

**DEVELOPMENT OF AN OPTIMIZED INTEGRATED  
RAINWATER HARVESTING MODEL FOR  
MULTISTOREY HOUSES**

THESIS SUBMITTED TO  
THE DEPARTMENT OF CIVIL ENGINEERING IN FULFILMENT OF  
THE REQUIREMENT FOR THE DEGREE OF  
Doctor of Philosophy

By  
**Sisuru Sendanayake**



SUPERVISED BY  
Prof. M. T. R. Jayasinghe  
(Department of Civil Engineering)

**DEPARTMENT OF CIVIL ENGINEERING  
UNIVERSITY OF MORATUWA  
SRI LANKA**

**SEPTEMBER 2010**

## Abstract

Rain Water Harvesting (RWH) is an ancient civil practice of more than 4000 years, drawing attention among scientists in recent decades, in the light of potable water shortages and water based natural disasters such as draughts and flash floods. It is noted that much focus has been on optimizing the sizes and operation of individual components, in relation to increased Water Saving Efficiency (WSE), in order to minimize the overall capital investment. However, if RWH is to proliferate, it should function on par with centralized service water supply, particularly in delivering water to service points reliably. This is most relevant in urban, multi story scenarios, where not only service reliability but optimized utilization of space and aesthetic aspects is also important. Taking in to consideration that pumping of collected rain water is energy consuming and therefore against the principles of sustainability, a Cascading Multi Tank Rain Water Harvesting (CMTRWH) system is introduced for multi story situations, where the energy requirement on pumping is much less compared to the conventional models.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations

Even though the CMTRWH model is energy efficient, unless an alternative, renewable power source is introduced to operate an efficient pump with total reliability, the system will have to depend on costly grid power, not only negating the positive impact of using RWH on sustainable development, but also depriving water security to vast communities of people without access to grid power. Sri Lanka being a tropical country, solar power option is pursued as the most desirable alternative energy source. Acknowledging the importance of a storage battery for the reliable operation of the power supply system, sizing curves are developed to select optimally matching pair of PV generator and battery for a given load, at a given location. In order to overcome the difficulty of obtaining measured incident solar radiation at remote locations, a methodology is developed to calculate solar radiation using easily obtainable rainfall data.

**Key Words:** *Cascading, Rainwater, Multi-Tank, Harvesting, Stand-Alone, Photo-Voltaic*

## **Declaration**

I, Sisuru Sendanayake, hereby declare that the work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

.....  
Sisuru Sendanayake  Date .....

University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## Acknowledgements

This thesis is the result of an interdisciplinary research under the Mechanical and Civil Engineering departments of University of Moratuwa, and I thank the respective Heads of Department for their support and encouragement for me to undertake a research on a subject of national importance.

It is my profound duty to thank Professor M.T.R. Jayasinghe the supervisor for the research, for his guidance and direction. A special word of thanks should go to Professor Jayasinghe, for without his insight and encouragement in bringing me back from the industry and commerce to the worthy process of academic research, this thesis would not have seen the light of the day, once again amply demonstrating Professor Jayasinghe's unstinted dedication to his sphere of work, the university and to the nation.

I wish to take this opportunity to thank Professors R.A Attalage and J. Bandara who as panel members of the research progress review committee have given valuable advice.

A special word of appreciation should also go to the National Meteorological Department of Sri Lanka for their support in providing with solar radiation and weather data.

