetheless, the villagers of Long Beruang can have some basic health care from the Flying Doctor Service, which was introduced by the Sarawak Health Department in 1973 (Health 2010). The Flying Doctor Team usually consists of a medical officer and a
medical assistant who will visit the village about once in a month, giving out prescriptions and medicines for minor illnesses. In case of serious disease, the Flying Doctor Service helicopters will provide medical emergency evacuation to transfer patients to nearest hospital in town.

1.3 STATEMENT OF THE PROBLEM

This thesis is aimed to design and build the Long Beruang Solar Project, from design phase to final implementation, and hence, discuss and review its sustainability.

Specifically, this thesis aims to

1) Identify suitable solar power system for the village based on its geographical advantage and daily energy consumption.
2) Design and build the proposed solar system.
3) Evaluate the sustainability of the system by observing the actual load growth.
4) Perform environmental and economic analyses on the system.

1.4 SIGNIFICANCE OF THE STUDY

This study intends to record the construction of a standalone solar power system for a rural village in interior Sarawak. The core value of this project is its community-based participatory approach, in which villagers were fully involved in the building of power house, assembly of system components and the routine maintenance after project implementation. This thesis also aims to fill in the void which is the insufficient solar radiation data available for Sarawak. Moreover, this thesis addresses itself to project engineers, researchers and interested practitioners in hope that they will gain insights on the applicability of similar projects in interior Sarawak.

1.5 SCOPE AND DELIMITATION

On-site preliminary fieldwork involved site survey and data collection which includes number of households, daily energy requirement, power equipment used by the villagers, etc. Subsequently during the design phase, careful planning and rational prediction in system sizing was made in order to meet system requirement while keeping the project cost within budget. Procurement and logistic planning came in after the design phase. Meanwhile the construction of power house was carried out by the villagers. Later,
actual system installation was carried out by experienced System Integrator and Testing and Commissioning was performed under the supervision of JKR. Finally, actual load profile and system feasibility in terms of environmental and economic aspect were studied.

Figure 1.2 displays the five stages undertaken in this project:-

| Preliminary Work | • Site survey  
|                  | • Data collection (number of households, daily energy requirement etc.) |
| Design Phase     | • System sizing |
| Installation Phase | • Actual system installations carried out by experienced System Integrator (SI) |
| Testing & Commissioning | • Testing and Commissioning performed under the supervision of JKR |
| Data Analysis    | • Actual load profile  
|                  | • System feasibility |

This study was delimited to the cost budget and its geographical location. Since this is a Community-Based project, the budget is tight and that restraints the purchase of extra monitoring equipment. Regrettably, the existing monitoring system does not track user load and external power logger had to be used to record actual load profile. Nonetheless the cost to send a person to the site is very high and time consuming. To take the shortest trip, one has to take forty minutes flight-trip from Miri to Long Banga, and then another two hours road-trip by four-wheel drive in the mountainous terrain to reach Long Beruang. Later, one is confined in the village until the driver comes at the appointed date simply because there is no other mean of transportation (very few villagers own a vehicle; for those who own one, they always work outstation and come home once in a few months). Thus this hindered the collection of actual load profile.
1.6 THESIS OVERVIEW

Chapter 2 is the review of literature covering major components in a solar power system; they are photovoltaic cells, inverters, charge controllers and energy storage system. In addition, power system topologies and review of similar photovoltaic systems in other remote areas are discussed. The chapter also highlights the development of renewable energy in Malaysia, as well as solar radiation model related to the state of Sarawak. Chapter 3 is the presentation of the project progress, from site survey to testing and commissioning. It also explains the system flow of the solar power system. In Chapter 4, the actual load profile of Long Beruang is presented. Two data sets taken in Year 2010 and 2012 are compared to show the village loading growth. Also, solar irradiation in Long Beruang is presented. On the other hand, the environmental and economic analyses are examined in Chapter 5. Also, the socioeconomic impact brought to the village will be briefly discussed. Chapter 6 presents the solar radiation model in Sarawak, based on two models, namely the Angstrom-Prescott model and the Cloudiness model. The final chapter concludes the whole thesis and discusses possible future work.
CHAPTER 2
LITERATURE REVIEW

This chapter reviews the development history and basic concepts of major components in a solar power system, which include photovoltaic cells, inverters, charge controllers and energy storage system. Various power system topologies will be briefly discussed in the end of the chapter.

2.1 PHOTOVOLTAIC (PV) CELLS

The energy radiated by the sun is around 7% ultraviolet (UV) light, 47% visible light and 46% infrared light. Solar radiation is attenuated before reaching Earth’s surface by an atmosphere that removes or alters part of the incident energy via reflection scattering and absorption, thus removing nearly all UV radiation and certain wavelengths in the infrared region. Diffuse radiation is the radiation scattered by striking gas molecules, water vapour or dust particles. Clouds are able to reduce direct radiation in so far as 80 to 90% (McGraw-Hill 2005, p. 656).

In quantum theory, light consists of packets of energy, called photons, whose energy depends only upon the frequency of the light. There is about \(4.4 \times 10^{17}\) photons strike on a square centimetre Earth’s surface every second on a clear day (Markvart 2000, p. 32). When light is absorbed by matter, photons provide sufficient energy for electrons to be freed from their respective atoms, and thus photoelectric effect occurred. In a photovoltaic device, the energy of the excited electrons creates a potential difference, or electromotive force (e.m.f.) which will drive electrons through a load in external circuit. When the sunlight falls on a solar panel, the light’s energy is transferred into the semiconductor material, causing electrons to be released and thus flow freely as a current. The resulting electric current is then drawn out with metal contacts on the top and bottom of the photovoltaic (PV) cells. Photovoltaic, coined from the Greek word \(\text{phos}\) meaning “light” and the word \(\text{volt}\) meaning “electricity or voltage”, is a device producing electrical power directly from light.
2.1.1 Brief History of Solar Cells

In 1839, Edmund Becquerel discovered the photovoltaic effect when he observed that an electric current was produced when light was directed on silver coated platinum (silver halide) electrode immersed in electrolyte. Later, photoconductivity had been explored by various scientists such as William Adams, Richard Days, Charles Fritts, Walter Schottky and others.

In 1950s, a breakthrough in manufacturing p-n junctions in silicon had inspired the development of PV application. The first silicon solar cell was reported by Chapin, Fuller and Pearson in 1954, converting sunlight at an efficiency of 6%. From 1950s to 1960s, PV had been widely used in extraterrestrial applications. In the 1970s, global concerns in energy supply due to the 1973 oil shock had stimulated the growth in solar cell technologies in the attempt to fabricate cheaper and more efficient commercial solar cells. In the late 1990s, the PV market expanded at a rate of 15–25% per annum, resulting in cost reduction in PV manufacturing (Nelson 2003, p. 4). Nowadays the PV technologies have become the focus of commercial renewable energy activity.

The major PV technologies include bulk silicon technologies, thin film technologies, and electrolyte technologies. Figure 2.1 below shows the physical appearance of solar cells made from monocrystalline, polycrystalline and amorphous silicon.

Figure omitted in the electronic version.

Figure 2.1 – Solar cells, made from monocrystalline, polycrystalline and amorphous silicon. (Photo courtesy: http://www.pvsolarchina.com)
2.1.2 Crystalline Silicon

2.1.2.1 Principles of Solar Cell Operation

Silicon in its pure state is an intrinsic semiconductor. A silicon atom has fourteen electrons, in which ten of them are tightly bound to the nucleus, another four are valence electrons. A valence electron is located in the valence shell of an atom, and can be transferred to or shared with another atom. Thus each silicon atom can share a valence electron from its adjacent atoms, forming a lattice as illustrated in Figure 2.2 (a).

At low temperature, crystalline silicon acts as an insulator as its valence electrons are tightly bound to the atomic nuclei. But when heat is applied, sufficient energy can break the bonds between valence electrons and nucleus, causing electrons to flow freely through the lattice, as shown in Figure 2.2 (b). The resulting atom is positively-charged, it is called a hole. Together they are known as an electron-hole pair (Lynn 2010).

The hole is stationary, but electron is mobile. When an electron leaves its own hole and goes into the vacant spot of another hole, the subsequent electron will move forward to fill the previously vacated hole, there is a flow of electron. Now the crystalline silicon is a conductor. In order to produce electricity from a pure silicon wafer, the p-n junction is needed to propel electron and hole in the opposite direction.

The nature of a p-n junction is determined by its dopants, which are impure atoms, often phosphorus or boron. A silicon crystal atom has four valence electrons, while phosphorus has five and boron has three. When silicon is doped with phosphorus, there is an extra electron which is weakly bound to its parent atom and is free to move in the lattice. In this case, surplus electrons are the majority carriers, thus the conductor is referred as negative-type or n-type. In contrast, holes will be the majority carriers when silicon is doped with boron. This is called a positive-type, or p-type conductor.

*Figure omitted in the electronic version.*

(a) (b)

*Figure 2.2 - (a) Silicon crystal lattice; (b) electrons and holes*
When a n-type semiconductor is placed together with a p-type semiconductor, its majority carriers (electrons) will diffuse to the p-type material and vice versa. This diffusion in opposite directions creates a strong electric field, a potential barrier that hinders further flow, forming the depletion region, sometimes called the junction region, as seen in Figure 2.3 – A p-n junction

Now the p-n junction acts as a diode, allowing current to flow in one direction only. In forward bias, the p-type material is connected positively to an external voltage with respect to the n-type. Current is produced at a specific fixed voltage called the cell voltage. Silicon’s cell voltage is around 0.6 V. On the contrary, when the voltage source is inverted, the diode is in a reverse bias situation, which increases potential barriers and limits current flow. This is when dark saturation current, $I_o$ exists (the diode current in this case). This reverse current is almost constant until the breakdown point is reached. The voltage-current characteristic of a silicon diode is shown in Figure 2.4. Current flowing through a diode is expressed as:

$$I = I_o \left[ \exp\left(\frac{qV}{kT}\right) - 1 \right]$$  \hspace{1cm} (2.1)

Where $I = \text{net current flowing through the diode (A)}$

$I_o = \text{dark saturation current (a constant) (A)}$

$q = \text{charge of an electron} (= 1.602 \times 10^{-19} \text{C})$

$V = \text{applied voltage across the diode’s terminals (V)}$

$k = \text{Boltzmann’s constant} (qV \text{K}^{-1})$

$T = \text{absolute temperature} (\text{K})$

The maximum current from the cell is the current drawn when all terminals are connected together. It is called the short circuit current, $I_{sc}$. For an ideal diode, the current can be defined by the following equation:

$$I = I_L - I_D$$

$$= I_L - I_o \left[ \exp\left(\frac{qV}{kT}\right) - 1 \right]$$  \hspace{1cm} (2.2)

Where $I_L = \text{light – generated current}$

$I_D = \text{diode current}$
Under open circuit when $I = 0$, all the light-generated current passes through the diode. Under short circuit when $V = 0$, all the current passes through the external load, $I_L = I_{sc}$. The maximum voltage of the cell, its open circuit voltage, $V_{oc}$, is the voltage developed when all terminals are isolated (infinite load resistance). When $I = 0$, $V_{oc}$ can be defined by the following equation:

$$
V_{oc} = \frac{kT}{q} \ln \left( \frac{I_L}{I_o} + 1 \right)
$$

An ideal solar cell is best illustrated in the equivalent circuit in Figure 2.5. When illuminated, a photocurrent is generated proportional to the light intensity. The higher the resistances, the more the photocurrent flows through the diode, creating a higher potential difference (photovoltage) between the cell terminals but a smaller current through the load.

*Figure omitted in the electronic version.*

*Figure 2.3 – A p-n junction*

*Figure omitted in the electronic version.*

*Figure 2.4 - The voltage-current characteristic of a silicon diode.*

*Figure omitted in the electronic version.*

*Figure 2.5 – The equivalent circuit of an ideal solar cell.*
2.1.2.2 Monocrystalline Silicon

Each monocrystalline PV cell is made from a single crystal of silicon. Monocrystalline silicon is the most efficient silicon hitherto, but it is costly due to manufacture reason. The monocrystalline silicon operates on the conventional p-n junction structures, the most common design. When a photon is absorbed by matter, electrons will be excited from its original energy state (ground state) to a higher energy state (excited state), as shown in Figure 2.6. The band gap separates the energy bands in order to prolong the time the excited electrons stay in the excited state so that electrons can be collected to produce electronic energy. If the band gap is too large, more energy from solar photons is needed to create the electron-hole pairs. Too small the band gap, excessive energy is dissipated as heat. Therefore the band gap should be close to the optimum for the intended solar spectrum. Band gap of silicon is 1.1 electron Volts (eV) while efficient energy harvest from sunlight requires band gaps in the range of 1.0–1.6 eV (Lynn 2010, p. 45).

The efficiency of a solar cell energy conversion is determined by its light absorption, charge separation and charge transport. Nelson (2003, p. 177) states that for good light absorption (or optical absorption), the optical depth should be high for energy above the band gap, and the reflectivity of the surface should be small. Optical losses can be reduced by minimizing the blocking of the light by the top contact of a cell, reflection from the top surface and reflection from the back contact (can be achieved through using an uneven black surface to trap incoming light within the cell by total internal reflection).

Figure omitted in the electronic version.

Figure 2.6 - Quantum effects in solar cell
Good charge separation can be realized through high doping. A potential barrier is created through doping, not only to reduce the recombination process of electron-hole, but also to produce more charge carriers. Recombination is the process whereby the excited electrons, instead of being driven across the p-n junction and collected, rejoin with the hole and are annihilated. The most common is the bulk recombination (occurrence in the centre of the cell), the others occur close to the cell’s surface, edges and metal contacts.

Lastly, for efficient charge transport, the minority carrier transport requires long lifetimes, long diffusion lengths, and small surface recombination velocities. While the majority carrier transport requires small series resistance and high shunt resistance to prevent carriers from returning back across the junction. Typical commercial monocrystalline module efficiencies are in the range of 12–16% while average surface area required is about 7 m²/kWp (Lynn 2010, pp. 26 - 52).

### 2.1.2.3 Polycrystalline Silicon

A polycrystalline silicon cell is produced from pure molten silicon through a casting process, where silicon is cooled in substantial blocks, then cut into small bricks and finally made into individual wafers. The crystal structure is irregular and random, thus polycrystalline silicon is less efficient compared to its cousin monocrystalline. Typical commercial module efficiencies are in the range of 11–15% while average surface area required is about 8 m²/kWp. Nonetheless, due to lower manufacturing costs in wafers, polycrystalline modules are cheaper and have overtaken monocrystalline in volume production in recent years (Lynn 2010, pp. 26 - 27).

### 2.1.3 Amorphous Silicon

The Latin word *morpho* means “form”. Amorphous silicon, a-Si, as the name suggests, means “no form”. Amorphous is a type of thin-film cells. A thin-film is a solar cell which involves depositing very thin layers of semiconductor on a substrate. Amorphous material is the large number of dangling bonds where atomic structure is quite random, compared to the tightly ordered structure of crystalline material. These however encourage recombination which reduces efficiency. Hydrogen is added to enhance the optoelectronic performance. Hydrogen dilution causes the growth of protocrystalline a-Si:H, which is commonly used in producing high-performance a-Si solar cells.
The basic cell structures of a-Si are different from those of crystalline silicon. Instead of the traditional p-n junction structures in crystalline silicone, p-i-n and n-i-p heterojunction cell structures are used to take advantage of the excellent properties of the intrinsic a-i:H and a-SiGe:H materials. A very thin p-layer is used to minimize optical absorption so as to achieve a high open circuit voltage. Light is absorbed in the i-layer, assisted by the internal electric field. The photo-generated carriers in a-Si cells must be collected primarily as a drift current due to the short carrier lifetimes caused by the localized gap states, in contrast to crystalline silicon whose photo-generated carriers are used as diffusion current (Carlson & Wronski 2006, pp. 218 – 243).

Under standard test conditions (1000 W/m$^2$, 25 °C), a-Si module efficiencies are typically 6–8% and the average surface area required is 16 m$^2$/kWp (Lynn 2010, p. 28). At first glance, the performance of a-Si is weak and incompetent compared to crystalline silicon modules. But when efficiency is not the main criterion, cheaper modules are always in favour. For instance, in recent years, there is a trend in using PV cladding as the building facades. a-Si module in this case is much more preferable because it is better in absorbing diffused sunlight, in contrast to crystalline silicones which perform well under direct beam sunlight but weak under diffuse sunlight.

### 2.1.4 Other Materials

Other types of PV cells include Copper Indium Diselenide (CIS), Cadmium Telluride (CdTe), Gallium Arsenide (GaAs) and dye-sensitized cells (DSCs). Often referred to as the ‘Second Generation’, thin-film modules like CIS and CdTe are common products in the PV market. They are named after their respective p-type materials (CIS absorber and CdTe absorber). They have direct energy gaps, exhibiting strong light absorption. Moreover high energy gap, 1.42 eV for CIS and 1.45 eV for CdTe, allows a greater percentage of the solar spectrum to be harvested, increasing efficiency. The module efficiencies of CIS range from 10–12% while CdTe’s efficiency is 11%. Simple deposition techniques also lead to lower production costs. Nonetheless these solar cells are not so environmental friendly because cadmium (Cd), a type of heavy metal, is cumulatively poisonous. And the compound of cadmium and sulphur (CdS) is used as the n-type material in both CIS and CdTe cells (Lynn 2010, pp. 61 – 66).

Since 1960s, GaAs-based solar cells have been used in space applications due to better temperature stability and higher radiation resistance in space compared to silicon.
GaAs solar arrays had been used in the Russian moon-cars in the 1970s, where operating temperature of these arrays on the illuminated moon surface was about 130 °C. GaAs cell is highly efficient; its efficiencies fall in the range of 18.3–34.0% (Andreev 2006, pp. 356). On Earth, GaAs is mostly used as mirror and lenses in terrestrial concentration system. The downside of this solar cell is its extremely expensive production cost, which is not a major concern for most space projects (Lynn 2010, pp. 66 – 69).

Regarded as the ‘Third Generation’ solar cells, DSCs work on a different basis contrary to convention PV systems in which light absorption and charge collection happen within the same semiconductor. In a DSC, these processes are separated: initially a dye “sensitizer” is doped into the semiconductor, titanium dioxide (TiO₂), light absorption occurs when the excited sensitizer injects an electron into the conduction band of TiO₂, where electrons are transported to an electrode. In short, the dye acts as a sensitizer to TiO₂, light absorption takes part in the dye while charge collection takes part in TiO₂. The early Grätzel DSCs cells recorded cell efficiency of 10% (Lynn 2010, p. 71), nonetheless recently a new benchmark of 12.3% cell efficiency have been reported (Dye-sensitized Cells break new record 2011). In 2007, module efficiencies are reported to be within 5–7%, but the figure is expected to reach 10% by 2015 (Pagliaro, Palmisano & Ciriminna 2008, p. 123). The colourful and transparent properties make DSCs popular products for building integrated PV, not to mention that they can be tailor-made to various sizes and shapes due to their flexibility.