Sisuru Sendanayake

September, 2010

# CONTENTS

|   |          |
|---|----------|
| Abstract  | i        |
| Key words   | i        |
| Statement of Authorship   | ii       |
| Acknowledgements  | iii      |
| Table of Contents   | iv       |
| List of Tables  | xii      |
| List of Figures   | xiii     |
| List of Charts  | xv       |
| <br>  |          |
| <b>Chapter 1</b>  |          |
| <b>INTRODUCTION</b>   | <b>1</b> |
| 1.1 General   | 4        |
| 1.2 Objectives  | 4        |
| 1.3 Research methodology  | 4        |
| 1.4 Main findings   | 5        |
| 1.5 An overview of chapters   | 7        |
| <br>  |          |
| <b>Chapter 2</b>  |          |
| <b>LITERATURE REVIEW</b>  |          |
| 2.1 General   | 8        |
| 2.2 Water and Energy: Global crisis and emerging trends                   | 8        |
| 2.3 Optimization of rain water harvesting systems                         | 12       |
| 2.3.1 Rain water harvesting   | 12       |
| 2.3.2 Optimization of system components                                   | 12       |
| 2.3.2.1 Optimization techniques   | 12       |
| 2.3.2.2 Performance of RWH Systems using Behavioral model                 | 13       |
| 2.3.2.3 Predicting the performance of RWH System using behavioral model   | 14       |
| 2.3.2.4 Optimization of storage size using water saving efficiency curves | 18       |
| 2.3.2.5 Important observations with regard to generic curves on WSE       | 19       |

|         |  |    |
|---------|--|----|
| 2.3.2.6 | Validation of water saving curves for Sri Lanka          | 22 |
| 2.3.3   | Overflow quantities in rain water harvesting systems     | 27 |
| 2.3.3.1 | Relating overflow to specific volume and specific demand | 27 |
| 2.4     | Solar pumping  | 28 |
| 2.4.1   | Pump types   | 28 |
| 2.4.2   | Centrifugal pumps  | 28 |
| 2.4.2.1 | Characteristic curves of a centrifugal pump              | 29 |
| 2.4.2.2 | Affinity laws for centrifugal pumps                      | 33 |
| 2.4.2.3 | System load curve-Batch transferring                     | 33 |
| 2.4.3   | Positive displacement pumps                              | 34 |
| 2.4.3.1 | Characteristic curves of PD pumps                        | 35 |
| 2.4.4   | Sizing of battery assisted SAPV systems                  | 38 |
| 2.4.4.1 | Stand Alone Photo Voltaic (SAPV) systems                 | 38 |
| 2.4.4.2 | Solar cell   | 39 |
| 2.4.4.3 | Electric load circuit of a simple cell                   | 41 |
| 2.4.4.4 | Performance characteristics of a solar cell              | 42 |
| 2.4.5   | Sizing methods   | 44 |
| 2.4.5.1 | Intuitive methods  | 44 |
| 2.4.5.2 | Numerical methods  | 44 |
| 2.4.5.3 | Analytical methods                                       | 45 |
| 2.4.6   | Development of Cs charts                                 | 45 |
| 2.4.6.1 | Numerical-Analytical approach to SAPV sizing             | 46 |
| 2.5     | Correlations to predict incident solar radiation         | 48 |
| 2.5.1   | Estimating incident solar radiation                      | 50 |

|         |   |    |
|---------|---|----|
| 2.5.2   | Estimating incident solar radiation using satellite images                  | 50 |
| 2.5.3   | Estimating incident solar radiation using spatial interpolation techniques  | 51 |
| 2.5.4   | Estimating incident solar radiation using predictive numerical correlations | 51 |
| 2.5.5   | Commonly used correlations  | 52 |
| 2.5.5.1 | Correlation 1 – Angstrom Method   | 52 |
| 2.5.5.2 | Correlation 2 – Akinoglu and Ecevit model                                   | 54 |
| 2.5.5.3 | Correlation 3 – Hargreaves-Samani equation                                  | 55 |
| 2.5.6   | Correlations based on cloud cover data                                      | 56 |
| 2.5.6.1 | Predicting mean sky transmittance of clear days ( $K_T$ ) <sub>C</sub>      | 57 |
| 2.5.6.2 | Predicting mean sky transmittance of overcast days ( $K_T$ ) <sub>O</sub>   | 58 |
| 2.5.7   | Impact of tilt angle on incident solar radiation                            | 60 |
| 2.6     | Summary   | 63 |