2.2 CHARGE REGULATOR, CONVERTER & INVERTER

2.2.1 Charge Regulator

Charge regulator, or charge controller, controls the charging and discharge of battery banks. Power intake will be restricted when battery voltage has risen to a predetermined maximum value to prevent overcharging. Similarly, excessive discharge is avoided by impeding batteries from discharging when battery voltage has dropped to a predetermined minimum value. The voltage regulation can be done by using a shunt regulator or a series regulator, as shown in Figure 2.7. A shunt regulator is a variable resistance element (usually bipolar transistor or metal oxide semiconductor field effect
transistor (MOSFET)) connected in parallel with batteries and PV arrays. When resistance is increased, more current from PV will flow to the battery banks. The downside of a shunt regulator is that large amount of power may be dissipated. Alternatively, when a regulator is connected in series with batteries and PV arrays, the series resistance will increase when the battery voltage increases (when battery is charged), thus limiting further increment in the battery voltage and current. Since the voltage across the element is small when the battery is nearly or fully charged, there is less power dissipation (Markvart 2000, pp. 100 – 102).

Usually, the charger will verify that the input voltage and frequency are in tolerance before ramping up slowly to prevent a transient load being presented to the input source.

2.2.2 DC / DC Converter

The voltage level of DC source generated from PV arrays can be transformed through DC/DC converter. As illustrated in Figure 2.8, two of the common types are the buck converter, which reduces the voltage, and the boost converter, which increases the voltage. The switch is an electronic switch, usually MOSFET or insulated gate bipolar transistor (IGBT) at higher power level. At pulse width modulation (PWM), the switches are driven at a constant switching frequency. At pulse frequency modulation (PFM), the pulse frequency is varied to change the duty ratio. In short, a DC/DC converter regulates the voltage closes to maximum power point.

2.2.3 DC / AC Inverter

A DC/AC inverter converts the polarity of DC from PV arrays through appropriate transformer, control circuit and switching. The DC power from PV arrays is converted to AC power to run AC appliances or to be fed into the utility grid. A solar inverter that is connected directly to the PV often has functions such maximum power point tracking and anti-islanding protection.
Figure omitted in the electronic version.

(a)

Figure omitted in the electronic version.

(b)

Figure 2.7 - (a) Shunt regulator; (b) Series regulator

Figure omitted in the electronic version.

(a)

Figure omitted in the electronic version.

(b)

Figure 2.8 - Circuit diagram of the (a) buck converter (b) boost converter.
2.3 ENERGY STORAGE SYSTEM

In a sustainable system, excessive energy is often stored up rather than being discarded. Not to mention most of the renewable energy sources are intermittent and inconsistent, for instance solar, wind and tidal energy which depend heavily on weather conditions. The energy storage can enhance system voltage stability and provide continuous operation in case the primary energy source is unattainable.

In this section, various types of energy storage will be briefly discussed. The main focus is the batteries, principally the lead-acid batteries, which are used in this project. Basic cell operation, battery charging patterns and their outcomes will be further discussed, followed by the use of lead-acid batteries and fuel cells in solar application.

2.3.1 Types of Energy Storage

Almost all types of energy storage systems store electricity in another form of energy before converting it back into electricity when it is necessary. Feasible energy storage forms comprise of potential energy (hydropower), kinetic energy (flywheel), chemical energy (rechargeable battery), electric charge (capacitor) and so on. The designs and selections over a certain energy storage system often take into account of the end-user’s necessity, actual site condition, scale of energy distribution, financial risk and environmental impact. Above all, practicality and sustainability are the major factors in choosing the type of energy storage (Duffie & Beckman 2006).

2.3.2 Batteries

A cell is an electrochemical device which converts chemical energy to electric energy, while a rechargeable cell can be recharged by electricity in a reverse process. A battery comprises of two or more cells, connected in desired series or parallel configurations to produce necessary operating voltage and capacity. Hence the basic electrochemical unit is the “cell”, even though the term “battery” is being widely used (probably due to the fact that most of the end-user’s products are sold as batteries) (Linden & Reddy 2002).

2.3.2.1 Types of Batteries

As shown in Figure 2.9 - Four categories of batteries, batteries can be grouped into four major categories, i.e. primary cells (non-rechargeable), secondary cells (rechargeable),
reserve cells and fuel cells. The primary cells are often light-weighted, inexpensive, and can be used only once. Therefore they are often used in one-off application. Nonetheless, high capacity primary batteries are also being used in military applications, signalling, etc.

On the other hand, the secondary cells are often labelled as “storage batteries” or “accumulators” due to their ability to be recharged. The secondary batteries are being utilized in two main categories, which are to act as an energy-storage device and being used essentially as a primary battery. In the first type of application, batteries often act as a backup source and they are connected to and charged by a primary energy source. Examples include automotive and aircraft system, uninterruptible power supply (UPS), stationary energy storage (SES) and hybrid electric vehicles. In the latter applications, secondary batteries are favoured over primary batteries for cost savings and environmental reasons. For instance, the batteries used in portable consumer electronics. Any single activated cell has the tendency of self-discharge, which is the loss of the cell stored capacity due to internal chemical reaction without any electrode connection. To overcome this problem, the reagent (electrolyte or solid electrolyte in the case of the thermal battery) is set apart from a primary battery prior to activation to prolong battery life for long term storage. This is called the reserve battery.

A fuel cell, like battery, is an electrochemical device which harnesses a chemical reaction between two reagents to produce heat and electricity. The main difference between a battery and a fuel cell is that the former is usually self-contained with reagents, whereas the reagents for the latter are supplied externally. Unlike batteries, which are considered flat once reagents are exhausted, a fuel cell continues running until it is turned off or when reagents are no longer supplied to it.
Figure omitted in the electronic version.

Figure 2.9 - Four categories of batteries
2.3.2.2 Principles of a Battery Cell Operation

In a lead-acid cell, negative plate is made of lead (Pb) plate and positive plate is made of lead plate coated with lead dioxide (PbO\(_2\)). Overall chemical reaction of charge/discharge mechanism is expressed by the following formula (arrow pointing to the right denotes discharge and vice versa):

\[
Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O \quad (2.4)
\]

During discharge, the lead on the negative electrode (active plate) and the lead dioxide on the positive electrode are converted into lead (II) sulphate (PbSO\(_4\)). The sulphuric acid (H\(_2\)SO\(_4\)) in the electrolyte is used up during discharge. The product is water (H\(_2\)O), which forms within the electrolyte. The continual formation of water dilutes the acidity of sulphuric acid. The flow of electrons can be explained if one looks at the reaction on cathode and anode separately. The reaction occurs at the negative electrode is expressed by the following formulae:

\[
Pb \rightarrow Pb^{2+} + 2e^- \\
Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4 
\quad (2.5)
\]

During discharge, the lead is oxidized into plumbum ion (Pb\(^{2+}\)), contributing two electrons to the external electrical circuit. The plumbum ion, in order to achieve stable form, reacts with the sulphate ions (SO\(_4^{2-}\)) in the electrolyte to form lead sulphate. The reaction occurs at the positive electrode is expressed by the following formulae:

\[
PbO_2 + 4H^+ + 2e^- \rightarrow Pb^{2+} + 2H_2O \\
Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4 
\quad (2.6)
\]

In short, during discharge, anodic reaction occurs at the negative electrode, in which the electrode experiences oxidation and loss of electrons; cathodic reaction occurs at the positive electrode, in which the electrode experience mass reduction and gain of electrons. On the other hand, the process operates in the reverse way for charging. During charging, cathodic reaction occurs at the negative electrode while anodic reaction occurs at the positive electrode. These electrochemical reactions are depicted in Figure 2.10 and Figure 2.11.
2.3.2.3 Battery Charging

There are three basic modes of charge/discharge for a battery, namely constant resistance, constant current and constant voltage. Under the same initial discharge condition (having the same discharge load), in the case of a constant resistance discharge, the current decreases in proportional to the decrease in the cell voltage, according to the Ohm’s Law:

\[
I = \frac{V}{R}
\]  

(2.7)
In the *constant current* mode, the voltage varies with the current remains constant. Battery can be charged in a shorter period compared to the constant resistance mode. In the *constant voltage* charging, the voltage input to the battery is maintained stable at a constant value. The potential difference exists between the battery charger voltage and battery cell voltage will induce high initial charge current. As the charging goes on, the potential difference will be reduced and the current will decrease. The current reaches zero when the battery reaches full state-of-charge (SOC). The constant voltage mode is sometimes referred to as the constant power mode, given that the power level almost remains constant throughout the charging process (power = current x voltage). Battery can be charged faster in this mode compared to the constant current mode.

The charging regime may have a drastic effect on the battery performance, thus battery charging algorithm is very important. The *Intermittent Charging* is the on/off control based battery charging. Battery cell is charged at constant current until its voltage reaches the end point charge voltage. Then the charging stops, causing voltage drop until it reaches the minimum floating voltage. Then the charging starts again, this time only to increase the voltage to maximum floating voltage. The charging goes on and off intermittently to maintain the battery voltage within the floating voltage threshold. The shortcoming of this method is the prolonged charging period as energy is cut off during the off time, which varies according to the battery SOC (Koutroulis & Kalaitzakis 2004, p. 192).

The *Three Stage Charging* involves three different charging phases. Initially the battery is bulk-charged to 70-80% of its capacity at constant maximum current until its voltage reaches the end point charge voltage, known as the absorption voltage. The second stage is the absorption charging, that is constant voltage charging at the absorption voltage to fill up the remaining capacity. The final stage is float charging, whereby battery is maintained in a fully charged condition by continuous, long-term constant voltage charging. Small current is supplied to maintain the voltage at a level sufficient to balance self-discharge (Armstrong, Glavin & Hurley 2008, p. 1470).

The *Interrupted Charge Control* is similar to the intermittent charging, where battery is charged at constant current with a chosen charge rate initially. The charging stops when the upper threshold limit is reached to allow the voltage drops to lower voltage threshold. Nonetheless, instead of being charged by a constant current as in the intermittent charging, battery is now being pulse charged to full capacity with a lower
charge rate until the upper voltage threshold is reached. The charging cycles repeat when the battery voltage falls to 97% SOC. This type of charging algorithm is reported to be suitable for standby application (Armstrong, Glavin & Hurley 2008, p. 1470).

The energy efficiency of a battery is defined by its Watt-hour efficiency, which is the ratio of the Watthours delivered on discharge of a battery to the Watthours needed to restore it to its original state under specified conditions of charge and discharge. It is the product of coulombic and voltage efficiencies, typically marked at 75%. While the coulombic efficiency (or charge efficiency) is defined by the Ampere-hour efficiency, the ratio of the output of a secondary cell or battery, measure in Ampere-hours, to the input required to restore the initial SOC, under specified conditions, typically 85% for lead-acid batteries. The voltage efficiency is simply the ratio of average voltage during discharge to the one during recharge, typically 90% (Lynn 2010, p. 138).

The battery capacity denotes the total number of Ampere-hours (Ah) that can be withdrawn from a fully-charged cell or battery under specified conditions of discharge. Normally battery manufacturers marked their reference rated capacity at C/10. C-rate is the charge or discharge current, in Amperes. It is also known as the Hourly Rate. 0.25C or C/4 means that time of discharge is 4 hours; likewise, 0.05C or C/20 indicates that time of discharge is 20 hours. C-rate can be expressed as:

\[ M = \frac{I}{C_n} \]  
(2.8)

Where \( M \) = multiple or fraction of \( C \)

\( I = \text{current}, A \)

\( C = \text{numerical value of rated capacity of a battery in} \)

\( \text{ampere} – \text{hours (Ah)} \)

\( n = \text{time in hours for which rated capacity is specified} \)

For instance, for a battery rated at 500 mAh at 0.05C or C/20 rate to be discharged at 50 mA, the discharge rate is

\[ M = \frac{I}{C_{0.05}} = \frac{0.050 A}{0.500 A} = 0.1C \text{ or } C/10 \]
For a specific rated battery capacity, 0.05C or C/20 has a much lower C-rate discharge compared to 5C or C/0.2. Lifetime of a lead-acid battery can be extended if battery operates at regular low C-rate charge/discharge cycles; on the contrary, irregular high C-rate discharge is undesirable, especially at low SOC.

Overcharge or undercharge a battery cell for a long period may have significant impact to its performance. Overcharging is defined by the numbers of ampere-hours (Ah) divided by the discharged times. Typical overcharge values for lead-acid batteries are between 105% and 130%. On the other hand, continuous undercharging may results in “hard” sulfation, stratification, and negative plate grid loss. Permanent premature capacity losses may be caused by the deprivation in the positive active mass (IEEE Standards 2003, pp. 3 - 25).

Undersized battery will typically have shorter lifetime. Nonetheless, over-sizing is not recommended as the overall energy performance will not improve significantly with increased battery size. Another reason for this is that battery will self-discharge regardless of the battery size. Maintaining high SOC can prolong battery lifetime.

2.3.2.4 Outcomes of Battery Charging

Apart from heat emission, the battery charge/discharge cycle will result in sulfation, stratification, and gassing. When a lead-acid battery is left in a discharged condition for an extended period, lead (II) sulphate crystals on the positive and negative plates will start to develop. This crystal-growth process is named sulfation. If the battery works normally, lead sulphate crystals will turn into lead in the charging process. Consistent undercharging means the battery will not be completely recharged and the remaining lead sulphate crystals on the plate will solidify throughout the time. An abnormal drop in electrolyte specific gravity after an equalization charge and by a gritty texture on the plates usually indicates an excessive sulfation or “hard” sulfation. The crystals form an insulating layer on the plate, preventing the flow of charge, and thus prolonging the charging time. Battery operating temperature will increase as well.

When the heavier acid formed by the decomposition of sulphates precipitates to the bottom and the lighter electrolyte moves to the top of the cell jar due to gravitational force, this phenomenon is called electrolyte stratification. The lighter electrolyte is often diluted; in some cases consist of almost pure water, which is a poor conductor of
electricity. Also, oxidation will occur on the upper part of the plates, and will cause corrosion, reduced battery capacity, shortened battery life and permanently damaging the battery. Destratification can be achieved through gassing and equalization in order to mix the electrolyte. For severe condition, extended heavy gassing for hours at voltages at or above 2.40V per cell is required to recover the battery cell (IEEE Standards 2003, p. 17).

Gassing is a result from hydrolysis where water molecules split into hydrogen cations (H\(^+\)) and hydroxide anions (OH\(^-\)) during charging process. The hydrogen gas, if accumulated up to a certain concentration (between 4 and 79% by volume at standard temperature and pressure), can be explosive if a spark is present. Therefore good ventilation is always desired in a battery room design. Malfunction in the cell plug or overheating in the room can also result in explosion. However, the VRLA battery operates on a recombination system whereby water refilling is done automatically when vapour from catalyst condenses on the wall of vent plugs and drips back into the cell. This system not only reduces the risk of potential oxygen outgassing, but also lowers the overall costs on ventilation and maintenance. Hydrogen gas and carbon dioxide are emitted in normal charge/recharge operation, but the amount is minimal (Linden & Reddy 2002, p. 24.39).

All of the above mentioned conditions may deteriorate due to poor charge/discharge pattern. Therefore battery management system is introduced to prevent battery from being overcharged or undercharged.

2.3.2.5 Types of Lead-Acid Batteries

There are basically three types of lead-acid batteries, i.e. flooded lead-acid, starved-type, and gelled-type, each named after their respective electrolytes. What has been discussed hitherto is flooded lead-acid, in which the electrolyte (sulphuric acid) is in aqueous solution form. The other two are valve-regulated lead-acid (VRLA) batteries, which are gas tight with a valve that only allow the release of gas in the case of overpressure in the cell. The electrochemical reactions are the same as flooded lead-acid since they also comprise of Pb/H\(_2\)SO\(_4\)/PbO\(_2\). The difference is in the electrolytes. In a starved electrolyte cell, sulphuric acid electrolyte is completely absorbed within a highly porous glass matt, which may be made of fibreglass and polyethylene. Thus it is sometimes referred as the absorbed glass mat (AGM) battery. Alternatively, fumed silica (SiO\(_2\)) gel
is added to the electrolyte in a gelled-type cell. Both types of batteries have immobilized electrode, thus batteries can be operated in any position, moreover, there is no spillage of electrolyte in case the cell jar breaks. In normal operation, since gas recombination occurs within the cell, there is no necessity to add water, reducing maintenance level.

Since VRLA batteries cannot be refilled with water, gassing must be reduced to prevent the cell from drying out. The battery is near the end of its lifetime after more than 10% water loss. Therefore VRLA batteries are not suitable for high current charging applications. Normally lead-calcium alloys grids are used in VRLA batteries to achieve low gassing rates. The use of such grids prevents excessive hydrogen evolution on the negative electrode, minimizing pressure build-up in the vented cell. On the contrary, flooded batteries use mainly lead-antimony alloys with less than 2.5% antimony (Sb) (Sauer 2005, pp. 829 – 832; Anderson & Carr 1993, pp. 475 - 476).

### 2.3.3 Batteries in Solar-PV Application

For lead-acid batteries, shallow cycle batteries are discharged no more than 25% of rated capacity on a daily basis, and up to 80% over the period of autonomy. They are designed to produce high energy over a short period of time, with longer autonomy periods. The term autonomy denotes the length of time during which a PV-battery system can provide energy to the load without energy from the photovoltaic array (IEEE Standards 2007, p. 24). Tubular plates are usually used as electrodes in multi-cycling batteries for solar application (Lynn 2010, p. 139).

Besides conventional batteries, fuel cells have also been integrated with photovoltaic module in various applications. A hybrid robotic wheelchair powered by solar panel, a hydrogen fuel cell, and a Nickel Hydrogen Battery is proposed to investigate optimal energy source performance (Takashi, Matsuo & Kawakami 2008, p. 1636). Fuel cells are often regarded as substitute to traditional battery storage. Thakur and Garg (2008, p. 2526) had studied the economic viability of Proton Exchange Membrane Fuel Cells (PEMFC) for harnessing solar, whereby power generated from solar panels was used to split water into hydrogen and oxygen, where hydrogen was kept inside storage tanks while oxygen was released into the air. The hydrogen would then again recombine with oxygen to produce electricity in the event of insufficient sunlight or at night.
2.4 PV CELLS, MODULES & POWER SYSTEM TOPOLOGIES

2.4.1 PV Cells & Modules Configuration

The basic unit of the PV system is the solar cell, generating a DC photovoltage of 0.5 to 1 V in action of sunlight (Markvart 2000, p. 85). A typical silicon cell will produce power between 2 to 3 W, i.e. equivalent to 3 to 5 A at its cell voltage (0.6 V) which is too small for most applications. Therefore solar cells must be arranged in series and in parallel to generate useful current and voltage according to power demand. Generally, the nominal operating voltage of the system has to be matched to the nominal voltage of the storage subsystem. Hence usually 28 or 36 pieces of solar cell are connected in series to produce a module which generates 12 Vdc under standard illumination condition to work with 12 Vdc batteries. The more the silicon cells connected in series in a module, the larger its output voltage. Modules of 72 silicon cells can produce voltage at maximum power point, $V_{mp}$ of 35 V.

A module consists of transparent front side, encapsulated solar cells and back contact. Low-ion and tempered glass is usually used as the substrate not only for illumination and encapsulation, but also as a supporting structure. Placed between the solar cells and the glass is usually a thin Ethylene Vinyl Acetate (EVA) foil. Cells are interconnected with thin contacts on the upper side of the semiconductor material. Not all cells are the same due to manufacturing defects, causing mismatch losses. These losses can be minimized by sorting cells of identical power output before interconnection.