### Chapter 3

## RAIN WATER HARVESTING SYSTEM DESIGN

|         |  |    |
|---------|--|----|
| 3.1     | General  | 68 |
| 3.2     | Rain water harvesting                            | 69 |
| 3.2.1   | Needs of RWH                                     | 69 |
| 3.2.2   | Benefits accrued from RWH                        | 70 |
| 3.2.3   | Global use of rain water harvesting              | 71 |
| 3.3     | Conventional RWH models and their limitations    | 72 |
| 3.3.1   | Fundamental types of RWH systems                 | 72 |
| 3.3.2   | Global RTRWH systems                             | 73 |
| 3.3.3   | Main types of global RTRWH systems               | 73 |
| 3.3.4   | RWH systems in Sri Lanka                         | 77 |
| 3.3.4.1 | RTRWH system with above ground ferro-cement tank | 77 |
| 3.3.4.2 | RTRWH system with partial underground tank       | 77 |
| 3.3.4.3 | RTRWH system with below ground brick tank        | 78 |

|         |  |     |
|---------|--|-----|
| 3.4     | Components of rain water harvesting systems          | 79  |
| 3.4.1   | Collector surface                                    | 80  |
| 3.4.2   | Conveyance system                                    | 81  |
| 3.4.3   | Storage facility                                     | 81  |
| 3.4.4   | Filtering devices in RWH systems                     | 81  |
| 3.4.5   | Draw-off devices used in RWH systems                 | 83  |
| 3.5     | Optimization of storage size                         | 84  |
| 3.5.1   | Space and weight restrictions                        | 84  |
| 3.5.2   | Alternative methods of storage tank positioning      | 85  |
| 3.6     | Cascading multi tank model                           | 90  |
| 3.6.1   | Description of concept                               | 90  |
| 3.6.2   | Assumptions adopted in system operation              | 92  |
| 3.6.3   | Advantages and limitations of CMTRWH systems         | 92  |
| 3.6.3.1 | Advantages   | 92  |
| 3.6.3.2 | Limitations  | 92  |
| 3.7     | System dynamics                                      | 93  |
| 3.7.1   | Development of system algorithm for CMTRWH systems   | 93  |
| 3.7.2   | Effective run-off and pumping requirement            | 94  |
| 3.7.3   | System limits  | 95  |
| 3.7.4   | System equations for equal loads at each floor level | 95  |
| 3.8     | Determining the validity of CMTRWH algorithm         | 95  |
| 3.8.1   | Methodology  | 96  |
| 3.8.2   | Calculation  | 96  |
| 3.8.3   | Results and discussion                               | 96  |
| 3.9     | Limiting values of Demand (D) for total gravity feed | 97  |
| 3.9.1   | Calculation of limiting values                       | 97  |
| 3.9.2   | Operating phases of a CMTRWH model                   | 100 |



|          |   |     |
|----------|---|-----|
| 3.10     | Energy requirement in CMTRWH systems                            | 103 |
| 3.10.1   | Energy required in pumping harvested rainwater                  | 103 |
| 3.10.2   | Energy required in pumping rainwater with make-up water         | 106 |
| 3.11     | Energy required in pumping rainwater with unbalanced load       | 107 |
| 3.12     | Impact of variation of the storage volume in CMTRWH systems     | 109 |
| 3.13     | Performance of a Two Tank cascading model – case study          | 111 |
| 3.13.1   | System dynamics – Two Tank Model                                | 112 |
| 3.13.2   | System performance  | 113 |
| 3.13.2.1 | System performance with change in capture area (A)              | 113 |
| 3.13.2.2 | System performance with change in demand (D)                    | 113 |
| 3.13.2.3 | System performance with change in rainfall (R)                  | 113 |
| 3.13.2.4 | System performance with change in upper tank capacity ( $S_U$ ) | 113 |
| 3.13.2.5 | Pumping requirements for water security                         | 115 |
| 3.13.2.6 | Make-up water requirement for water security                    | 116 |
| 3.14     | Control of overflow quantities                                  | 117 |
| 3.14.1   | Objective   | 117 |
| 3.14.2   | Methodology   | 118 |
| 3.14.3   | Calculations  | 118 |
| 3.15     | Summary   | 120 |