*Figure omitted in the electronic version.*
The second type of losses is the hot-spot formation, in which a malfunctioning cell degrades the performance of the entire string. Consequently, bypass diodes are integrated into cells to avoid complete power loss in case of single component failure. Usually a few cells will share one bypass diode. Similarly, as shown in can be applied to modules connected in series. At the end of each string, blocking diodes (red colour) are used to ensure that current only flows out from the PV module. It also serves to prevent PV from providing a discharge path for the batteries during night-time operation (Markvart 2000, pp. 85 – 92).

2.4.2 Power System Topologies

As shown in Figure 2.13, a direct current (DC) coupled system supplies electricity directly to DC loads without back-supply is possibly the simplest PV system. However it has scalability limitations as number of components is to be kept to an absolute minimum. Usually battery is used as energy storage to avoid the problem of load matching with the PV array. The PV charges the battery bank while supplying electricity to DC loads. Maximum power point tracking (MPPT) is commonly used to allow the module to operate at the voltage at which the module is able to produce maximum power, instead of operating at the battery voltage during the charging.

There are three configurations for alternating current (AC) loads system, namely series, switched and parallel, depending on the way energy from the generator is used, and the used of different types of inverters. Figure 2.14 shows a series system, in which all of the supplementary energy provided by the generator passes through both the battery charger and the battery bank, and passes through power inverter for AC loads.

*Figure omitted in the electronic version.*

*Figure 2.13 - PV system supplying DC loads without backup supply.*
The DC bus is easy to interface and to expand because battery bank, inverter and backup generator can be optimally matched. However, since the inverter is to handle all the output power, it must be sized accordingly to cope with the peak load. Failure in inverter will result in complete power loss.

As for a switched system as shown in Figure 2.15, the supplementary energy from the generator is supplied directly to the AC bus and to the battery charger. Battery bank is separated from the load and maintained in a state of full charge. Only when the backup power source fails, then the load is switched to the batteries. In this case, energy loss from generator incurred in the series system can be avoided but brief power interruption will occur during the power switching. Apart from that, switched configuration has the same characteristics as series configuration.

In a parallel configuration as shown in Figure 2.16, bi-directional inverter is used to interconnect the DC bus and the AC bus. It can charge the batteries as well as connect the generator supply to the AC loads while the generator is running. The inverter must synchronize with the generator supply before connection. The grid can still supply to AC load directly (either from generator or utility grid) if the bi-directional inverter fails which makes the system less dependent on battery bank.
Figure 2.15 - Switched Configuration

Figure 2.16 - Parallel Configuration

Figure 2.17 - AC-connected Parallel Configuration

Figure 2.17 exhibits an AC-connected parallel configuration. It is similar to a parallel configuration, excluding the DC bus. Battery bank is linked to the bi-directional inverter and inverters can be sized to match power sources. All the inverters are
integrated on the standardized AC bus and must be synchronized to the grid supply. The system can easily be extendable in the future by adding more solar modules, charge controller, batteries and inverters. A major advantage of this system is that the system can be connected to the main-utility power grid or power lines whenever it reaches the village. A disadvantage of the system is the restriction of mini-grid size. Larger energy requirement would involve extra individual mini-grids.

Nowadays for AC loads system, most PV-inverters are integrated with MPPT (Monsour & Burton 2002). Contrary to the common believes that configurations with more inverters will respond better to partial shading, studies have shown that more-inverter-configuration can lead to greater losses if inverters fail to find the PV’s MPP (Garcia et. al. 2008, p. 529).

2.4.3 Review of Systems

In 1968, a 48 Wp PV system was set up to power an educational television for a school in Niger. It was the first formally reported photovoltaic application in rural electrification. Since then, more PV installations had been established, ranging from small-powered street-lighting or solar pump, to large scale solar home systems. Large PV rural electrification systems often include PV modules and other balance-of-system (BOS) components such as inverters, batteries, charge controllers and sometimes backup generator. Studies have shown that breakdown of such BOS components often contribute to system failure; PV modules, on the other hand, are rare to fail since they are highly standardized and internationally validated certification procedures for PV are much more established compared to other components (Lorenzo 1997).

In Malaysia, Madmud (2010) had evaluated the Solar Hybrid System for Rural School in Sabah. He concluded that although the PV-battery-generator combination would induce higher start-up cost compared to diesel-generator, it would however reduce the operating cost since less service and maintenance are required. Madmud also highlighted that battery system is critical as it not only contributes almost half of the total lifetime cost, but also supply almost half of the daily load consumption for the schools.
2.5 MICROGRIDS

In spite of the widely distributed grid connection in most of the developed countries, there are still remote areas where electricity is not available. In the case of medium or large scale solar home systems, microgrid is introduced. A microgrid usually consists of a group of distributed energy resources within the low and middle voltage grids. Equipped with protection systems and real-time control systems, a smart microgrid can either connect to the main distribution grids, acting as a distributed generator, or operate in stand-alone mode. In the former situation, whenever faults occur in the distribution grid, the microgrid is capable of islanding; continue to supply power within its local distribution network and then reconnecting to the grid later after the event. Multiple microgrids have been successfully implemented in some RE-leading countries in Europe, United States and Japan. The operation of microgrids not only increases penetration of RE and other distributed energy resources, but also provides higher availability and power quality compared with the main utility grid in meeting mounting electricity demand in rural areas. A microgrid is only efficient under well-planned networking of the distributed sources, but it also offers dynamic characteristic in incorporating various energy sources.

2.6 DEVELOPMENT OF RENEWABLE ENERGY IN MALAYSIA

The Malaysian government has started looking into sustainable development since the Seventh Malaysia Plan (7MP, 1996 – 2000). In the Eighth Malaysia Plan (8MP, 2001 – 2005), the Fifth Fuel Policy 2000 was announced on top of the previous Four Fuel Diversification Policy 1981, and hence the five fuels now include oil, gas, coal, hydro and renewable energy (RE). RE was declared as the fifth fuel to supplement the conventional energy supply to promote green energy in Malaysia. The Centre for Education and Training in Renewable Energy and Energy Efficiency (CETREE) Started as a joint programme between the Malaysian Government and the Danish International Development Agency (DANIDA) in 2000. It was introduced to educate students on RE as well as to raise public awareness on the importance of RE and Energy Efficiency (EE). Competitions, campaigns and learning tours related to RE and EE have been
organized by CETREE (Centre for Education and Training in Renewable Energy and Energy Efficiency (CETREE) 2009).

On the other hand, the government has launched the Small Renewable Energy Programme (SREP) on the 11\textsuperscript{th} May 2001 to promote private investment in the RE. Under SREP, private sectors who utilize RE in their power generation plants can sell back electricity to the Utility through the Distribution Grid System. Licenses are awarded to the RE electricity producers for a period of 21 years, which will be effective from the date of commissioning of the plant. The selling price and other aspects must concur to the Renewable Energy Power Purchase Agreement (REPPA) which states the electricity ceiling price, hours of connection to the grid and the penalty of non-compliance. Although the power exported to the grid is limited to 10 MW, a RE power generation plant is allowed to have its capacity of more than 10 MW. Besides, the Ministry of Energy, Green Technology and Water (KeTTHA, or Kementerian Tenaga, Teknologi Hijau dan Air) has established the Special Committee of Renewable Energy (SCORE) (not to be confused with Sarawak Corridor of Renewable Energy which is also known as SCORE) to further coordinate the approval of RE application under the SREP (Small Renewable Energy Power Programme (SREP) 2009).

The Biomass-based Power Generation and Cogeneration Project (BioGen) is a Global Environmental Facility (GEF) Operational Program (OP-6) initiated by the Malaysia Green Technology Corporation (formerly known as the Malaysia Energy Centre, or Pusat Tenaga Malaysia (PTM), a non-profit company set up to act as a linkage between universities, research institutions and industries) in October 2002 on behalf of the KeTTHA. The main aim of BioGen is to encourage biomass and biogas power generation in grid-connected projects through excess oil palm biomass residues disposal.

In 2004, the Low Energy Building (LEO) was set up in Putrajaya. The building energy index was reported to be 114 kWj/m\textsuperscript{2}/year in 2005 but the value has decreased to 104 kWj/ m\textsuperscript{2}/year in 2006. Nonetheless, energy index of the LEO Building is still lower than conventional buildings (Energy Efficiency 2009). This is a positive sign of government’s planning in promoting sustainable building. Later, on 3\textsuperscript{rd} January 2009, the Malaysia’s Green Building Index (GBI) was introduced by the Malaysian Institute of Architects (PAM, or Pertubuhan Akitek Malaysia). It is the only other rating tool
for the tropical zones, the other being Singapore Government’s GREENMARK (Green Building Index 2011).

The Malaysia Building Integrated Photovoltaic Technology Application Project (MBIPV) commenced on 25th July 2005 with the intention to encourage long-term cost reduction of non-emitting Green House Gas (GHG) technology via Building Integrated Photovoltaic (BIPV). It was a five year project, ending in 31st December 2010. The target amount of annual GHG emissions avoided from fossil fuel-based power generation in tonnes carbon dioxide and of the cumulative installed PV capacity are 1168 tonnes and 1545 kWp respectively. These figures are inclusive of awarded Suria 1000 capacity but not yet commissioned by the date of the report (ANNEX 1: INDICATORS WITH ANNUAL TARGET VALUES (updated August 2007) 2012).

The Suria 1000 programme is part of the MBIPV incentives, which intends to set up BIPV market in the residential and commercial sector. Every year starting from 1st December 2006, limited number of grid-connected solar PV systems were offered to the public on a bidding (auction) concept. At the initial stage, Suria 1000 started off with 40kWp target capacity and 75% subsidy borne by the government. Subsequently at every new call of bidding, the target BIPV capacity (kWp) available would be increased, whereas the percentage for maximum bidding incentive would be reduced (Suria 1000 Programme 2012). Another government incentive initiated is that any project developed under the SREP programme is eligible for Pioneer Status (PS) or Investment Tax Allowance (ITA). Companies which invest in BIPV for their own use can enjoy the privilege of “double tax deduction”, when they get ITA benefits on top of the Capital Allowance (CA). For PS to benefit from the RE to be sold under the SREP scheme: 100% of investment against 100% of statutory income (taxable income) for 10 years; for ITA, however, 100% against 100% of statutory income (taxable income) for 5 years are given for both REs to be sold under the SREP scheme and for own consumption (Government Incentives 2012).

The 9th Malaysian Plan (2006–2010) further emphasizes on energy efficiency and the utilization of renewable energy to tackle the nation's energy challenge in proportion to the sustainable development. Launched on 21st March 2006, the National Biofuel Policy aims to reduce the country’s reliance on depleting fossil fuels and promoting demand for palm oil through five strategic thrusts, i.e. Biofuel for transport, industry,
technologies, export and cleaner environment. Chua and Oh (2010, pp. 2916-2925) have highlighted the National Biofuel Policy as below:

1. Producing a biodiesel fuel blend of 5% processed palm oil with 95% petroleum diesel.
2. Encouraging the use of biofuel by giving incentives for providing biodiesel pumps at fuelling stations.
3. Establishing industry standard for biodiesel quality under Standards and Industrial Research Institute of Malaysia (SIRIM).
4. Setting up of a palm oil biodiesel plant.

Commenced in 24th July 2009, the National Green Technology Policy carries the responsibility to promote sustainable development and facilitate Green Technology of the nation in the long run (expected to last till the 12th Malaysia Plan). In a nutshell, the National Green Technology Policy is based on four fundamental pillars: (a) Energy – to seek to attain energy independence and promote efficient utilisation, (b) Environment – to conserve and minimize the impact on the environment, (c) Economy – to enhance the national economic development through the use of technology, and (d) Social – to improve the quality of the life for all. The main areas of development are focused at four sectors, i.e. energy, buildings, water and waste water management, and transport sector. Five strategic key thrusts are listed in order to achieve long term success (Ministry of Energy, Green Technology and Water) (National Green Technology Policy Pillars 2011).

Although the government has tried hard to promote RE since 2001, the development of the Malaysia RE market has been growing on a relatively small scale. Consequently, KeTTHA proposed the National Renewable Energy Policy and Action Plan (National Renewable Energy Policy and Action Plan 2010) to address these issues and to regulate existing policy to fit current situation. The major obstacles faced by the RE industries are identified as (a) market failure, (b) constraints, (c) arbitrary price setting, (d) tensions and trade-offs, (e) absence of regulatory framework, (f) poor governance, (g) limited oversight, and (h) lack of institutional measures. Drawing lessons from the past, new policy objectives and key thrusts are set as the National RE Policy aims to achieve 21,370 MW Cumulative Total RE with 73% share of RE capacity and 24% RE Mix by the end of 2050.
Under the National Renewable Energy Policy and Action Plan, the Malaysia Feed-in Tariff (FiT) mechanism is introduced to further promote sustainable energy in the nation. The Sustainable Energy Development Authority (SEDA) is set up under KeTTHA to administer the operation of FiT. The four major sectors which are eligible for FiT covers Biomass (including solid waste), Biogas (including landfill gas and sewage), Small-hydro and Solar PV. For the Feed-in Approval Holder, electricity generated from the aforementioned indigenous renewable energy resources can be sold to power utilities (the Distribution Licensees) at a fixed premium rate for a specific period. An effective period of 16 years is set for Biomass and Biogas, and 21 years for Small-hydro and Solar PV. The FiT rate differs based on different RE resources and their installed capacities. When bonus criteria are met, Feed-in Approval Holders will enjoy the privilege of bonus FiT rates. On the other hand, a RE tariff had long been initiated under the SREP since 2001, which has not been much successful due to various reasons. Therefore, the existing SREP holders are entitled to convert their SREP to FiT at their own free will. Upon conversion, duration and payment will be adjusted accordingly to their respective Commercial Operation Date (COD) (FiT Handbook English 2011).

Nonetheless, survey conducted by Muhammad-Sukki et. al. (2011, p. 223) reveals low public awareness of the national initiatives, around 63.1% of the respondents are oblivious of any RE incentives available. While 57% of them are not concern about the electricity sources, only 51.4% are willing to pay for higher electricity bill if electricity is generated from RE. Feedbacks from the public unveil the poor performance of government awareness programme in promoting RE; where 73% rated the effectiveness as either ‘very poor’ or ‘poor’, 22% maintained neutral and only 5% rated the performance as ‘good’. None have chosen ‘excellent’.

On the other hand, FiT is not applicable to the state of Sarawak as the electricity supply in Sarawak is governed by its own legislation and regulations. The RE Act refers to the Electricity Supply Act under the purview of the Federal Government (FAQs on FiT 2011). In brief, constant efforts and integration from the government and private sectors are needed to further promote RE in Malaysia. Overview of the development of RE in Malaysia is shown as follows:-
- Renewable Energy included as the fifth fuel to supplement the conventional energy supply (Fifth Fuel Policy 2000)
- Centre for Education and Training in Renewable Energy and Energy Efficiency (CETREE)
- Small Renewable Energy Programme (SREP) was launched in 2001
- Biomass-based Power Generation and Cogeneration (BioGen) Project was introduced in 2002
- LEO (Low Energy Office) Building in Putrajaya was first occupied in 2004
- Malaysia Building Integrated Photovoltaic Technology Application Project (MBIPV) was commenced in 2005

- National Bio-fuel Policy 2006
- National Green Technology Policy 2009

10th Malaysian Plan (2011 – 2015)
- introducing the Feed-in Tariff and Renewable Energy Fund to promote RE projects

2.7 SOLAR RADIATION MODELS RELATED TO MALAYSIA

Solar radiation is a critical criterion in solar energy system design. Mathematical modelling is the most common practice to estimate solar radiation. Other means of prediction include satellite images utilization (Azhari et. al. 2008, p. 373). Understanding the basis of the sun’s position from any location on earth is crucial to determine the amount of terrestrial solar radiation received. There are many terms to describe energy from the sun, depending on their empirical characteristics. Muneer (2004, p. xxxiii) provides a concise explanation to those terms:
“Solar radiation (W/m²) or luminance (candela (cd)/m²) refers to the energy emanating from the sun. Luminance is the energy contained within the visible part of the solar radiation spectrum (0.39 – 0.78 µm). The term irradiation (Wh/m² or J/m²) and illumination (lumen-hour (lm-h)/m²) refer to the cumulative energy incident on a surface in a given period of time. Irradiance (W/m²) and illuminance (lm/m²) refer to the instantaneous incident energy.”

In this chapter, the fundamentals of solar radiation model which include the algorithm to calculate the sun’s position and related geometry will be explored. The equations used are mostly based on Muneer (2004, p. 5 - 45). Monthly-averaged daily horizontal global irradiation models and the statistical evaluation of the models will be reviewed subsequently. Finally, empirical models generated for cities in Malaysia will be discussed in the last section.

2.6.1 Fundamentals

2.6.1.1 Equation of Time and Solar Declination

The equation of time (EOT) denotes the difference between the standard time and solar time. The solar declination angle (DEC) is the angular position of the sun at noon at apparent solar time (AST) with respect to the equatorial plane. The high precision Yallop’s Algorithm is adapted to compute the EOT and DEC. Muneer (2004) reported an accuracy of 3s for the EOT and 1 min of arc for DEC for the period 1980 to 2050.

For a given year (y), month (m), day (D), hour (h), minute (min) and seconds (s):-

\[ t = \frac{[(UT/24) + D + 30.6m + 0.5 + 365.25(y - 1976) - 8707.5]}{36525} \]

where

\[ UT = h + \left(\frac{mins}{60}\right) + \left(\frac{s}{3600}\right) - \left(\frac{LONG}{15}\right) \]

if \( m > 2 \), then \( y = y \) and \( m = m - 3 \); otherwise \( y = y - 1 \) and \( m = m + 9 \)

The following terms are then determined:-

\[ G = 357.528 + 35999.05t \]

\[ C = 1.915sinG + 0.020sin2G \]

\[ L = 280.460 + 36000.770t + C \]

\[ \alpha = L - 2.466sin2L + 0.053sin4L \]
If necessary, add or subtract multiples of 360° to $G, L$ and GHA to set them in the range of 0-360°

**Obliquity of the ecliptic**, $\varepsilon = 23.4393 - 0.013t$

\[
\begin{align*}
DEC, \delta &= \tan^{-1}(\tan \varepsilon \sin \alpha) \quad \text{(in degree)} \quad (2.9) \\
EOT &= \frac{60(L - \alpha)}{15} \quad \text{(in minutes)} \quad (2.10)
\end{align*}
\]

### 2.6.1.2 Sunrise and Sunset Time

The sunrise and sunset time is described by the sunrise-sunset hour angle,

\[
\omega_s = \cos^{-1}(-\tan DEC \tan LAT) \quad (2.11)
\]

In reality, sunrise will appear earlier and sunset will be later compared to the computational value due to light refraction by the earth’s atmosphere.

The computational sunrise and sunset time for Long Beruang lies within 5.9571 to 6.0429 (in hours). Since the deviation is small, and it is relatively close to the actual sunrise and sunset at site, data from 6 a.m. to 6 p.m. will be analyzed throughout this paper.