## **Chapter 4**

### **SELECTION AND SIZING OF BATTERY ASSISTED PV PUMPING SYSTEMS IN RWH**

|         |   |     |
|---------|---|-----|
| 4.1     | General                                       | 123 |
| 4.2     | Types of pumps                                | 126 |
| 4.2.1   | Centrifugal pumps                             | 126 |
| 4.2.1.1 | Hydraulic output of a centrifugal pump        | 127 |
| 4.2.1.2 | Losses and efficiencies of a centrifugal pump | 127 |

|  |     |
|--|-----|
| 4.2.1.3 Advantages of centrifugal pumps over PD pumps      | 128 |
| 4.2.1.4 Limitations of centrifugal pumps                   | 129 |
| 4.2.2 Positive Displacement pumps                          | 129 |
| 4.2.2.1 Hydraulic output of a PD pump                      | 130 |
| 4.2.2.2 Losses and efficiencies                            | 131 |
| 4.2.2.3 Advantages of PD pumps over centrifugal pumps      | 131 |
| 4.2.2.4 Limitations of PD pumps                            | 132 |
| 4.3 Photo Voltaic (PV) pumping                             | 132 |
| 4.3.1 Characteristics of photo voltaic pumping systems     | 132 |
| 4.3.2 Direct coupled PV pumping                            | 134 |
| 4.3.2.1 Direct coupled centrifugal pumps                   | 135 |
| 4.3.2.2 Direct coupled Positive Displacement pumps         | 137 |
| 4.3.3 System sizing in PV pumping                          | 138 |
| 4.3.4 Performance comparison of pumps in PV pumping        | 139 |
| 4.4 Battery assisted PV pumping                            | 139 |
| 4.5 Components of a SAPVP system                           | 141 |
| 4.5.1 PV generator   | 141 |
| 4.5.2 Charge accumulator (Battery)                         | 142 |
| 4.5.2.1 Performance characteristics of a lead-acid battery | 142 |
| 4.5.2.2 Cycles vs. Life                                    | 144 |
| 4.5.1.3 Battery failure                                    | 146 |
| 4.5.2 Motor and pump                                       | 146 |
| 4.5.3 Inverter   | 146 |
| 4.5.5 Charge controller                                    | 147 |

|         |  |     |
|---------|--|-----|
| 4.6     | SAPV system sizing   | 147 |
| 4.6.1   | SAPV sizing for Sri Lanka  | 147 |
| 4.6.2   | Deriving SAPV sizing curves for Sri Lanka                        | 148 |
| 4.6.2.1 | Selection of system components                                   | 148 |
| 4.6.2.2 | Methodology  | 149 |
| 4.6.3   | Developing $C_A$ vs. $C_S$ charts for Central Hills of Sri Lanka | 152 |
| 4.7     | Summary  | 152 |

## **Chapter 5**

### **SOLAR RADIATION IN SRI LANKA**

|       |  |     |
|-------|--|-----|
| 5.1   | General  | 158 |
| 5.2   | Objectives   | 162 |
| 5.3   | Measuring incident solar radiation                                 | 163 |
| 5.4   | Estimating incident solar radiation                                | 165 |
| 5.5   | Predicting solar radiation values for Sri Lanka                    | 168 |
| 5.6   | Effect of rainfall on incident solar radiation                     | 176 |
| 5.7   | Comparison of GSR data – Measured vs. RF Model                     | 187 |
| 5.8   | Estimating solar radiation on a tilted surface                     | 188 |
| 5.8.1 | Comparison of data from Collarez correlation with SWERA TMY values | 193 |
| 5.8   | Summary  | 199 |

## **Chapter 6**

### **CASE STUDY**

|     |  |     |
|-----|--|-----|
| 6.1 | General  | 201 |
| 6.2 | Pumping quantity required (Q)                      | 202 |
| 6.3 | Energy required for pumping                        | 203 |
| 6.4 | Selecting the matching PV Generator & Battery size | 204 |
| 6.5 | Summary  | 205 |

## Chapter 7

### CONCLUSIONS AND FUTURE WORKS

|            |   |     |
|------------|---|-----|
| 7.1        | General   | 207 |
| 7.1.1.     | Cascading Multi Tank RWH systems                  | 208 |
| 7.1.2.     | Improving retention volumes based on overflow     | 209 |
| 7.1.3.     | PD pumps for RWH systems                          | 210 |
| 7.1.4.     | Correlation to calculate incident solar radiation | 210 |
| 7.1.5      | Calculating SR from rainfall data                 | 211 |
| 7.1.6      | Effect of tilt angle on incident solar radiation  | 212 |
| 7.1.7      | Sizing of SAPV systems                            | 212 |
| 7.2        | Future work                                       | 213 |
| REFERENCES |   | 215 |

### APPENDICES



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

#### Appendix 1

- 1.1 Data from prototype CMTRWHS (Yield and Rainfall)
- 1.2 Calculation of WSE values from prototype.
- 1.3 Calculation of  $Q/Q_0$  for CMTRWH systems

#### Appendix 2

- 2.1 Data on overflow quantities from prototype RWHS

#### Appendix 3

- 3.1 Data from prototype battery assisted SAPV system (OCV values)
- 3.2 Calculation of  $C_S$  and  $C_A$  values from prototype.

#### Appendix 4

- 4.1 Solar radiation data measured in Colombo, 2009 (Meteorology Dept.)

- 4.2 Solar radiation data measured at site – Colombo and Anuradhapura
- 4.3 Calculation of monthly average daily solar radiation in Colombo,
- 4.4 Calculation of regression coefficients for  $K_{T(\text{Clear})}$  and  $K_{T(\text{Overcast})}$
- 4.5 Calculation of incident solar radiation on a tilted surface.



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)

## List of Tables

|           |   |
|-----------|---|
| TABLE 2.1 | $C_f$ for different roof types  |
| TABLE 2.2 | Loss percentages in Silicon solar cell systems  |
| TABLE 2.3 | Regression for different solar heights  |
| TABLE 3.1 | Energy requirement % vs. Demand in Two Tank model   |
| TABLE 3.2 | Energy requirement % vs. Demand in Three Tank model   |
| TABLE 3.3 | Energy requirement % vs. Demand in 2 Tank model – with make-up water                                  |
| TABLE 3.4 | Energy requirement % vs. Demand in 3 Tank model – with make-up water                                  |
| TABLE 3.5 | Energy requirements for rain water pumping-unbalanced load  |
| TABLE 3.6 | WSE for 3 Tank unbalanced load model  |
| TABLE 3.7 | Energy requirements in pumping with variation in parent tank volume                                   |
| TABLE 3.8 | Annual OF quantities for given SD and SS  |
| TABLE 5.1 | Statistical error parameters for the correlations compared with measured data                         |
| TABLE 5.2 | % variation of predicted radiation from Angstrom model to measured data                               |
| TABLE 5.3 | Percentage variation of mean radiation from Angstrom model to mean measured data                      |
| TABLE 5.4 | Statistical error parameters for the two correlations   |
| TABLE 5.5 | Percentage deviation of $G_m-h$ (ARF) from corresponding measured data                                |
| TABLE 5.6 | Percentage deviations of mean wet & dry values of $G_m-h$ from mean wet & dry values of measured data |
| TABLE 5.7 | Percentage variation of tilt factor $R_m$ from 1.0 for the four stations                              |
| TABLE 5.8 | Statistical error parameters for $D_{m-h}/G_{m-h}$ , Collarez vs MSR                                  |