### 2.6.1.3 Solar Altitude & Solar Azimuth

The sun’s position in the sky for any place at anytime is determined by solar altitude angle (ALT) and solar azimuth angle (AZM). The solar altitude is the vertical angle, or elevation, of the sun above the horizon, whereas the azimuth angle is the angle measured from true North within the horizontal plane. In this paper, clockwise from North is considered positive.

\[
\text{Apparent Solar Time, } AST = LCT + \left\lfloor EOT - 4(LSM - LONG) \right\rfloor / 60 \quad (2.12)
\]

where
- LCT = Local Clock Time
- LSM = Local Standard Meridian
- LONG = Longitude

\[
\text{Hour Angle, } HRA = 15 \times (AST - 12) \quad \text{(in degree)} \quad (2.13)
\]

\[
ALT = \sin^{-1} [\sin LAT \sin DEC + \cos LAT \cos DEC \cos HRA] \quad (2.14)
\]
2.6.2 Monthly-averaged Daily Horizontal Global Irradiation

2.6.2.1 Ångström-related Equation

The original Ångström regression equation (Ångström 1924, p. 121) relates daily irradiation to clear sky irradiation. Based on data in Stockholm, Ångström derived the following equation:

\[ AZM = \cos^{-1}\left[ \frac{\cos DEC (\cos LAT \tan DEC + \sin LAT \cos HRA)}{\cos ALT} \right] \]  \hspace{1cm} (2.15)

Where if \( \sin(HRA) \leq 0 \), \( AZM = AZM \)

else if \( \sin(HRA) > 0 \), \( AZM = 360^\circ - AZM \)

The original Ångström regression equation (Ångström 1924, p. 121) relates daily irradiation to clear sky irradiation. Based on data in Stockholm, Ångström derived the following equation:

\[ \frac{Q_S}{Q_o} = 0.25 + 0.75S \]  \hspace{1cm} (2.16)

where \( Q_S \) = the total radiation-income during the day  
\( Q_o \) = the total radiation-income which corresponds to a perfectly clear day  
\( S \) = the time of sunshine expressed in the greatest possible time of sunshine as unit

Since it is sometimes difficult to define a clear sky day, the equation is generalized to replace the term \( S \) with fractional possible sunshine, \( \frac{n}{N} \) by Prescott (1940, p.114) as:

\[ \frac{Q}{Q_A} = a + b \frac{n}{N} \]  \hspace{1cm} (2.17)

where \( Q \) = daily terrestrial (sometimes refer as global) irradiation on a horizontal surface  
\( Q_A \) = daily extraterrestrial irradiation on a horizontal surface  
\( n \) = daily hours of bright sunshine  
\( N \) = maximum possible daily hours of sunshine (day length)  
\( = 2\omega_s / 15 \)

41
For monthly regression equation:

\[ \frac{\bar{G}}{\bar{E}} = a + b \frac{n}{N} \]  \hspace{1cm} (2.18)

where \( \bar{G} \) = monthly-averaged daily terrestrial (sometimes refer as global) irradiation on a horizontal surface  

\( \bar{E} \) = monthly-averaged daily extraterrestrial irradiation on a horizontal surface

Whereas \( a \) and \( b \) are empirical coefficients. The sum of \( a \) and \( b \) represents the maximum atmospheric transmission coefficient, \( \tau \).

Daily extraterrestrial irradiation on a horizontal surface, \( E \) may be calculated by:

\[ E \text{ (kWh/m}^2\text{)} = (0.024/\pi) I_{SC}[1 + 0.033\cos (360DN/365)] \]

\[ \times [\cos LAT \cos DEC \sin \omega_x + (2\pi \omega_x/360) \sin LAT \sin DEC] \]  \hspace{1cm} (2.19)

where \( I_{SC} \) is the solar constant (= 1367 W/m\(^2\)).

Glover and McCulloch (1958, p. 172) proposed an adaptation to relate the Ångström equation at each latitude over the range of \( 0^\circ \) - \( 60^\circ \). The Glover-McCulloch model derived from daily records generated in the Union of South Africa and Kew, England, may be expressed as:-

\[ \frac{G}{E} = 0.29 \cos LAT + 0.52 \left( \frac{n}{N} \right) \]  \hspace{1cm} (2.20)

Other empirical models to estimate daily terrestrial irradiation have been proposed. Meteorological, geographical and climatological parameters used include relative humidity, air temperature (Akpabio & Etuk 2003, p. 161), etc.

So far only the global irradiation has been discussed. Liu and Jordan (1960) first developed a regression between monthly-averaged daily diffuse irradiation, \( \bar{D} \) and global irradiation, \( \bar{G} \) as a function of monthly-averaged sky clearness index (or cloudiness index), \( \bar{K}_T = \bar{G}/\bar{E} \):

\[ \frac{\bar{D}}{\bar{G}} = a - b\bar{K}_T \]  \hspace{1cm} (2.21)
2.6.2.2 The Inequality of Daily- and Monthly-averaged Regressions

There is a fundamental difference between a daily-based regression and a monthly-averaged regression. As mentioned in Muneer (2004), a daily-based regression derived by Saluja and Muneer (1986) demonstrates a significant different regression compared to the monthly-averaged regression derived by Page (1977). To further clarify this erroneous perception which some researchers have overlooked, theoretical proof had been developed by Muneer (1987) and Saluja et. al. (1988).

2.6.3 Statistical Assessment

Statistical methods are essential to identify uncertainty and variation in scientific data, especially when the sample size is huge. It not only simplifies the work to organise, analyse and interpret data, but also enables data forecast and prediction. In short, statistical assessments improve the quality of a dataset.

There are many statistical methods to evaluate a model. A few of the common statistical evaluation of models are mean bias error (MBE), mean percentage error (MPE), root mean square error (RMSE), correlation coefficient (R) and the Student’s \( t \)-test.

**Mean Bias Error**

\[
MBE = \frac{1}{n} \sum_{i=1}^{n} (H_{i,calc} - H_{i,meas})
\]  

(2.22)

where \( n \) is the number of observation, \( H_{i,calc} \) and \( H_{i,meas} \) are the respective calculated and measured values for the \( i^{th} \) event.

MBE exhibits the overall trend of a model in the long run, whether the data generated is overestimated or underestimated. A positive value indicates that the data is overestimated and vice versa. With that aspect, overestimated and underestimated values will cancel out each other in the process.
**Mean Percentage Error**

\[ MPE(\%) = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{H_{i,calc} - H_{i,meas}}{H_{i,meas}} \right) \times 100\% \]  

(2.23)

As the name suggests, MPE is simply the mean percentage error of two sets of data.

**Root Mean Square Error**

\[ RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (H_{i,calc} - H_{i,meas})^2} \]  

(2.24)

RMSE is used to measure the difference between estimated data with actual data. Smaller value indicates better performance of a model.

**Correlation Coefficient & Coefficient of Determination**

\[ R_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \]  

(2.25)

where \( x_i \) and \( y_i \) are the \( x \) and \( y \) value for the corresponding \( i^{th} \) event whereas \( \bar{x} \) and \( \bar{y} \) are their respective mean values.

The coefficient of correlation, \( R \) denotes the linear relationship between variables on a scale ranging between +1 and -1. Positive value of \( R \) shows that \( y \) is directly proportional to \( x \) and vice versa.

The square of coefficient of correlation is called the coefficient of determination, \( R^2 \). It is a measure of the proportion of variability explained by the fitted model. The larger the value of \( R^2 \), the better is the model performance. However, sometimes the value of \( R^2 \) can be increased by adding too many unnecessary model terms, resulting in over-fitting. Also, the acceptable value of \( R^2 \) varies depending on individual cases.
**Student’s t-test**

\[
 t = \left( \bar{X} - \bar{Y} \right) \frac{n(n-1)}{\sqrt{\sum_{i=1}^{n} (\hat{X}_i - \hat{Y}_i)^2}}
\]  

(2.26)

where \( \hat{X}_i = (X_i - \bar{X}) \) and \( \hat{Y}_i = (Y_i - \bar{Y}) \)

\( t \)-test is used to evaluate the statistical significance of a normally distributed model. It is often used to deal with problems regarding the population mean or comparative sample (i.e. to determine if means from two samples are significantly different). If \( t \) value is smaller than \( t \)-critical, the data is said to be statistically significant, or that the probability of it happening by chance is very small. The significance level, \( \alpha \) of 0.05 is used in this paper. The \( t \) value can also be expressed in terms of MBE and RMSE as in the following equation:-

\[
 t = \frac{(n-1)(MBE)^2}{\sqrt{(RMSE)^2 - (MBE)^2}}
\]  

(2.27)

**Outliers**

Outliers are the observations which lie remarkably far from a bulk of the data. They are sometimes regarded as ‘rare events’ as the probability of their occurrence is small compared to the others. An outlier does not always mean to be a ‘bad data’; rather it indicates peculiarity or change. Therefore an outlier should be examined closely before being eliminated from the whole dataset.

There is no rigid way to determine an outlier. In this paper, the *three-sigma-rule* shall be applied. The upper and lower control limits shall be set by the three-sigma limits from the mean, where sigma, \( \sigma \) represents standard deviation. For small sampling numbers (e.g. \( n < 30 \)), outliers shall be events which are beyond two-sigma limits.
2.6.4 Models related to Malaysia

Malaysia consists of the Malay Peninsula and Sabah and Sarawak (on the upper part of Borneo). A variety of studies on global solar radiation have been carried out over the time. However, solar radiation estimates on specific areas are relatively scarce. Earliest modelling data available in Malaysia was conducted by Chuah and Lim (1981, p. 33) in the 1970s, using the Ångström-Prescott regression for three major towns in the Malay Peninsula, namely Kuala Lumpur, Penang and Kota Baru. Later on, the values of $a$ and $b$ for Kuala Lumpur were used to solar radiation estimation for Malacca, Johor Baru and Mersing. On the other hand, those of Penang were used for Alor Setar, Ipoh, Sitiawan and Cameron Highlands while those of Kota Baru were used for Kuala Terengganu and Kuantan. Daily solar radiation data for four years (1975 – 1978) and monthly average sunshine duration for the aforementioned twelve towns over a period of fifteen years (1961 – 1975) were used. According to Chuah and Lim, the value of $a$ and $b$ for Malaysia lie within the range of 0.22 to 0.39 and 0.38 to 0.64 respectively. And the atmospheric transmission under clear skies, which is represented by the sum $(a + b)$, is in the range of 0.76 to 0.96.

Later in the 1990s, Sopian and Othman (1991, p. 319) performed a more complete data collection, covering eight towns in Malaysia, including Kuching which is the capital city of the state of Sarawak and Kota Kinabalu, the capital city of the state of Sabah. Unlike Chuah and Lim, who used the monthly-averaged value of sunshine duration of a different period, the sunshine duration data used in their analysis was of the same period as that for the global solar radiation. Sopian and Othman reported that for Malaysia, the values of $a$ range from 0.17 to 0.32, whereas the values of $b$ range from 0.28 to 0.62. The sum $(a + b)$ range from 0.56 to 0.77. For the analysis in Sarawak, which is Kuching, a linear regression equation of $\dot{G}/\dot{E} = 0.28 + 0.28(\bar{n}/\bar{N})$ was presented based on three years data (1986 – 1989). The R value for the regarding equation is 0.61. Based on this regression equation, the annual mean value for monthly-averaged daily solar irradiation for Kuching was 4.022 kWh/m$^2$; annual mean value for daily sunshine duration was 5.15 hours.

Subsequently, a case study on the diurnal pattern of global solar radiation in Bangi, Malaysia over a period of five years since Year 1985 was performed by Othman et. al. (1993, p.741). From their studies, the pattern of global solar radiation could be
categorized into five groups, namely global solar radiation pattern for a clear day (15.7%), a fully cloudy day (51.0%), a partly cloudy day with instantaneous intensity higher than solar constant (2.8%) and pattern with afternoon rain (16.5%). The rare occurrence of high instantaneous solar radiation (1400W/m²) recorded on 6th January 1986 was due to reflection and refraction of sunbeam by water molecules, dust, aerosol in clouds and diffusion of anisotropic radiation at the horizon.

In the Malay Peninsula, Muzathik et al. (2011, p.75) have carried out a set of empirical models based on Ångström-Prescott model to estimate the monthly-averaged daily global solar radiation in Kuala Terengganu, the capital of the state of Terengganu. The empirical models consist of the original Ångström-Prescott model, quadratic, cubic, linear logarithmic, etc. They summarized that \( \frac{G}{E} = 0.2207 + 0.5249(\bar{n}/\bar{N}) \) based on Ångström-Prescott model gave the best performance. Nonetheless, the author disagrees with the selection of Glover-McCulloch model as one of the comparing models in Muzathik et al.’s paper. In 1957, Glover and McCulloch had proposed \( G/E = 0.29 \cos \text{LAT} + 0.52(n/N) \) based on the original Ångström equation. The proposed model claimed to be adaptable for latitude (LAT) over the range of 0° to 60°. Nonetheless, it is noteworthy to mention that the original Glover-McCulloch model was derived from annual regression constant \( a \) and \( b \), which was calculated from daily total solar radiation on a horizontal surface, \( G \) and daily hours of sunshine, \( n \). Whilst linear regression based on daily values differs from monthly-averaged values, it is apparent that the values of \( a \) and \( b \), for daily data set and monthly-averaged data set will be different. Naturally, the Glover-McCulloch model fails the statistical significance test in comparison with monthly-averaged data.

In Perlis, a state situated in the Northern Malay Peninsula, Daut et al. (2011, p. 445) performed a mathematical model to calculate clear sky global solar irradiance on tilt angles. Based on the coordinates of Perlis, the tilt angles throughout the years for a PV module are reported to be in the range of -17.16° (facing north) to 29.74° (facing south). The clear sky global irradiance consists of beam, diffuse and reflected solar irradiance. The average annual global solar irradiance in Perlis is computed to be 1019 W/m², while the monthly-averaged beam, diffuse and reflected solar irradiance are 968.36 W/m², 88.22 W/m², and 4.70 W/m² respectively.
On the other hand, in East Malaysia, Jakhrani et.al. (2010, p. 1) proposed a new model to estimate global solar radiation for the four locations in Sarawak, namely Sri Aman, Sibu, Bintulu and Limbang:-

\[
H = H_o \left[ \alpha + \left( \frac{T_{\text{max}}}{\text{RH}} \right) s \right]
\]  

(2.28)

H denotes monthly-averaged daily global solar radiation (MJ/m\(^2\)), \(H_o\) denotes monthly-averaged extraterrestrial solar radiation, \(\alpha\) is the location constant depending on geographical condition (0.24 for Sarawak), \(T_{\text{max}}\) denotes average maximum temperature (°C), \(\text{RH}\) is the relative humidity taken as whole instead of in fraction (e.g. 75% is taken as 75 instead of 0.75) while \(S\) is the fraction of monthly-averaged daily bright sunshine \(\bar{n}/\bar{N}\). This new model is accessed alongside with other six solar radiation models, i.e. Angstrom, Glover-McCulloch, Tasdemirglu, Bahel, Hargreaves and Sayigh Universal formula. Actual measured global solar radiation data for Kuching from the year 2005 to 2009 is used; while other climatological parameters are obtained from the weather stations for each corresponding town. Jakhrani et.al. concluded that the Angstrom model outperforms the others while the proposed model also demonstrates reasonable results, further evaluation is needed.

Hitherto the aforementioned solar radiation predictions in Malaysia are of the use of mathematical modeling. Azhari et.al. (2008, p. 373) has presented a different approach to predict solar radiation by using satellite image. Annual average daily solar irradiations of 4.21 kWh/m\(^2\) to 5.56 kWh/m\(^2\) were reported. While the highest solar radiation was estimated at 6.8 kWh/m\(^2\) in August and November, the month of December marked the lowest value at 0.61 kWh/m\(^2\).
CHAPTER 3
SYSTEM DESIGN & INSTALLATION

This chapter intends to describe the system design criteria and installation for Long Beruang 54 kWp off-grid PV power system. The following contents and plans are solely provided for the purpose of thesis discussion only. Much of the design and implementation depends on the actual geological aspects, cost of labour, and materials availability. The project timeline is as follows:-

- July 2009
  - Site Survey.
  - Meeting with the village committee.
- July / August / September / October 2009
  - System Sizing.
  - Purchase of Equipment.
- November 2009
  - PV Mounting Structures were completed.
  - Site clearing in progress.
- December 2009
  - Components such as PV modules & mounting structures, batteries, inverters and accessories were being delivered to site.
  - Testing done on individual PV modules and battery cells.
- March / April 2010
  - Installation of Balance-of-system (BOS) and Very Small Aperture Terminal (VSAT).
  - Testing & commissioning of the system.

The Long Beruang solar system is an AC-connected parallel configuration as discussed in Chapter 2.
3.1 SITE SURVEY

Preliminary fieldwork on site selection is an essential measure in PV power system as it will affect the overall power output performance. The followings are the criteria in site selection:

1. Avoid shading – Shadows of nearby buildings and trees that will cause partial shading on the PV modules, which in turn will decrease the overall voltage output of a PV string.

2. Sufficient compound – the site should be spacious enough to place all the components together, allowing easy maintenance and prevention of cable loss.

3. Solid ground – the site selected should be on firm and solid compound to reduce extra work for foundation.

4. Strategic location – location of the power plant should not be too far from the village to prevent cable loss.

With the above considerations, a compound of about 70 x 20 m² (red square in Figure 3.1) between the church and the long house was chosen as the project site. There are three main reasons for choosing such a location, i.e. solid and flat compound (the other places are too high or too mushy), no nearby trees that cause shading, and the location chosen is in the centre of the village.

*Figure omitted in the electronic version.*

*Figure 3.1 – Village Layout Plan*
3.2 SYSTEM SIZING

The following system sizing follows the steps and guidelines in the book *Solar Photovoltaic Power: Designing Stand-Alone Systems*, written by Shaari et. al. (2010), except for the inverter sizing. The values used in most of the equations are also from this book unless otherwise specified. The contents of this book are based on the trainings organized by the MBIPV project team, and is also used in the ISP accredited training programmes conducted by the UiTM, as part of the MBIPV Project.

The author is aware that in the subsequent off-grid PV installation courses, there are some changes made to the course materials. As such, system sizing discussed is valid and correct as of system commissioned date 10\textsuperscript{th} April 2010 and solely for this project only.

3.2.1 System Equipment/Instrument Selection

The equipment and instrument used in the project are selected based on system sizing and actual logistic consideration.

Table 1 below is the finalized item list after trial-and-error in calculation and careful consideration of items’ feasibility in the project. The subsequent system sizing (sec. 3.2.2-3.2.5) presented is based on the following item list.