## List of Figures

- FIGURE 2.1 Access to improved water source in % of total population
- FIGURE 2.2 World fresh water resources per capita
- FIGURE 2.3 Generic configuration of a rainwater collection system
- FIGURE 2.4 Components of a rainwater collector sizing model
- FIGURE 2.5 Schematic drawing of a centrifugal pump
- FIGURE 2.6 Schematic diagram of a positive displacement pump
- FIGURE 2.7 A typical commercial silicon solar cell
- FIGURE 2.8 Electric load circuit of a simple cell
- FIGURE 2.9 Incident angles of solar radiation (a)
- FIGURE 2.10 Incident angles of solar radiation (b)
- FIGURE 3.1 Dry RTWHS
- FIGURE 3.2 Wet RTWHS
- FIGURE 3.3 The Total Flow type
- FIGURE 3.4 The Diverter type
- FIGURE 3.5 The Retention and Throttle type
- FIGURE 3.6 The Infiltration type RTRWHS
- FIGURE 3.7 RTRWHS with above ground Ferro-Cement tank
- FIGURE 3.8 RTRWHS with partial underground Ferro-Cement tank
- FIGURE 3.9 RTRWHS with below ground tank
- FIGURE 3.10a Typical RTRWHS for multi-story house
- FIGURE 3.10b Typical RTRWHS for multi-story house (schematic drawing)
- FIGURE 3.11 A typical mesh filter
- FIGURE 3.12 A typical first flush device
- FIGURE 3.13 Plumbing configuration for RTRWHS – scenario (a)
- FIGURE 3.14 Plumbing configuration for RTRWHS – scenario (b)
- FIGURE 3.15 Plumbing configuration for RTRWHS – scenario (c)
- FIGURE 3.16 Plumbing configuration for RTRWHS – scenario (d)
- FIGURE 3.17 Plumbing configuration for RTRWHS – scenario (e)

- FIGURE 3.18 CMTRWH systems for a two storey house
- FIGURE 3.19 Schematic diagram of a CTTRWH system
- FIGURE 4.1 Batch transfer pumping with variable head
- FIGURE 4.2 Components of a PV pumping system
- FIGURE 4.3 Direct and In-direct solar pumping
- FIGURE 4.4 PVP system; B-Battery, M-Motor, P- Pump
- FIGURE 5.1 Weather stations in Sri Lanka under the SWERA program
- FIGURE 5.2 Annual average solar radiation on a tilted plate at tilt angle equal to latitude
- FIGURE 5.3 Climatic zones of Sri Lanka
- FIGURE 5.4 SR in Sri Lanka, map for flat plate tilted at latitude- NE monsoon
- FIGURE 5.5 SR in Sri Lanka, map for flat plate tilted at latitude- 1<sup>st</sup> Inter monsoon
- FIGURE 5.6 SR in Sri Lanka, map for flat plate tilted at latitude- SW monsoon
- FIGURE 5.7 SR in Sri Lanka, map for flat plate tilted at latitude- 2<sup>nd</sup> Inter monsoon



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)



## List of Charts

- CHART 2.1 Generic curves for Water Saving Efficiency (WSE) (Fewkes, 1999b)
- CHART 2.2 The sensitivity of WSE to rainfall loss (Fewkes, 1999a)
- CHART 2.3 Relationship between overflow and specific rainwater consumption for given specific storage volumes.
- CHART 2.4 Head vs. Discharge for different pump speeds
- CHART 2.5 Output power vs. Discharge for different pump speeds
- CHART 2.6 Efficiency vs. Discharge for different pump speeds
- CHART 2.7 Operating characteristic curves
- CHART 2.8 Constant efficiency curves for centrifugal pumps
- CHART 2.9 Constant Head and Constant Discharge curves
- CHART 2.10 Typical load curve in batch transfer process
- CHART 2.11 Indicator diagram for a single-cylinder, single-acting PD pump
- CHART 2.12 The modified indicator diagram showing the effect of acceleration
- CHART 2.13 The friction effect in the suction & delivery pipes on the indicator diagram
- CHART 2.14 The typical current-voltage characteristics of the solar cell
- CHART 2.15 V-I curve with the variation of solar radiation
- CHART 2.16 V-I curve with the variation of cell temperature
- CHART 2.17  $C_A$  against  $C_S$  curves for a few selected cities.
- 
- CHART 3.1 Comparative WSE values obtained from prototype CMTRWHS
- CHART 3.2 Lower-limiting values for D/AR for different floor levels
- CHART 3.3 Upper-limiting values for D/AR for different floor levels
- CHART 3.4 Energy requirement % vs. Demand in Two and Three Tank models
- CHART 3.5 Energy requirement (E) % vs. Demand in 2 & 3 Tank models  
With make-up water
- CHART 3.6 Percentage pumping energy required for unbalanced load
- CHART 3.7 Percentage total energy required for unbalanced load
- CHART 3.8 Energy requirements in pumping with variation in parent tank volume
- CHART 3.9 Overflow % for different specific storage volumes