<table>
<thead>
<tr>
<th>No.</th>
<th>Items</th>
<th>Brand Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>PV Modules</td>
<td>Trina TSM-DC01_EU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(180Wp monocrystalline module)</td>
</tr>
<tr>
<td>2.</td>
<td>PV-grid inverters for AC coupling between solar modules and AC grid</td>
<td>SMA 7000TL &amp; SMA 11000TL</td>
</tr>
<tr>
<td>3.</td>
<td>Bi-directional inverters for generating AC grid and recharging of batteries</td>
<td>SMA SI5048</td>
</tr>
<tr>
<td>4.</td>
<td>Batteries</td>
<td>SEC Cellyte – 2TLAM</td>
</tr>
<tr>
<td>5.</td>
<td>Broadband connectivity for remote monitoring</td>
<td>MAXIS VSAT</td>
</tr>
</tbody>
</table>

Table 1 – System Equipment/Instrument.
3.2.2 Energy Calculation

The following table is the estimations of daily energy consumption based on 55 households (as some families live together, that make 68 families into 55 doors. We shall address these as 55 households hereafter).

<table>
<thead>
<tr>
<th></th>
<th>Power (W)</th>
<th>Quantity per Unit</th>
<th>Possible Unit</th>
<th>Daily Hours (h/day)</th>
<th>Daily Energy Consumption (Wh/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JKR MONITORING CENTRE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting Point</td>
<td>8</td>
<td>5</td>
<td>-</td>
<td>0.1</td>
<td>4</td>
</tr>
<tr>
<td>Power Point</td>
<td>150</td>
<td>5</td>
<td>-</td>
<td>0.1</td>
<td>75</td>
</tr>
<tr>
<td>CHURCH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting Point</td>
<td>8</td>
<td>5</td>
<td>-</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>Power Point</td>
<td>150</td>
<td>5</td>
<td>-</td>
<td>2</td>
<td>1500</td>
</tr>
<tr>
<td>HOUSE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting Point</td>
<td>8</td>
<td>3</td>
<td>55</td>
<td>3</td>
<td>3960</td>
</tr>
<tr>
<td>Icebox</td>
<td>75</td>
<td>1</td>
<td>30</td>
<td>24</td>
<td>54000</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>500</td>
<td>1</td>
<td>30</td>
<td>1</td>
<td>15000</td>
</tr>
<tr>
<td>Rice cooker</td>
<td>300</td>
<td>1</td>
<td>30</td>
<td>1</td>
<td>9000</td>
</tr>
<tr>
<td>TV</td>
<td>120</td>
<td>1</td>
<td>30</td>
<td>2</td>
<td>7200</td>
</tr>
<tr>
<td>Radio</td>
<td>5</td>
<td>1</td>
<td>55</td>
<td>5</td>
<td>1375</td>
</tr>
<tr>
<td>Table Fan</td>
<td>20</td>
<td>1</td>
<td>53</td>
<td>5</td>
<td>5300</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>97497</td>
</tr>
</tbody>
</table>

Table 2 - Estimation of daily energy consumption.

Energy Requirement, \( \varepsilon = 97.497 \text{ kWh/day} \)

Solar Contribution = 100% of \( \varepsilon = 97.497 \text{ kWh/day} \)

AC load, \( \varepsilon_{ac} = \text{Solar Contribution} = 97.497 \text{ kWh/day} \)

Energy Required Daily, \( \varepsilon_{req,daily} = \varepsilon_{dc} + \frac{\varepsilon_{ac}}{\eta_{inv,grid,tied}} \) (3.1)

\[
= 0 + \frac{97.497 \text{ kWh/day}}{0.977} \\
= 99.792 \text{ kWh/day}
\]

where \( \varepsilon_{dc} = \text{total energy required daily for DC load (Wh)} \)

\( \varepsilon_{ac} = \text{total energy required daily for AC load (Wh)} \)

\( \eta_{inv,grid,tied} = \text{average efficiency of inverter for AC load} \)

(in our case is grid – tied inverter)
Max. Demand = Peak Load \times 30\% \text{ buffer above Peak Load}

= 35.396 \text{ kW/day} \times 1.3

= 46.0148 \text{ kW/day}

### 3.2.3 Battery Sizing

* System Voltage follows the inverter voltage, which is 48 Vdc.

\[
C_{req,\text{daily}} = \frac{E_{req,\text{daily}}}{\text{System Voltage}} \tag{3.2}
\]

\[
= \frac{99.792 \text{ kWh/day}}{48 \text{ Vdc}} = 2,079 \text{ Ah/day}
\]

\[
C_{bank,req} = C_{req,\text{daily}} \times \frac{T_{\text{autonomy}}}{DOD} \tag{3.3}
\]

\[
= \frac{2,079 \text{ Ah/day} \times 1 \text{ day}}{0.8} = 2,598.75 \text{ Ah}
\]

<table>
<thead>
<tr>
<th>Temperature (^{\circ}\text{C})</th>
<th>(f_{\text{temp,batt}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 (^{\circ})C</td>
<td>1.00</td>
</tr>
<tr>
<td>30 (^{\circ})C</td>
<td>1.04</td>
</tr>
<tr>
<td>40 (^{\circ})C</td>
<td>1.07</td>
</tr>
</tbody>
</table>

**Table 3 - Battery Temperature Correction Factor, \(f_{\text{temp,batt}}\)**

Assume temperature at 30 \(^{\circ}\)C

**Revised Battery Capacity Required,**

\[
C_{\text{revised,bank,req}} = \frac{C_{\text{bank,req}}}{f_{\text{temp,batt}} \times f_{\text{ageing,batt}}} \tag{3.4}
\]

\[
= \frac{2,598.75 \text{ Ah}}{1.04 \times 0.95} = 2,630.53 \text{ Ah}
\]

where \(f_{\text{ageing,batt}} = \text{battery ageing factor} (95\% \text{ capacity @C10 after 15 years})

* refer to APPENDIX for battery specifications
Proposed $C_{\text{bank, selected}} = 1400\text{Ah} @ C10 \times 2$

Total bank Discharge Current, $I_{\text{bank, disch}} = I_{\text{total, load, current}}$

\[
= \frac{1}{SV} \left[ \sum \text{DC Power} + \frac{\sum \text{AC Power}}{\eta_{\text{inv bi-di}}} \right] \quad (3.5)
\]

\[
= \frac{1}{48V} \left[ 0 + \frac{46.0148\text{kW}}{0.85\text{p.f.}} \right]
\]

\[
= 1,187.17\text{A}
\]

Where $\eta_{\text{inv bi-di}} = \text{efficiency of charge controller connected to battery}$

(in our case is bi – directional inverter)

* refer to APPENDIX for SMA’s SI 5048 specifications

Battery Bank Discharge Rate, $T_{\text{bank, disch}} = \frac{C_{\text{revised, bank, req}}}{I_{\text{bank, disch}}} \quad (3.6)$

\[
= \frac{2,630.53\text{Ah}}{1,187.17\text{A}}
\]

\[
= 2.2\text{h}
\]

<table>
<thead>
<tr>
<th>Surge Demand for</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Inductive Loads</td>
<td>$SD \geq 5 \times I_{\text{nominal, load}}$</td>
</tr>
<tr>
<td>▪ Non-Inductive Loads</td>
<td>$SD = I_{\text{nominal, load}}$</td>
</tr>
</tbody>
</table>

In PV-SA system, maximum continuous discharge is given 5 hr rating. Surge Demand is given 1 hr rating.

**Table 4 - Surge Demand for inductive and non-inductive load**

Max. Continuous Discharge Rate for Inductive Load,

\[I_{\text{disc inductive, load}} = 5 \times I_{\text{total, load, current}} \quad (3.7)\]

Assume that only 50% of the inductive load will start motor at the same time.

Revised Max. Continuous Discharge Rate for Inductive Load,

\[
I_{\text{rev disc inductive, load}} = 5 \times I_{\text{total, load, current}} \times 0.5
\]

\[
= 5 \times 1,187.17\text{A} \times 0.5
\]

\[
= 2,967.925\text{A}
\]
Check from the battery constant current discharge table, for 1,400Ah @C10.

\[ I_{\text{disch}} @ C1 = 798A \quad I_{\text{disch}} @ C5 = 287A \]

(*refer to APPENDIX – battery data sheet)

\[
N_{\text{series}} = \frac{\text{System Voltage}}{\text{Nominal Battery Voltage}}
\]
\[ = \frac{48V_{dc}}{2V} = 24 \text{ pcs} \]

\[
N_{\text{parallel}} = \frac{C_{\text{revised bank req}}}{C_{\text{bank selected}}}
\]
\[ = \frac{2,499Ah}{1,400 Ah/\text{string}} \approx 2 \text{ strings} \]

\[
DOD_d = \frac{C_{\text{req daily}}}{C_{\text{bank selected}}}
\]
\[ = \frac{2,079 Ah}{1,400 Ah x 2} \approx 0.74 \]

3.2.4 PV Sizing

* refer to APPENDIX for Trina TSM-DC01_EU specifications.

Cell Effective Temperature,

\[
T_{\text{cell}} = T_{\text{amb}} + \left( \frac{NOCT - T_{\text{NOCT}}}{G_{\text{NOCT}}} \right) \times G
\]
\[ = 28^\circ C + \left( \frac{46^\circ C - 20^\circ C}{800W m^{-2}} \right) \times 850W m^{-2} \]
\[ = 28^\circ C + 27.625^\circ C = 55.625^\circ C \]

where \( T_{\text{amb}} = \text{ambient temperature (}^\circ \text{C)} \)

\( T_{\text{NOCT}} \) = NOCT ambient temperature (\( ^\circ \text{C) (} = 20^\circ \text{C) \)

\( NOCT \) = nominal operating cell temperature(\( ^\circ \text{C) \)

\( G \) = Direct Normal Irradiance (\( = 850 W m^{-2} \)

\( G_{\text{NOCT}} \) = NOCT Irradiance(\( = 800 W m^{-2} \)

NOCT is the equilibrium mean solar cell junction temperature when a module is mounted at tilt-angle 45° from the horizon, and exposed under irradiance 800 Wm⁻²
ambient temperature 20°C and wind speed is 1 ms⁻¹. It is a guideline to the temperature at which a module will operate in the field (DSM, MS IEC 61215:2006, p.33). On the other hand, standard test conditions (STC) are used to test and rate photovoltaic cells and modules under the following reference conditions: PV cell temperature of 25°C, irradiance in the plane of the PV cell or module of 1,000 Wm⁻² and light spectrum corresponding to an atmospheric air mass of 1.5 (DSM, MS1837:2010, p.7). 850 W/m² is the direct normal irradiance accounts for reduced irradiance in direct beam (Kurtz et al. 2011, p. 2),

\[ \text{Temperature Derating Factor, } f_{\text{temp}} = 1 + \gamma_{\text{pmp}}(T_{\text{cell}} - T_{\text{STC}}) \]  

\[ = 1 + \left( -\frac{0.485}{100} \right)(55.625°C - 25°C) \]

\[ = 1 - 0.149 = 0.851 \]

where \( \gamma_{\text{pmp}} = \text{temperature coefficient of current} \ (\approx -0.485\% \ \text{per°C}) \)

\( T_{\text{STC}} = \text{temperature at standard test conditions} \ (\approx 25°C) \)

**Corrected Output Power of Module,**

\[ P_{\text{mod,corrected}} = P_{\text{mp,STC}} \times f_{\text{temp}} \times f_{\text{mm}} \times f_{\text{dirt}} \]  

\[ = 180\ W \times 0.851 \times 0.97 \times 0.97 = 144.127 \ W \]

where \( P_{\text{mp,STC}} = \text{rated power at standard test conditions} \ (W) \)

\( f_{\text{mm}} = 1 - \text{derating factor for manufacturer tolerance} \ (\approx 3\%) \)

\( f_{\text{dirt}} = 1 - \text{derating factor for dirt} \ (\approx 3\%) \)

**Efficiency of the PV Subsystem,**

\[ \eta_{\text{pv,ss}} = \eta_{\text{pv,batt}} \times \eta_{\text{wh,batt}} \times \eta_{\text{mppt}} \]  

\[ = 0.97 \times 0.85 \times 0.95 \]

\[ = 0.783 \]

where \( \eta_{\text{pv,batt}} = \text{efficiency of the PV sub-system} \)

\( \eta_{\text{wh,batt}} = \text{watt-hour or coulombic efficiency of the battery} \)

\( \eta_{\text{mppt}} = \text{efficiency of the MPPT charge controller} \)
Total no. of modules required to meet the energy required daily,

\[
N_T = \frac{\varepsilon_{\text{req,daily}} \times f_0}{P_{\text{mod,corrected}} \times PSH \times \eta_{\text{pv,ss}}}
\]  
\[
= \frac{99.792\text{kWh/day} \times 1.3}{144.127\text{Wp} \times 4\text{hr} \times 0.783}
\]
\[
= 287.39\text{pcs} \approx 288\text{pcs}
\]

where \(f_0\) = over-supply coefficient (dimensionless)

PSH = peak sun hour

The typical over-supply coefficient, \(f_0\) for a PV + battery system is between 1.3 to 2.0; and for a PV hybrid system is 1. According to the *Malaysian Standard on Solar Photovoltaic Energy Systems* (2010), the watt-hour efficiency, \(\eta_{\text{wh}}\) is defined as “Ratio of the amount of electrical energy removed during discharge conditions to the amount of electrical energy added during charge conditions in an electrical energy storage device.” where

\[
\eta_{\text{wh}} = \frac{I_d T_d V_{dav}}{I_c T_c V_{cav}} = \frac{\eta_{\text{ah}} V_{dav}}{V_{cav}}
\]  
\[
(3.16)
\]

where \(I_d\) = discharge electric current (A)

\(T_d\) = discharge time (h)

\(V_{dav}\) = average discharge voltage (V)

\(I_c\) = charge electric current (A)

\(T_c\) = charge time (h)

\(V_{cav}\) = average charge voltage (V)

\(\eta_{\text{wh, batt}}\) is typically between 0.8 to 0.9. On the other hand, peak sun hour (PSH) is the equivalent number of hours in a day when solar power intensity is 1,000 Wm\(^{-2}\) (Shaari *et. al.* 2005, p.4). Since there is no existing information on PSH for Long Beruang, peak sun hour of 4 is assumed for Long Beruang, based on information available for Miri, which is the nearest city to Long Beruang. Annual monthly-averaged sunshine hour for Miri is 6.6 hours as recorded by sunshine recorder at the Meteorological Department.
Determine the operating voltage limits:

**Max. open circuit voltage at effective cell temperature,**

\[ V_{\text{max,oc}} = V_{\text{oc, stc}} + \gamma_{\text{Voc}} \left( T_{\text{min}} - 25^\circ C \right) \]  
\[ = 44.2\, V + \left( -\frac{0.35}{100} \right) (25^\circ C - 25^\circ C) = 44.2\, V \]

where \( V_{\text{oc, stc}} = \text{open circuit voltage at standard test conditions (V)} \)

\( \gamma_{\text{Voc}} = \text{temperature coefficient of } V_{\text{oc}} \left( = -0.35\% \text{ per } ^\circ C \right) \)

\( T_{\text{min}} = \text{minimum temperature } ^\circ C \)

**Max. voltage at maximum power at effective cell temperature,**

\[ V_{\text{max,mp}} = V_{\text{mp, stc}} + \gamma_{\text{Vm}} \left( T_{\text{min}} - 25^\circ C \right) \]  
\[ = 36.8\, V + \left( -\frac{0.45}{100} \right) (25^\circ C - 25^\circ C) = 36.8\, V \]

where \( V_{\text{mp, stc}} = \text{maximum power voltage at standard test conditions (V)} \)

\( \gamma_{\text{Vm}} = \text{temperature coefficient of } V_{\text{mp, stc}} \left( = -0.45\% \text{ per } ^\circ C \right) \)

**Min. voltage at maximum power at effective cell temperature,**

\[ V_{\text{min,mp}} = V_{\text{mp, stc}} + \gamma_{\text{Vm}} \left( T_{\text{max}} - 25^\circ C \right) \]  
\[ = 36.8\, V + \left( -\frac{0.45}{100} \right) (75^\circ C - 25^\circ C) = 36.575\, V \]

where \( T_{\text{max}} = \text{maximum temperature } ^\circ C \)

Determine the maximum modules connected in series:

**No. of modules connected in series (based on } V_{\text{max,oc}}, \)**

\[ N_s = \frac{0.95 \times \text{Max. Input Voltage of Charge Controller}}{\text{Max. } V_{\text{oc}} \text{ of Solar Module}} \]  
\[ = \frac{0.95 \times 500\, V}{44.2\, V} = 10.74 \text{ pcs} \approx 10 \text{ pcs} \]
No. of modules connected in series (based on $V_{\text{max,mp}}$),

$$N_s = \frac{0.95 \times \text{Max. Window Voltage of Charge Controller}}{\text{Max. } V_{\text{mp}} \text{ of Solar Module}}$$

$$= \frac{0.95 \times 500V}{36.8V} = 20.04 \text{ pcs} \approx 20 \text{ pcs}$$

No. of modules connected in series (based on $V_{\text{min,mp}}$),

$$N_s = \frac{1.1 \times \text{Min. Window Voltage of Charge Controller}}{V_{\text{min,mp}} \times \text{Cabling Efficiency for PV String to ChargeController}}$$

$$= \frac{1.1 \times 333V}{36.575V \times 0.85} = 11.78 \text{ pcs} \approx 11 \text{ pcs}$$

Eq. 3.18a is selected because the open-circuit voltage is greater than the maximum power point voltage. It is critical to ensure that the output voltage of the array is within the voltage operating window of the inverter. Also, since the modules are energized by sunlight, the open-circuit voltage of the arrays is the applied voltage when all the system components are first connected together (before the inverters start to operate and feed to the load).

Thus, from eq. 3.18a, select $N_s = 10$ pcs; from eq. 3.15, $N_T = 288$ pcs

Thus no. of strings in parallel, $N_p = \frac{288\text{pcs}}{10\text{pcs}} = 28.8 \approx 29$

Proposed total no. of modules = 10 pcs $\times$ 29 = 290 pcs

Peak capacity of array, $P_{\text{array,mppt,cc}} = P_{\text{array,module,sc}} \times N_s \times N_p$ \hspace{1cm} (3.19)

$$= 180 \text{ Wp} \times 10 \text{ pcs} \times 29 = 52,200 \text{ Wp}$$

Proposed Total Peak capacity of array = $180 \text{ Wp} \times 300 \text{ pcs} = 54,000 \text{ Wp}$

Average daily energy output of PV array, $E_{\text{pv, out}} = P_{\text{array,mppt,cc}} \times PSH$ \hspace{1cm} (3.20)

$$= 54 \text{ kWp} \times 4h = 216 \text{ kWh}$$

Check that the average daily energy output of PV array must be at least equal to or greater than the total energy required daily by the load (eq. 3.1), i.e.:
Solar fraction indicates the contribution of PV-battery system, as in how much of the daily energy need is met by the solar energy source.

### 3.2.5 Inverter Sizing

* refer to APPENDIX for inverters specifications.

#### Sizing for Grid-Tied Inverter

Based on SMA 11000TL Inverter (Max. DC Output is 11.4 kW per unit)

\[
\text{No. of SMC 11000TL} = \frac{\text{Proposed Total Peak capacity of array}}{\text{Max. DC output of SMC11000TL}}
\]

\[
= \frac{54 \text{kW}}{11.4 \text{kW}} = 3.86 \approx 4 \text{ units}
\]

Based on SMA 7000TL Inverter (Max. DC Output is 7.2 kW per unit)

\[
\text{No. of SMC 7000TL} = \frac{\text{Proposed Total Peak capacity of array}}{\text{Max. DC output of SMC7000TL}}
\]

\[
= \frac{54 \text{kW}}{7.2 \text{kW}} = 7.5 \approx 8 \text{ units}
\]

Due to component availability, the following combination is chosen: two units of SMA 11000TL and four units of SMA 7000TL are used:

\[
\text{Max. DC output from Grid – tied Inverter} = 2(11.4 \text{ kW}) + 4(7.2 \text{ kW}) = 51.6 \text{ kW} \geq \text{Max. Demand (46.0148 kW)}
\]

#### Sizing for Bi-directional Inverter

Bi-directional inverters and the battery bank will not be sized to cater maximum demand; rather they are sized for energy requirement. A battery bank is controlled by a cluster of bi-directional inverters, which consists of a master and two slaves.

\[
\text{No. of } SI5048 = \text{No. of strings of Batteries in parallel, } N_{\text{parallel}} \times 3 \text{ units} \quad (3.24)
\]

\[
= 2 \text{ strings } \times 3 \text{ units} = 6 \text{ units}
\]
3.3 SYSTEM INSTALLATION

3.3.1 System Overview

The following figures show the layout of solar PV plant and its arrays arrangement. The total area of the plant is about 23.5 x 51.5 m². As illustrated in Figure 3.2, the power house is situated at the centre of the compound. PV modules are being fixed on the PV mounting structure, at the inclination of 5° facing the South. The maximum height of the structure is about 1.6m, which makes cleaning of modules easy for the Penans. Modules in arrays A, B, E and F are grouped in the configuration of 15S x 3P while modules in arrays C and D are grouped in 15S x 3P, as shown in Figure 3.3. Such arrangement is made to suit grid-inverters of different power capacities.

Figure omitted in the electronic version.

Figure 3.2 - Plant Layout Plan.

Figure omitted in the electronic version.

Figure 3.3 - Solar array mounting structures
As shown in Figure 3.5, the grid inverters are placed on the outer wall while the bi-directional inverters are placed in the inner wall, close to the batteries. This is to reduce cable length as DC power from PV is being delivered to the grid inverters, which converts DC to AC and feed the power directly to AC bus, as depicted in Figure 3.6. The village household are connected to the AC bus. Since the system is load-centric, power will be delivered to end-users’ load first, excessive power will only then be used to charge up the batteries. The standalone bi-directional inverters supply AC power to the AC bus from the batteries when power generated from PV is insufficient.
These inverters are incorporated with battery chargers, thus they can recharge the batteries from AC bus. Three bi-directional inverters act as a cluster; two slave inverters are controlled by a master inverter. Each cluster controls one bank of batteries. The AC power output is in three-phase. But in the case of Long Beruang, the system is single-phase. Thus village households are divided into three groups, each using one phase respectively. A major advantage of this AC coupling system is that it is easily extendable in the future by adding more solar modules, inverters and batteries. An additional advantage is that when the utility grid reaches the village, the system can be integrated and synchronized to the standard AC grid bus.

The system is connected to a fixed Internet Protocol (IP) address through a C-band VSAT. Therefore administrators are able to remote monitor, diagnose and configure the settings of the solar power system through internet.

### 3.3.2 Site Clearing and Power House Construction

Figures 3.7 to 3.22 in Section 3.3.2 to 3.3.6 explain the progress of the power plant from scratch to BOS installation. These figures show the building of power house and spread footing foundation for the PV arrays. In-ground reinforced concrete was used to sustain the weight of PV arrays. Before the marking of foundation, total array size and weight ought to be determined. Section 3.3.3 shows the installation of PV mounting structures and modules. The poles and beams are hot-dip galvanized steels which were pre-manufactured from factory. Holes were pre-drilled to facilitate on-site work. Hence, PV modules could be attached directly on the structures with fine alignments after
unloading. Figure 3.12 shows the Visual inspection and individual module checking that were performed on a bright sunny day. $V_{oc}$, $V_{mp}$ and $I_{mp}$ were measured using multimeter. Likewise, nominal cell voltage for each battery cell was measured; it has to be around 2.00 volts per cell. The installation of power inverter, sensors, VSAT and communication system came in much later. Last but not least, Section 3.3.6 demonstrates the active involvement of villagers in this project. Soil had been dug from nearby borrow pit to smooth out foundation and for fencing. Stones and gravels collected from nearby river were laid on the ground not only to prevent grass from growing, but also to prevent soil erosion.

*Figure omitted in the electronic version.*

*Figure 3.7 - Power house under construction.*

*Figure omitted in the electronic version.*

*Figure 3.8 - Marking and preparing stumps for PV array poles.*
3.3.3 PV Mounting Structures & Modules installation

Figure omitted in the electronic version.

Figure 3.9 - Constructing footings for the poles.

Figure omitted in the electronic version.

Figure 3.10 - Erecting PV mounting structure.

Figure omitted in the electronic version.

Figure 3.11 - Modules were mounted directly mounted on the structures after unloading at 8 p.m.
3.3.4 Batteries Installation

*Figure omitted in the electronic version.*

*Figure 3.12 - Testing of batteries.*

*Figure omitted in the electronic version.*

*Figure 3.13 – Installed battery banks and battery fuse boxes.*

3.3.5 Inverters and VSAT Installation

*Figure omitted in the electronic version.*

*Figure 3.14 – Grid-tied inverters for AC coupling between solar modules and AC grid*
Figure omitted in the electronic version.

Figure 3.15 - Bi-directional inverters connecting AC grid and batteries

Figure omitted in the electronic version.

Figure 3.16 – Installation of BOS

Figure omitted in the electronic version.

Figure 3.17 - Installation of VSAT communication system
Figure omitted in the electronic version.

(a) (b)
Figure 3.18 – (a) Anemometer; (b) Solar radiation sensor.

Figure omitted in the electronic version.

Figure 3.19 - C-band VSAT

3.3.6 Involvement of Local Community

Figure omitted in the electronic version.

Figure 3.20 - Soil from borrow pit for the foundation and fencing structures.

Figure omitted in the electronic version.

Figure 3.21 - Stones and Gravels collected from nearby river.
3.3.7 Testing & Commissioning

Prior to the checking, all DC and AC connections were switched off. First, a start-up test on the PV arrays was performed on a clear sky day. The $V_{oc}$, $V_{mp}$ and $I_{mp}$ of individual modules had been tested before connecting them to form a string. Later, the same parameters for the PV strings were measured and checked again to ensure there is no malfunctioning component. The same process was performed when testing the batteries; individual cells voltage was measured before connecting them in strings, and the strings output were measured before final connection.

The system was tested and commissioned on the 10th April 2010 by experienced system integrator (SI).
CHAPTER 4
RESULTS & FINDINGS

4.1 ACTUAL LOAD PROFILE

4.1.1 Load Profile in December 2010

The actual voltage and current root-mean-square measurement from 19th to 22nd December 2010 was recorded at an interval of five minutes using Fluke 1735 Power logger. Maximum, average and minimum values were recorded. The average values are used and real power is calculated at 0.8 power factor.

Figure 4.1 shows the actual AC loads for four consecutive days (19th, 20th, 21st, and 22nd of December, 2010). Day 19th was Sunday while the rest were weekdays. Every Sunday the villagers will go for church service in the morning. It is obvious that Day 20th, Day 21st and Day 22nd share the same load pattern. During weekdays, the peak power load generally occurred between 7a.m. and 8.30a.m., when people performed their daily chores such as laundry etc. Later, power consumption decreased when most of the villagers were at work in the field. After 4 p.m., the load slowly increased when people returned home from work, started cooking dinner and turned up the lights. Daily energy consumption and peak load is shown in Table 5. The load patterns of weekdays and Sunday are similar; the only difference is the power consumption in the afternoon, as shown in Figure 4.1 (a). Since Sunday was a rest day, most of the villagers stayed at home instead of working in the field, which resulted in the increase of power consumption. The raise in power consumption in a soothing Sunday afternoon compared to weekdays is approximately 1.3kW.

Figure 4.2 illustrates the average daily load profile for these four days. The average peak load was 2.238 kW, which happened around 8 a.m. Power consumption later plunged to around 0.5kW in the afternoon, and then increased gradually in towards evening. The average power usage at night was about 1.7 kW.
Figure omitted in the electronic version.

Figure 4.1 – Daily load profile in December 2010; (a) Difference in power consumption in weekdays and weekend

Figure 4.2 - Average daily load profile in December 2010

<table>
<thead>
<tr>
<th></th>
<th>19/12/10</th>
<th>20/12/10</th>
<th>21/12/10</th>
<th>22/12/10</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kWh/day)</td>
<td>35.848</td>
<td>30.839</td>
<td>31.384</td>
<td>32.338</td>
<td>32.602</td>
</tr>
<tr>
<td>Peak Load (kW/day)</td>
<td>2.358</td>
<td>3.131</td>
<td>2.438</td>
<td>2.296</td>
<td>2.238</td>
</tr>
</tbody>
</table>

Table 5 - Daily energy consumption and peak load in December 2010
4.1.2 Load Profile in March 2010

In March 2012, a set of two weeks data was recorded. Due to some unfortunate events, only the current load is available. Therefore, the current data taken in December 2010 is used in comparison with the current data taken in March 2012 to show the growth in loading.

As illustrated in Figure 4.2, the average daily current profile in December 2010 shares the same pattern as in March 2012. Nonetheless, there is a fourfold increase in the average daily current usage, from average 5.18 A to 20.22 A@240V<sub>ac</sub>. This indicates that more households had installed electrical appliances. The most noteworthy change is the boost in the average power usage at night. In Year 2010, the variation of the night time current usage compared to the one in the afternoon was about 5 A@240V<sub>ac</sub> (Figure 4.3 (b)); and the graph was quite constant throughout the night, at about 7 A@240V<sub>ac</sub>. On the contrary, this variation during day and night has tripled in Year 2012, at about 15 A@240V<sub>ac</sub> (Figure 4.3 (a)). The current usage at night was no longer constant seeing that much more power were consumed from 6.30-9.30 p.m. This might be caused by the increase of luxury electrical products such as televisions and laptops.

Figure omitted in the electronic version.

Figure 4.3 - Comparison of average daily current pattern for Year 2010 and 2012; (a) Difference in average current usage at daytime and night-time in Year 2012; (b) Difference in average current usage at daytime and night-time in Year 2010
Assume that the growth of power consumption is linear, the below calculation is done to estimate the daily energy consumption and peak load in March 2012.

**Energy a Power a (Current x Voltage)**

Assume that voltage, V is constant,

\[
\frac{P_{avg,1}}{I_{avg,1}} = \frac{P_{avg,2}}{I_{avg,2}}
\]

(4.1)

where \( P_{avg,1} \) = *Average Peak Load in December 2010* (2.238kW)

\( P_{avg,2} \) = *Average Peak Load in March 2012*

\( I_{avg,1} \) = *Average Current in December 2010* (5.18A)

\( I_{avg,2} \) = *Average Current in March 2012* (20.22A)

Thus,

\[
P_{avg,2} = P_{avg,1} \times \frac{I_{avg,2}}{I_{avg,1}}
\]

For every event \( i \):-

\[
P_2 = \frac{1}{n} \sum_{i=24hr}^{n} P_{2,i} \times \frac{I_{2,i}}{I_{1,i}} = 7.219 \text{ kW}
\]

Similarly, average daily energy consumption in March 2012 can be estimated:

\[
\varepsilon_2 = \frac{1}{n} \sum_{i=24hr}^{n} \varepsilon_{1,i} \times \frac{I_{2,i}}{I_{1,i}} = 116.502 \text{ kWh/day}
\]

The average daily consumption is shown in Figure 4.4 on the next page:
4.1.3 Section Summary

Table 6 below shows the growth in electricity consumption in the period of two years.

<table>
<thead>
<tr>
<th></th>
<th>Dec 2010</th>
<th>Mar 2012</th>
<th>Percentage Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kWh/day)</td>
<td>32.602</td>
<td>116.502</td>
<td>257%</td>
</tr>
<tr>
<td>Peak Load (kW/day)</td>
<td>2.238</td>
<td>7.219</td>
<td>223%</td>
</tr>
</tbody>
</table>

The latest daily energy consumption is 116.502 kWh/day and the peak load is 7.219 kW. The energy consumed is very close to the maximum energy that can be supplied by the system, 130.098 kWh/day. Villagers will have to be prudence in using electricity so as not to exceed the limitation.
4.2 SOLAR RADIATION IN LONG BERUANG

Figure 4.5 shows the monthly-averaged daily solar irradiation for Year 2011. Highest solar irradiation occurred in the month of July, marking at 4.91 kWh/m$^2$, followed closely by the month of September at 4.82 kWh/m$^2$ and November at 4.65 kWh/m$^2$. On the other hand, January has the lowest solar irradiation, marking at only 4.19 kWh/m$^2$. The annual mean value for monthly-averaged daily solar irradiation is 4.6 kWh/m$^2$. The weather pattern in Long Beruang is pretty much governed by the northeast monsoon, which typically brings rainfalls from November to March.

*Figure omitted in the electronic version.*

*Figure 4.5 - Monthly Averaged Daily Solar Irradiation*
CHAPTER 5
FEASIBILITY REPORT

This chapter investigates the environmental impact in terms of carbon dioxide (CO\textsubscript{2}) mitigation and economic analysis.

In the environmental study, two scenarios are considered, namely the Diesel-Generator and the Grid-Connected. Ideally a solar power plant will have little or near zero carbon dioxide emission, thus it is our concern to know the amount of carbon dioxide mitigation of the solar plant in comparison to the aforementioned scenarios. This analysis is an exclusive ‘in-operation’ comparison.

Later in the economic analysis, Energy Delivery Factor, Initial Capital Cost, Operation and Maintenance Cost, Unit Cost of Energy, Net Present Cost of the project are examined. It is then followed by brief explanations on the Return of Investment and Payback Period. All these analyses are based on the actual situation (rural off-grid solar project). Finally, the scenarios of the Diesel-Generator and the Grid-Connected are studied in terms of Annual Electricity Payable and Unit Cost of Energy respectively.

5.1 ENVIRONMENTAL CONSIDERATIONS

The main aim of promoting renewable energy is to fight against deteriorating environmental issues, for instance global warming, which is principally caused by the massive GHG emission. The GHG in the Earth’s atmosphere include carbon dioxide, methane, nitrous oxide and ozone. The concentrations of these trace gases have increased significantly since 20\textsuperscript{th} century due to human activities. Nonetheless, the most prominent of all is the escalating concentration of carbon dioxide in the atmosphere. In Year 2000, the earth’s atmospheric carbon dioxide was reported at 369 ppm (parts per million), which is about thirty-percent increment before the industrial revolution in the 18\textsuperscript{th} century. Lifetime emission of carbon dioxide for a photovoltaic power generation in Europe was reported to be 5 tonnesCO\textsubscript{2}/GWh, i.e. equivalent to 0.005 kgCO\textsubscript{2}/kWh (Breeze 2005, p. 16). However other countries have reported a higher figure: 0.053 kgCO\textsubscript{2}/kWh for Japan, 0.050 kgCO\textsubscript{2}/kWh for Sweden, and 0.095 kgCO\textsubscript{2}/kWh for
Finland (*Energy Analysis of Power Systems* 2011). Since the average lifetime of most of solar power plants is more than twenty years, annual carbon dioxide emissions are relatively small (contributing less than 0.5 kgCO₂/kWh) compared to other power generation such as coal or oil and gas.

Established under the Article 12 of the Kyoto Protocol (*Article 12 of the Kyoto Protocol* 2010), the Clean Development Mechanism (CDM) aims to promote co-operative measures between the developed (Annex I) countries and the developing (non-Annex I) countries to achieve sustainable development. Malaysia falls under the category of non-Annex I countries. The reduction in GHG is an important criterion in assessing a CDM project.

### 5.1.1 Scenario A: Diesel-Generator

Before the building of solar power plant, diesel generators were the main power source for the village of Long Beruang. According to the Intergovernmental Panel on Climate Change (IPCC) (Gómez & Watterson et al. 2006, p. 2.16), for stationary combustion in the energy industries, the emission factor for gas or diesel oil is 74,100 kgCO₂/TJ. To translate it into kgCO₂/kWh:

\[
\frac{74,100 \text{kgCO}_2}{\text{TJ}} = \frac{74,100 \text{ kgCO}_2}{1 \text{ TJ}} \times \frac{1 \text{ TJ}}{277777.78 \text{ kWh}}
\]

\[
= 0.26676 \text{ kgCO}_2/\text{kWh}
\]

Thus the volume of carbon dioxide produced in a year is:

\[
V_{CO_2,a} = 0.26676 \text{ kgCO}_2/\text{kWh} \times 130.098 \frac{\text{kWh}}{\text{day}} \times \frac{365 \text{ days}}{\text{year}}
\]

\[
= 12,667.30 \text{ kgCO}_2 \approx 12.67 \text{ tonnes CO}_2
\]

### 5.1.2 Scenario B: Grid-Connected

As reported by PTM and DANIDA (Aman 2006, p. 4), the emission factor for CO₂ in Sarawak is 1.116 kgCO₂/kWh. The value was generated from three years data (Year 2002 to 2004) using the Combined Margin Method (by averaging Simple Operating Margin with Build Margin) based on the Approved Consolidated Baseline Methodology (ACM0002), dated 3rd December 2004. The ACM0002 methodology is applicable to grid-connected renewable power generation projects, including solar plants. As the
Sarawak main grids lie along the coastal area, connecting Kuching to Miri, and are independent of themselves (as in not interconnected with Sabah and the Malay Peninsula), therefore all power plants that could be dispatched to the grid without transmission constraints were included in the project boundary. However, the emission factor for diesel used in this account was based on the IPCC report in Year 1996, i.e. 0.073 tCO$_2$/GJ, equivalent to 0.2628 kgCO$_2$/kWh (Aman 2006, p. 19). Therefore a more updated figure published by IPCC in 2006 is preferred in Sec. 5.1.1.

If the village were connected to the SEB utility grid, the volume of carbon dioxide produced in a year could have been:

$$V_{co_2,b} = 1.116 \frac{kgCO_2}{kWh} \times 130.098 \frac{kWh}{day} \times \frac{365 \text{ days}}{year}$$

$$= 53,353.39 \text{ kg} \approx 53.35 \text{ tonnes}$$

### 5.1.3 Section Summary

Table 7 below summarizes the reduction in annual CO$_2$ if the village electricity power were produced by the following scenarios:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CO$_2$ Emission Factor (kgCO$_2$/kWh)</th>
<th>Annual CO$_2$ Produced (tonnes/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Diesel-Generator</td>
<td>0.26676</td>
<td>12.67</td>
</tr>
<tr>
<td>B. Grid-Connected</td>
<td>1.116</td>
<td>53.35</td>
</tr>
</tbody>
</table>

Table 7 - Comparison of Diesel-Generator and grid-connected scenarios in terms of CO$_2$ emission.