- CHART 4.1 Output characteristics of a PV module
- CHART 4.2 Characteristic curves for centrifugal pumps
- CHART 4.3 Characteristic curves for positive displacement pumps
- CHART 4.4 Battery life vs Depth of Discharge (DOD)
- CHART 4.5 12V Lead Acid Battery SOC vs. Voltage while under discharge
- CHART 4.6 SAPV sizing curves for the wet and dry regions of Sri Lanka
- 
- CHART 5.1 Global SR in Colombo
- CHART 5.2 Global SR in N'eliya
- CHART 5.3 Global SR in A'pura
- CHART 5.4 Global SR in H'tota
- CHART 5.5 Measured SR values (2008) against TMY data for Colombo, SL
- CHART 5.6 Radiation from measured data
- CHART 5.7 Radiation from Angstrom model
- CHART 5.8 Mean SR for wet and dry regions (measured data)
- CHART 5.9 Mean SR for wet and dry regions (Angstrom model)
- CHART 5.10 Measured wet against Angstrom wet
- CHART 5.11 Measured dry against Angstrom dry
- CHART 5.12 Comparison of GSR for Colombo
- CHART 5.13 Comparison of GSR for N'eliya
- CHART 5.14 Comparison of GSR for A'pura
- CHART 5.15 Comparison of GSR for H'tota
- CHART 5.16 Angstrom vs ARF model (Colombo)
- CHART 5.17 Angstrom vs ARF model (N'eliya)
- CHART 5.18 Angstrom vs ARF model (A'pura)
- CHART 5.19 Angstrom vs ARF model (H'tota)
- CHART 5.20 Comparison of GSR(RF), (Colombo)
- CHART 5.21 Comparison of GSR(RF), (N'eliya)
- CHART 5.22 Comparison of GSR(RF), (A'pura)
- CHART 5.23 Comparison of GSR(RF), (H'tota)
- CHART 5.24 Gm-h TMY for all locations
- CHART 5.25 Gm-h ARF for all locations

- CHART 5.26 Gm-h mean MD for all locations
- CHART 5.27 Gm-h mean ARF for all locations
- CHART 5.28 Comparison of RF model outcomes with TMY data for Colombo
- CHART 5.29 Tilt factor, Rm for Colombo, Wet zone
- CHART 5.30 Tilt factor, Rm for Nuwara Eliya, Wet zone-Central Hills
- CHART 5.31 Tilt factor, Rm for Anuradhapura, Intermediate zone
- CHART 5.32 Tilt factor, Rm for Hambantota, Dry zone
- CHART 5.33 GSR on a south facing surface tilted at an angle equal to latitude
- CHART 5.34 GSR on a south facing surface tilted at an angle equal to  $30^{\circ}$
- CHART 5.35 Monthly averages Diffuse/Global SR on flat plate in Colombo
- CHART 5.36 Monthly averages Diffuse/Global SR on flat plate in N'Eliya
- CHART 5.37 Monthly averages Diffuse/Global SR on flat plate in A'pura
- CHART 5.38 Monthly averages Diffuse/Global SR on flat plate in H'tota



University of Moratuwa, Sri Lanka.  
Electronic Theses & Dissertations  
[www.lib.mrt.ac.lk](http://www.lib.mrt.ac.lk)