Comparing the annual CO$_2$ of the above scenarios shown in Table 7, it is apparent that diesel-generator will produce much less CO$_2$, at only 23.75% of Grid-Connected. This significant gap is due to the difference in CO$_2$ emission factor: The emission factor for Grid-connected is obtained using Combined Margin Method, which is the average of Simple Operating Margin and Build Margin. As of Year 2004, the value of Build Margin for Sarawak is 1.246 kgCO$_2$/kWh. This high value is due to the incorporation of three coal fired power plants, thus contributing to high CO$_2$ emission factor (Aman 2006, p. 22-23).
5.2 ECONOMIC ANALYSIS

5.2.1 Energy Delivery Factor

Not all power produced from the photovoltaic modules will be delivered to end-users due to power losses such as self-consumption of system components and electrical resistances. Energy Delivery Factor (EDF) is a measurement to denote the how efficient the plant is utilized to deliver the maximum possible energy. It is defined as the ratio of the possible energy delivered to end-users to the possible energy could be produced by a plant assuming that it operates at full installed capacity for twenty-four hours per day for the year. Maximum daily energy delivered as calculated in Chapter 3: System Sizing is 130.098 kWh/day.

The average annual EDF can be expressed as follows:

\[
\text{Average annual EDF} = \frac{kWh \text{ delivered over the year}}{\text{installed capacity x no. of operating hours in the year}}
\]  

(5.1)

In our case, the average annual EDF in percentage is

\[
\frac{47,485.77 kWh/yr}{54 kWp \times 8760 \text{ hr/yr}} \times 100\% = 10.04\%
\]

However, it is noteworthy that the EDF of a solar farm will vary throughout the year as solar radiation received is closely related to cloud cover, which inturn is affected by the monsoon seasons. Also, the installed capacity of 54 kWp is only covered by PV modules, which generate electricity only when sunshine is available. In the events of rainy days and night-time, electricity is produced from the battery banks which operate at full capacity of 30 kW. Therefore, by assuming that the solar modules operate at full capacity eight hours per day and the battery banks operate sixteen hours per day, which translate into one-third and two-third of the year respectively, the revised average annual EDF is:

\[
\frac{47,485.77 \text{ kWh/yr}}{54 \text{ kWp} \times 2920 \text{ hr/yr} + 30 \text{ kWp} \times 5840 \text{ hr/yr}} \times 100\% = 14.27\%
\]

This value will be used to predict energy delivered over a year for Long Beruang solar system and it is used in energy cost estimates in Sec. 5.2.4.
5.2.2 Initial Capital Cost

The Initial Capital Cost (ICC) is RM 1,543,531. The percentage breakdown of the component costs is shown in Figure 5.1 – Initial Capital Cost

Since Long Beruang is a community project, the villagers were involved in the construction of the power plant, thus labour cost and local materials contribute little to the overall costs. As expected, the major cost items are the equipment such as photovoltaic modules, inverters, batteries, cabling, etc.

5.2.3 Maintenance

The solar plant, being static and has no moving parts, is silent in operation and requires little or no maintenance; unlike wind turbines, whose annual maintenance costs takes up to 1.5% to 2% of the initial turbine cost (Patel 2006, p. 303). The only maintenance the villager committee has to do is to regularly check the operational status of system components. The power house has to be cleaned from time to time to prevent component breakdown due to insect infestation or other contaminants. Modules are
being washed once a week to avoid dirt accumulation which will affect the amount of receiving solar radiation.

The officers from JKR will conduct routine check on the once a year. In case of component breakdown, JKR will ask for new fund from the Federal Ministry of Rural Development. However, the power plant is expected to serve for at least fifteen to twenty years without failure if it is being maintained with great care, except in the case of natural disasters such as lightning strike. Moreover, considering the high transportation cost in rural area, it is expected that official visiting will only happen once in a few years if no major deficits are reported from the ground. To ease the process of economic analysis, the average annual maintenance fee is estimated at one-thousand ringgit Malaysia. This constant figure is based on the price for transportation, accommodation and labor costs as of the Year 2010 and not the current value since average real interest rate.

5.2.4 Energy Cost Estimates

To know the performance of the solar plant, the unit cost of energy (UCE) is computed. It is expressed as follows:-

Unit Cost of Energy (UCE)

\[
UCE = \frac{ICC(AMR + TIR + OMC)}{EDF \times kW \times \text{no. of operating hours in a year}}
\]

(5.2)

\[
UCE = \frac{ICC(AMR + TIR + OMC)}{\text{energy delivered over a year}}
\]

where

- AMR = amortization rate per year as a fraction of the ICC (=0%)
- TIR = tax and insurance rate per year as a fraction of the ICC (=0%)
- OMC = operating and maintenance costs per year as a fraction of the ICC
- kW = kilowatt electric power capacity installed

Thus,

\[
UCE = \frac{RM 1,000}{47,485.77 \text{ kWh}}
\]

= RM 0.021/kWh
5.2.5 Net Present Cost

The Net Present Cost (NPC) of a system is the present value of all the costs over the project lifetime deducting the present value of all the revenues generated during the project lifetime. Sometimes regarded as the life-cycle cost, NPC offers designers and investors a more realistic speculation on the project while taking into account of the “time value” of money, which is not available in methods like the simple payback period and rate of return. The NPC includes the discount rate, which is the rate above general inflation at which money could be devoted in other investments, hence predicting the future monetary value of the project (Lynn 2010, p.194). Real interest rate is used to calculate discount rate.

In order to perform the NPC, the salvage value of each system component must be evaluated. The salvage value is the remaining value of a component at the end of the project lifetime. Methods from the renowned energy modeling software for hybrid renewable energy systems, HOMER (HOMER Energy 2012) are used for the calculation of NPC and salvage value. HOMER assumes linear depreciation of component, therefore the salvage value of a component is directly proportional to its remaining life.

\[
Salvage\ Value, S = C_{\text{rep}} \times \frac{R_{\text{rem}}}{R_{\text{comp}}} \tag{5.3}
\]

where

\( C_{\text{rep}} = \text{replacement cost (RM)} \)

\( R_{\text{comp}} = \text{component lifetime (year)} \)

\( R_{\text{rem}} = \text{remaining life of the component at the end of the project lifetime} \)

While

\[
R_{\text{rem}} = R_{\text{comp}} - (R_{\text{proj}} - R_{\text{rep}}) \tag{5.4}
\]

where

\( R_{\text{proj}} = \text{project lifetime (year)} \)

\( R_{\text{rep}} = \text{replacement cost duration (year)} \)

While
In order to find the NPC of the solar power system over a project lifetime of 20 years \( (N = 20) \), the following assumption must be made:-

a. The component lifetimes of PV and inverters are more than 20 years.

b. From “Battery Sizing” (sec. 3.2.3), estimated battery DOD is 0.74, thus no. of cycle is 1350. (see APPENDIX). Battery lifetime is 1350/365 days = 3.67 years.

c. Replacement cost for 2 banks of 24 battery cells in series is RM 96,000 per year.

d. The real interest rate, \( i \) is defined as the lending interest rate adjusted for inflation as measured by the Gross Domestic Product deflator. Average real interest rate for Malaysia from Year 2001 to 2010 is 2.91% (Real Interest Rate 2012).

e. The discount factor is a ratio used to calculate the present value of a cash flow that occurs in any year of the project lifetime and it is defined as \( f_d = \frac{1}{(1+i)^N} \)

\( (HOMER Energy 2012) \)

f. Project OMC is RM 1000 per year.

Thus, the salvage value after 20 years for battery bank alone:-

\[
R_{rep, batt} = 3.67 \times INT \left(\frac{20}{3.67}\right) = 18.35 \text{ yr}
\]

\[
R_{rem, batt} = 3.67 - (20 - 18.35) = 2.02 \text{ yr}
\]

Salvage Value for battery, \( S_{batt} = RM \ 96,000 \times \frac{2.02}{3.67} = RM 52,839.24 \)

Table 8 on the following page presents the calculation of NPC for over 20 years project lifetime. Since the net present value and the net present cost differ only in sign, so the net present cost of the solar power plant over the project lifetime of 20 years is RM 1,977,128.11.
<table>
<thead>
<tr>
<th>Year</th>
<th>Discount Factor</th>
<th>Discounted Cash Flow</th>
<th>ICC</th>
<th>Replacement</th>
<th>Salvage</th>
<th>OMC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.00</td>
<td>-1,543,531</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-1,543,531.00</td>
</tr>
<tr>
<td>1</td>
<td>0.972</td>
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<td>-971.82</td>
<td>-971.82</td>
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<td>2</td>
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<td>3</td>
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<td>3.67</td>
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<td>5</td>
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</tr>
<tr>
<td>11.01</td>
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<td>-96,000.00</td>
<td>-</td>
<td>-96,000.00</td>
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<td>12</td>
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<td>-49.70</td>
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<td>14.68</td>
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<td>-96,000.00</td>
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</tr>
<tr>
<td>15</td>
<td>0.651</td>
<td>-</td>
<td>-32.37</td>
<td>-32.37</td>
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</tr>
<tr>
<td>16</td>
<td>0.633</td>
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<td></td>
</tr>
<tr>
<td>17</td>
<td>0.615</td>
<td>-</td>
<td>-12.60</td>
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<td>18</td>
<td>0.598</td>
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<tr>
<td>18.35</td>
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<td>-96,000.00</td>
<td>-</td>
<td>-96,000.00</td>
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</tr>
<tr>
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<td>0.581</td>
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<td>-4.38</td>
<td>-4.38</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.565</td>
<td>52,839.24</td>
<td>-2.47</td>
<td>52,836.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>-1,543,531</td>
<td>-480,000.00</td>
<td>52,839.24</td>
<td>-6,436.35</td>
<td>-1,977,128.11</td>
<td></td>
</tr>
</tbody>
</table>

Table 8 - Calculation of Net Present Cost of 20 years of project lifetime.

5.2.6 Return of Investment

In the case of grid-connected solar projects, for a solar plant at a capacity above 24 kWp, and up to including 72 kWp, the FiT rate is RM1.18 kWh and the effective period is 21 years, at 8% annual degression rate.

Daily average energy produced is $130.098 kWh/day$, thus annual average energy production is $47,485.77 kWh/yr$.

The return of investment (ROI) is indicated by the net profit generated from the power plant over its initial capital cost. Nonetheless, since Long Beruang is not grid-
connected, also looking at the fact that presently daily energy consumption (116.502 kWh/day) is very close to the estimated maximum daily energy the plant can produced (130.098 kWh/day), it is pointless to carry out ROI in terms of FiT because little or no revenue will be generated.

\[
ROI = \frac{\text{Net Profit}}{\text{ICC}} \times 100\% \quad (5.6)
\]

### 5.2.7 Scenario A: Diesel-Generator

The price of subsidized diesel fuel in Sarawak was RM 1.75 per litre in Year 2010. The capacity of the diesel generators used ranges from 5 kW to 10 kW per household.

Assume that a household uses a 10 kW MITSUBISHI S3L2-SD diesel generator only during the night, engine fuel consumption is 3.1 litre per hour at 100% prime power (refer to APPENDIX),

\[
\text{Annual Diesel Cost per Household} = \frac{\text{RM} \times 1.75 \times 3.1 \text{ l/hr} \times 12 \text{ hr/day} \times 365 \text{ days/year}}{\text{l}}
\]

\[
= \text{RM} \ 23,761.50 /\text{year} / \text{household}
\]

The fact is that not all households could afford to buy a diesel generator, not to mention daily usage was rarely up to 12 hours per day.

Alternatively, if the electricity power were generated by one single diesel generator, the sizing of the generator should be as the following:-

**Diesel Generator Size during maximum demand,**

\[
S_{\text{gen, sw max demand}} = \frac{S_{\text{max ac demand}} \times f_{\text{go}}}{f_{\text{g, derate}}} \quad (5.7)
\]

where \( S_{\text{max ac demand}} = \text{maximum AC load demand (VA)} \)

\( f_{\text{go}} = \text{diesel generator oversize factor} = 1.1 \)

\( f_{\text{g, derate}} = \text{diesel generator derating factor} \)

Assume that the diesel generator derating factor is 1 and power factor is 0.80
Choose the capacity of diesel generator and check on its specification.

To determine the derating factor of diesel generator:

a. Long Beruang’s Altitude = sea level

b. Long Beruang’s Temperature = 20~38°C

c. CUMMINS 73kVA diesel generator (Model C80D5), Engine 4BTA3.9G3 can operate at 1500 rpm up to 1,220 m and 40 °C without power duration. For sustained operation above these conditions, power derates by 4% per 300 m and 2% per 11 °C

d. In this case, derating factor (refer to APPENDIX)
   i. \( f_{alt,\,manuf} = 0\% \)
   ii. \( f_{temp,\,manuf} = 0\% \)
   iii. \( f_{RH,\,manuf} = N/A \)

e. Thus the total derating factor, \( f_{g,\,derate} = 1 \)

f. CUMMINS 73 kVA diesel generator is selected for further calculation.

Assume that the diesel generator runs twenty-four hours per day at full load, engine fuel consumption is 18 litres per hour at 100% prime power

\[
Annual\, Diesel\, Cost = \frac{RM\, 1.75}{l} \times \frac{18\, l}{hr} \times \frac{24\, hr}{day} \times \frac{365\, days}{year} = RM\, 275,940\, /\, year
\]

Rated prime power for model C80D5 is 58 kW:-

\[
Annual\, kWh\, produced = 58\, kW \times \frac{24\, hr}{day} \times \frac{365\, days}{year} = 508,080\, kWh\, /yr
\]

\[
Unit\, Cost\, of\, Energy = \frac{RM\, 275,940}{508,080\, kWh} = RM\, 0.543\, /kWh
\]
5.2.8 Scenario B: Grid-Connected

Hitherto there is no tariff charge on rural off-grid solar projects in Sarawak. If the village were connected to the SEB utility grid (not in terms of special PV project), each household would be charged at the domestic tariff as shown in Table 9 below:

<table>
<thead>
<tr>
<th>SEB Tariff for Domestic Usage</th>
<th>Rate per Unit*</th>
</tr>
</thead>
<tbody>
<tr>
<td>For the first 100 units per month</td>
<td>RM 0.34</td>
</tr>
<tr>
<td>For the next 300 units per month</td>
<td>RM 0.29</td>
</tr>
<tr>
<td>For each additional units per month</td>
<td>RM 0.33</td>
</tr>
<tr>
<td>Minimum monthly charge</td>
<td>RM 5.00</td>
</tr>
</tbody>
</table>

*one unit means one kilowatt-hour

Table 9 - SEB Tariff for Domestic Usage

(Tariff Rate 2011)

Monthly energy consumption for each household is:

\[
\frac{130.098 \text{ kWh/day}}{54 \text{ households}} \times 30 \text{ days} = 72.3 \text{ kWh/mth/household}
\]

Monthly electricity bill for each household is:

\[72.3 \text{ kWh/mth/household} \times RM 0.34/\text{kWh} = RM 24.58/\text{mth/household}\]

Annual electricity bill for the whole village is:

\[RM 24.58/\text{mth/household} \times 54 \text{ households} \times 12 \text{ mths} = RM 15,929.16/\text{yr}\]

\[\text{Unit Cost of Energy} = \frac{RM 15,929.16}{47,485.77 \text{ kWh}} = RM 0.335/\text{kWh}\]

5.2.9 Section Summary

Table 10 gives an overview of the financial value of this project:

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Energy Delivery Factor</td>
<td>14.27%</td>
</tr>
<tr>
<td>2.</td>
<td>Initial Capital Cost</td>
<td>RM 1,543,531</td>
</tr>
<tr>
<td>3.</td>
<td>Operation and Maintenance Cost</td>
<td>RM 1000/yr</td>
</tr>
<tr>
<td>4.</td>
<td>Unit Cost of Energy</td>
<td>RM 0.021/kWh</td>
</tr>
<tr>
<td>5.</td>
<td>Net Present Cost</td>
<td>RM 1,977,128.11</td>
</tr>
</tbody>
</table>

Table 10 - Overview of the project financial value.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual Electricity Payable</th>
<th>Unit Cost of Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Diesel-Generator (single generator)</td>
<td>RM 275,940.00 / yr</td>
<td>RM 0.543 / kWh</td>
</tr>
<tr>
<td>B. Grid-Connected</td>
<td>RM 15,929.16 / yr</td>
<td>RM 0.335 / kWh</td>
</tr>
</tbody>
</table>

Table 11 - Comparison of Diesel-Generator and grid-connected scenarios in financial terms

Table 11 summarizes the annual electricity bill and cost of energy (disregard of initial capital cost, tax and insurance, operating and maintenance cost and amortization cost) if the village electricity power were produced by the abovementioned scenarios.

5.3 SOCIOECONOMIC IMPACT

Now with the installation of VSAT, villagers not only enjoy the privilege of the Internet, but also can use the fixed telephone line supplied by the telecommunication company. Moreover, JKR intends to transform its monitoring centre into Information and Communication Technology (ICT) centre for the village, to educate villagers on basic computing knowledge. In the hope that Long Beruang can evolve out of its current situation, the village committee intends to develop home stay programme to attract backpackers or trackers who travel in the inland Borneo.

5.4 SUMMARY OF THE CHAPTER

As summarized in the Table 12 below, solar power plant is a better alternative for rural electrification projects such as Long Beruang. Compared to diesel-generation and grid-connection, solar-powered option outperforms in terms of carbon dioxide emission, and also has the least unit cost of energy.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual CO$_2$ Emission (tonnes / year)</th>
<th>Unit Cost of Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Diesel-Generator</td>
<td>12.67</td>
<td>RM 0.543 / kWh</td>
</tr>
<tr>
<td>B. Grid-Connected</td>
<td>53.35</td>
<td>RM 0.335 / kWh</td>
</tr>
<tr>
<td>C. Solar-Powered</td>
<td>&gt; 0.5</td>
<td>RM 0.021 / kWh</td>
</tr>
</tbody>
</table>

Table 12 - Performance of different scenarios of power generation in terms of CO$_2$ emission and unit cost of energy
CHAPTER 6
SOLAR RADIATION MODELS IN SARAWAK

In view of the lack of information for the state of Sarawak, a set of analysis is performed to produce an appropriate model to estimate monthly-averaged daily global solar radiation for Sarawak. The town of Kuching and Miri are chosen due to the fact that solar radiation data is only available from the weather station set up by the Meteorological Department in these two towns. In the case of Long Beruang, an Angstrom-Prescott model is generated based on monthly average daily sunshine hours for Miri.

6.1 DATA & METHODOLOGY

6.1.1 Data
Three sets of climatological data, i.e. monthly average sunshine hours, monthly total solar radiation, and monthly average cloud cover are obtained from the Kuching Branch. For Kuching, data is generated at the Kuching Airport (01°29’ north latitude, 110°20’ east longitude; 21.7m above M.S.L.). Monthly average sunshine hours, \( \bar{n} \) over 29 years (1971 - 1999) and monthly average daily terrestrial solar radiation, \( \bar{G} \) over 6 years (2005 - 2010) and monthly average cloud cover, \( \bar{C} \) over 19 years (1991 - 2010) are used. For Miri, data is generated at the Miri Airport (04°20’ north latitude, 113°59’ east longitude; 17.0m above M.S.L.). Monthly average sunshine hours, \( \bar{n} \) over 29 years (1971 - 1999) and monthly average daily terrestrial solar radiation, \( \bar{G} \) over 3 years (2005 - 2007) and monthly average cloud cover, \( \bar{C} \) over 28 years (1983 - 2010) are used. For Long Beruang (3° 17’ 02.5” north latitude, 115° 25’ 34.7” east longitude; 598m above M.S.L.), monthly average daily terrestrial solar radiation, \( \bar{G} \) in year 2011 is used since it is the only complete data available at the completion of thesis. Moreover, in replace of the absence of sunshine hours data available for Long Beruang, the aforementioned monthly average sunshine hours, \( \bar{n} \) for Miri is used based on the fact that it is the nearest city from Long Beruang. For all the data, outliers are eliminated and replaced with values attained from linear interpolation.
Other data such as monthly average extraterrestrial irradiation on a horizontal surface, $\bar{E}$ and monthly average maximum possible daily hours of sunshine (i.e. day length), $\bar{N}$ is generated using equations.

6.1.2 Models

6.1.2.1 Model based on sunshine hours:

*Angstrom–Prescott model*

The famous Angstrom-Prescott model (eq. 2.18) is widely used to estimate monthly average daily terrestrial solar radiation, $\bar{G}$.

Daily solar radiation data is recorded using Kipp & Zonen pyranometers CM5 and CM6. Tracing of sunshine hours have been made using Campbell-Stokes Tropical Sunshine Recorder. For a Campbell-Stokes recorder, a glass sphere is placed on the stand and a thin paper card is concentrically mounted with the sphere. Sunlight passes through the sphere will be focused on the card and the card will be burnt. The record card is marked with hourly intervals and thus traces of burning length indicate hours of bright sunshine.

6.1.2.2 Model based on cloud cover:

*Cloudiness model*

Instead of the possible sunshine fraction $\bar{n}/\bar{N}$, Angstrom-Prescott model is modified to use cloud cover to estimate $\bar{G}$. Cloud cover is estimated as the apparent coverage of the total sky as seen by an observer. In the Meteorological Department, it is observed by trained meteorological assistant. The cloud amount is expressed in oktas, with zero okta denoting clear sky, four oktas denoting half cloud-covered sky, and eight oktas denoting overcast sky. The scale of cloud cover can be defined by the following terms:-

- 0 okta = 'No cloud/Sky clear'
- 1 - 2 oktas = 'Few'
- 3 - 4 oktas = 'Scattered'
- 5 - 7 oktas = 'Broken'
- 8 oktas = ‘Overcast’ (i.e. full cloud coverage)

The Cloudiness model may be expressed as:
\[
\frac{\bar{G}}{\bar{E}} = a + b\bar{C}
\]  

(6.1)

where \( \bar{C} = \) monthly average cloud cover in ratio (e.g. 2 oktas is 0.25 and 4 oktas is 0.5)

6.2 RESULTS & DISCUSSION

6.2.1 Data

6.2.1.1 Model based on sunshine hours:

\textit{Angstrom–Prescott model}

First of all, data comparison is done based on each corresponding year, e.g. estimated monthly average daily terrestrial solar radiation, \( \bar{G}_{est} \) acquired from the linear regression model of year 2005 will be weighed against the actual monthly average daily terrestrial solar radiation, \( \bar{G}_{act} \) of that year.

\textbf{Kuching Station}

Since the actual value for monthly average daily sunshine hours, \( \bar{n} \) from year 2005 to year 2010 is not available, mean values over the 29 years, from year 1971 to year 1999 will be used (refer to APPENDIX).

From the data, it is deduced that \( \frac{\bar{G}}{\bar{E}} = 0.2096 + 0.5211(\bar{n}/\bar{N}) \) generated from mean values of six years gives the best result. Thus it is chosen to calculated the estimated value of monthly average terrestrial solar radiation, \( \bar{G}_{est} \).

\textbf{Miri Station}

Since the actual value for monthly average daily sunshine hours, \( \bar{n} \) from year 2007 to year 2007 is not available, mean values over the 29 years, from year 1971 to year 1999 will be used. The monthly average daily terrestrial solar radiation, \( \bar{G} \) for Miri station is only up to 3 years (2005 - 2007) (refer to APPENDIX).

\( \frac{\bar{G}}{\bar{E}} = 0.1568 + 0.5891(\bar{n}/\bar{N}) \) is chosen to calculated the estimated value of monthly average terrestrial solar radiation, \( \bar{G}_{est} \).
**L. Beruang Station**

Hitherto there is no information on the actual value for monthly average daily sunshine hours, \( \bar{n} \), therefore mean values from Miri over the 29 years, from year 1971 to year 1999 will be used. The monthly average daily terrestrial solar radiation, \( \bar{G} \) for Long Beruang station in year 2011 is used (refer to APPENDIX).

### 6.2.1.2 Model based on cloud cover:

**Cloudiness model**

**Kuching Station**

Same as the case in Angstrom-Prescott model, mean values of monthly average daily sunshine hours, \( \bar{n} \) over the 29 years, from year 1971 to year 1999 will be used. Also, mean values of monthly average cloud cover, \( \bar{C} \) over 19 years (1991 - 2010) are used. The result \( \bar{G} / \bar{E} = 3.005 - 2.9871 \bar{C} \) is chosen to calculated the estimated value of monthly average terrestrial solar radiation, \( \bar{G}_{est} \).

**Miri Station**

Mean values for monthly average cloud cover, \( \bar{C} \) over 28 years (1983 - 2010) are used. The monthly average daily terrestrial solar radiation, \( \bar{G} \) for Miri station is only up to 3 years (2005 - 2007). \( \bar{G} / \bar{E} = 4.266 - 4.3043 \bar{C} \), is chosen to calculated the estimated value of monthly average terrestrial solar radiation, \( \bar{G}_{est} \).

### 6.2.2 Statistical Evaluation

For both Kuching and Miri Station, a set of statistical assessment is performed to evaluate the linear regression equations which are developed based on their respective models:

**Kuching Station**

*Angstrom-Prescott:*

\[
\frac{\bar{G}}{\bar{E}} = 0.2096 + 0.5211 \left( \frac{\bar{n}}{\bar{N}} \right) \quad (6.2)
\]

*Cloudiness Method:*

\[
\frac{\bar{G}}{\bar{E}} = 3.005 - 2.9871 \bar{C} \quad (6.3)
\]
Miri Station

*Angstrom-Prescott:*

\[
\frac{\bar{G}}{E} = 0.5891 + 0.1568 \left( \frac{n}{N} \right) \tag{6.4}
\]

*Cloudiness Method:*

\[
\frac{\bar{G}}{E} = 4.266 - 4.3043 \bar{C} \tag{6.5}
\]

Long Beruang Station

*Angstrom-Prescott:*

\[
\frac{\bar{G}}{E} = 0.4139 + 0.0681 \left( \frac{n}{N} \right) \tag{6.6}
\]

The estimated monthly average daily terrestrial solar radiation, \( \bar{G}_{est} \) is obtained from the above derived equations, and is compared to the actual monthly average daily terrestrial solar radiation, \( \bar{G}_{act} \).

The statistical tests of the two models are shown in the following tables:

<table>
<thead>
<tr>
<th>Statistical Tests for Kuching</th>
<th>Angstrom-Prescott</th>
<th>Cloudiness Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE</td>
<td>-0.0009492</td>
<td>-0.0018</td>
</tr>
<tr>
<td>MPE (%)</td>
<td>0.6783</td>
<td>0.7746</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.3326</td>
<td>0.3582</td>
</tr>
<tr>
<td>t-stat</td>
<td>0.02405</td>
<td>0.04227</td>
</tr>
<tr>
<td>Two tailed t-critical</td>
<td>1.9939</td>
<td>1.9939</td>
</tr>
<tr>
<td>R</td>
<td>0.7008</td>
<td>0.6407</td>
</tr>
<tr>
<td>R²</td>
<td>0.4911</td>
<td>0.4105</td>
</tr>
</tbody>
</table>

*Table 13 - Statistical justification of the models for Kuching.*

<table>
<thead>
<tr>
<th>Statistical Tests for Miri</th>
<th>Angstrom-Prescott</th>
<th>Cloudiness Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE</td>
<td>-0.0034</td>
<td>-0.0016</td>
</tr>
<tr>
<td>MPE (%)</td>
<td>0.3088</td>
<td>0.2768</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.2672</td>
<td>0.2575</td>
</tr>
<tr>
<td>t-stat</td>
<td>0.076</td>
<td>0.0358</td>
</tr>
<tr>
<td>Two tailed t-critical</td>
<td>2.0301</td>
<td>2.0301</td>
</tr>
<tr>
<td>R</td>
<td>0.8074</td>
<td>0.8145</td>
</tr>
<tr>
<td>R²</td>
<td>0.6519</td>
<td>0.6634</td>
</tr>
</tbody>
</table>

*Table 14 - Statistical justification of the models for Miri.*
### Statistical Tests for Long Beruang

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Angstrom-Prescott</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE</td>
<td>0.0027</td>
</tr>
<tr>
<td>MPE (%)</td>
<td>0.2132</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.2153</td>
</tr>
<tr>
<td>t-stat</td>
<td>0.0409</td>
</tr>
<tr>
<td>Two tailed t-critical</td>
<td>2.2010</td>
</tr>
<tr>
<td>R</td>
<td>0.2304</td>
</tr>
<tr>
<td>R²</td>
<td>0.0531</td>
</tr>
</tbody>
</table>

*Table 15 - Statistical justification of the models for Long Beruang.*

#### 6.2.3 Discussion

For Kuching station, the Angstrom-Prescott model gives the best performance for it has the smaller value for all the error tests. Cloudiness model also provides relatively good results, with a slightly higher error results compared to the Angstrom-Prescott model. Both models are statistically significant, with \( t \)-stat values much smaller than \( t \)-critical. As shown in Table 13, when comparing the actual data with estimated data generated from the models, both models show relatively poor coefficient of correlation marking at \( R_{\text{Angstrom}} = 0.70 \) and \( R_{\text{cloudiness}} = 0.64 \) respectively. This indicates that the estimated data will have some deviation from the actual data.

For Miri station, in overall the Angstrom-Prescott model performs slightly better than the Cloudiness model. The variation in terms of MBE, MPE and RMSE are not much. Both models are statistically significant, with \( t \)-stat values much smaller than \( t \)-critical. However, the Cloudiness model offers a slightly better coefficient of correlation whereby \( R_{\text{Angstrom}} = 0.65 \) compared to the Cloudiness model \( R_{\text{cloudiness}} = 0.66 \); as presented in Table 14.

The model for Long Beruang shows satisfying results in terms of MBE, MPE and RMSE. Also, it is statistically significant, with \( t \)-stat values much smaller than \( t \)-critical. However, when comparing the actual data with estimated data generated from the models, the model shows very poor coefficient of correlation marking at \( R_{\text{Angstrom}} = 0.23 \), as shown in Table 15. Thus, the estimated data will diverge in a great deal from the actual data.
Therefore, it is prudent to use Angstrom-Prescott model to estimate monthly-averaged daily terrestrial solar radiation for Kuching. The Angstrom-Prescott model for Kuching is \( \frac{\bar{G}}{\bar{E}} = 0.2096 + 0.5211\left(\frac{\bar{n}}{\bar{N}}\right) \). Whereas for Miri, Cloudiness model \( \frac{\bar{G}}{\bar{E}} = 4.266 - 4.3043\bar{C} \) is recommended. On the other hand, although the Angstrom-Prescott model \( \frac{\bar{G}}{\bar{E}} = 0.4139 + 0.0681\left(\frac{\bar{n}}{\bar{N}}\right) \) for Long Beruang seems inappropriate due to its poor coefficient of correlation, nonetheless, the Angstrom-Prescott method is justifiable provided more data collection and sampling are done in future to produce a model with higher accuracy.

From Angstrom-Prescott models, the overall atmospheric transmissions under clear skies \((a + b)\) are made known, as shown in Table 16. Clear skies index for Long Beruang is omitted since its Angstrom-Prescott model is not well-founded.

<table>
<thead>
<tr>
<th>Location</th>
<th>a</th>
<th>b</th>
<th>a + b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuching</td>
<td>0.2096</td>
<td>0.5211</td>
<td>0.7307</td>
</tr>
<tr>
<td>Miri</td>
<td>0.1568</td>
<td>0.5891</td>
<td>0.7459</td>
</tr>
</tbody>
</table>

Table 16 - Overall atmospheric transmissions under clear skies for Kuching and Miri.

In addition, monthly average clearness index, \( \bar{K}_T \) for Kuching and Miri can be acquired from the data. Clearness index is defined by the ratio of terrestrial solar radiation and extraterrestrial solar radiation (Muneer, p.41). It is a parameter to indicate the actual solar radiation received on a horizontal from the available solar radiation.

\[
\bar{K}_T = \frac{\bar{G}}{\bar{E}}
\]  

(6.7)

Values of \( \bar{K}_T \) for Kuching from Year 2005 to 2010 range from 0.2796 to 0.5245; while its mean value is 0.4276. On the other hand, values of \( \bar{K}_T \) for Miri from Year 2005 to 2007 range from 0.4112 to 0.5520; while its mean value is 0.4939. The smaller the value of \( \bar{K}_T \), the larger the fraction of the solar radiation is diffused.
CHAPTER 7
CONCLUSIONS & FUTURE WORK

A 54 kWp stand-alone solar power system for a rural village in Sarawak has been discussed in this thesis. The main contributions of this thesis are identified as: project documentation from design phase to final implementation, feasibility studies in terms of environmental and economic impact, actual load profile and solar irradiation records of the project site, and the generation of empirical models to estimate monthly-averaged daily terrestrial solar radiation for the two towns in Sarawak, which are Kuching and Miri.

Located in Ulu Baram (a rural area in the Miri division of Sarawak), the Long Beruang Solar Project is a community-based project, in which villagers were involved in the construction and system installation. Much of the building materials and labour forces are contributed by the local community to reduce project cost. Each household is given three lighting points and two power points. Operation and maintenance training were provided to the villagers. Henceforth responsibility to maintain the system is now sorely borne by the village committee. This project was implemented and monitored by the Public Works Department of Sarawak; and the power control settings of the system are controlled by authorized personnel. The system was commissioned on the 10th April 2010.

This 54 kWp stand-alone solar power system utilizes AC coupling system, which allows future grid connection and system expansion. Electricity is supplied by three hundreds pieces of 180 Wp monocrystalline PV modules, grid-tied inverters convert DC power from PV modules to AC power and feed in directly to village load through the AC bus. In case of non-sunshine hours, power is supplied by two banks of 1400 Ah@C10 batteries, which are connected to the AC bus through bi-directional inverters. System sizing follows the steps and guidelines in the book Solar Photovoltaic Power: Designing Stand-Alone Systems (Shaari et. al., 2010), which is used in the ISP accredited training programmes conducted by the UiTM, as part of the MBIPV Project. Only the inverter sizing was done according to the recommendation from manufacturers.
System monitoring, data storage and remote diagnosis can be done through internet via VSAT installation on-site.

Later, actual loadings were measured using power logger. Two sets of actual load profile were compared: the first set of data was recorded in December 2010 (about six months after the project implementation); another set of data was recorded in March 2012. It is found that in the period of fifteen months, the daily energy consumption has increased by 257% (from 32.6 kWh/day to 116.5 kWh/day) and peak load growth has increased by 223% (from 2.24 kW to 7.22 kW). The current daily energy consumption of 116.5 kWh/day is very close to the maximum energy that can be supplied by the system, which is 130.098 kWh/day. For this reason, villagers are advised to be prudent in using electricity so as not to exceed the limitation since there is no further funding on this project. This also provides a valuable insight into the behaviour changes of a rural Sarawakian village in terms of power usage, especially in the increasing numbers of more lavish electrical appliances such as televisions and laptops. It is always sensible that future projects would have to look into the growth of energy demands and the villagers’ purchasing power at design stage.

The environmental and economic impact of this solar power system was examined. It was compared to two presumed scenarios, by assuming that the village is either Diesel-Generator or grid-connected. The inspection was done in terms of CO₂ emissions and annual electricity payable. It is noteworthy to point out that the village now enjoys the privilege of free electricity, as the system is not connected to the utility grid.

The major limitation encountered in this project is the lack of information on actual weather/climatological data and village load profile in the initial design stage. The latter could be resolved through long-term observation on the actual loading for the village itself. Whereas in the former situation, the only useful analysis is Kuching (in the west of Sarawak) conducted by Sopian and Othman in the late 1980s: annual mean value for monthly-averaged daily solar irradiation was 4.022 kWh/m² while annual mean value for daily sunshine duration was 5.15 hours (in system sizing, peak sun hour of 4 was used instead). Although valuable, but these figures might not be applicable to Long Beruang, which is situated in the east of Sarawak, not to mention the data was generated almost twenty years ago. At present, alongside the solar power system, a solar radiation sensor was installed and thus solar irradiation in Long Beruang could be
recorded. The annual mean value for monthly-averaged daily solar irradiation in Long Beruang for Year 2011 was 4.6 kWh/m$^2$. Furthermore, in hopes to fill the void of solar radiation data in Sarawak, two empirical models were proposed to estimate monthly-averaged daily terrestrial solar radiation for the two towns in Sarawak, namely Kuching and Miri (nearest town to Long Beruang). It is concluded that the Angstrom-Prescott model $\frac{\bar{G}}{\bar{E}} = 0.2096 + 0.5211(\bar{n}/\bar{N})$ performs best for Kuching while for Miri, the Cloudiness model $\frac{\bar{G}}{\bar{E}} = 4.266 - 4.3043\bar{C}$ is recommended. Then again, for Long Beruang, on-site observations of monthly-average daily sunshine hours, $\bar{n}$ and monthly-averaged cloud cover in ratio, $\bar{C}$ are not available. Therefore, the mean value of $\bar{n}$ of Miri is used to generate Angstrom-Prescott model $\frac{\bar{G}}{\bar{E}} = 0.4139 + 0.0681(\bar{n}/\bar{N})$ for Long Beruang. However, the model is not applicable due to poor coefficient of correlation. Nevertheless, if more data are accessible in future, a more accurate Angstrom-Prescott model can be generated empirically. This could provide a more accurate method in predicting solar irradiation in Ulu Baram.

As for future expansion, it is possible that there is a necessity to expand the power system to meet growing energy demand in the village. Nonetheless, looking at the current population growth, this is expected to occur in the next five or ten years in future, provided the villagers can use electricity in prudence. Due to geographical constraint, expansion on the current power plant seems impossible. Nonetheless, in future, other power systems can be built in other suitable locations and be connected to the existing AC bus. Moreover, in conjunction with the government’s efforts in rural electrification, it is only a matter of time before neighbouring villages of Long Beruang also received electricity. If the solar power system is connected to the main utility grid, the DC side (batteries) can be disconnected from the system or serves as backup. However, in view of the challenging terrains of the vast inland of Sarawak, power generations from RE sources to form microgrids are more economically efficient and environmentally friendly in comparison with the main utility grid. Apart from solar power generation, micro-hydro power is well worth considering since the terrain of Ulu Baram is covered with streams and rivers. Wind energy would require careful planning and data collection considering the wind flow in the area is not always consistent.
REFERENCE


PRESCOTT, J. A. 1940. Evaporation from a water surface in relation to solar radiation. Transactions of the Royal Society of South Australia, 64, 114-118.


