TECHNO-ECONOMIC FEASIBILITY ASSESSMENT OF ENERGY STORAGE SYSTEM CONFIGURATIONS FOR GRID-CONNECTED SOLAR PV SYSTEMS FOR SOUTHERN PROVINCE OF SRI LANKA.

Sammu Arachchige Nadeesha Erandi Kumudu

(199444T)

Degree of Master of Engineering

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

July 2024

TECHNO-ECONOMIC FEASIBILITY ASSESSMENT OF ENERGY STORAGE SYSTEM CONFIGURATIONS FOR GRID-CONNECTED SOLAR PV SYSTEMS FOR SOUTHERN PROVINCE OF SRI LANKA.

Sammu Arachchige Nadeesha Erandi Kumudu

(199444T)

Thesis submitted in partial fulfilment of the requirements for the degree
Master of Engineering

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

July 2024

DECLARATION

I declare that this is my work and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to the University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

UOM Verified Signature

Signature:……………………….. Date: 16/07/2024

S.A.N.E. Kumudu

The above candidate has carried out research for the Master's Thesis under my supervision.

Signature::……………………….. Date: …………………….

Dr. L.U. Subasinghe

ACKNOWLEDGEMENT

I am deeply appreciative to Dr. Lihil U. Subasinghe for his constant backing and direction throughout my research. His forbearance, drive, and vast knowledge were pivotal in moulding my thesis's orientation and triumph. I highly value his guidance and the time he devoted to assisting me at every phase of my research and writing.

I would also like to express my heartfelt gratitude to Dr. Indrajith D. Nissanka, the Coordinator of the Master of Engineering in Energy Technology, whose perspectives during my advancement assessments were priceless in directing my research towards its prosperous completion. My appreciation also reaches all other lecturers who have given direction and crucial evaluations that significantly enriched my work.

I have distinctive gratitude to my fellow workers and the administration at the Sri Lanka Institute of Advanced Technological Education for their comprehension and support, which was essential in harmonizing my studies with my professional obligations.

Moreover, I appreciate the companionship and backing from all my MEng Energy Technology program acquaintances. Their support and collective sagacity have been a fount of resilience and motivation throughout this voyage.

Lastly, I am thankful to everyone who directly or indirectly contributed to my research. This accomplishment is not solely mine but also pertains to all who steered and backed me along the path.

ABSTRACT

The discrepancy between peak solar energy generation and peak demand necessitates energy storage projects to effectively utilize this sustainable resource. This research conducts a techno-economic feasibility assessment of two energy storage systems: Lithium-ion Battery Energy Storage System (Li-ion BESS) and Pumped Hydro Power Plant (PHPP) integrated with grid-connected Solar PV. The aim is to store solar energy during off-peak hours and release electrical energy during peak demand in the southern province of Sri Lanka. Various configurations have been proposed for integrating the two energy storage systems with grid-connected solar PV. The required solar PV capacities for storage purposes in different regions of the southern province are analyzed using HOMER Pro. Present Cost (PC), Levelized Cost of Electricity (LCOE), Net Present Value (NPV) and Payback Period (PP) are determined by considering the construction, operation, and maintenance costs of both energy storage systems along with the relevant grid-connected solar PV costs. Both energy storage mechanisms demonstrate favourable Net Present Value (NPV) and possess Internal Rates of Return (IRR) that surpass the actual discount rate. Nevertheless, the Li-ion BESS distinguishes itself with its notably superior NPV and IRR, rendering it the more appealing financial choice. The outcomes reveal a higher initial capital cost associated with grid-connected Solar PV with PHPP. In contrast, grid-connected Solar PV with Li-ion BESS exhibits the lowest LCOE in the southern province. A shorter payback period is observed with grid-connected Solar PV integrated with Li-ion BESS. These research findings offer valuable insights for the prospective implementation of large-scale solar PV and energy storage projects in Sri Lanka.

Keywords: Peak Demand, Grid Connected PV, PHPP, Li-ion BESS, LCOE

TABLE OF CONTENTS

DECLARATION ii

ACKNOWLEDGEMENT iii

ABSTRACT iv

TABLE OF CONTENTS v

LIST OF FIGURES ix

LIST OF TABLES xi

LIST OF ABBREVIATIONS xii

1.0 INTRODUCTION 1

1.1 Solar energy 1

1.2 Current issues of the power sector in Sri Lanka 1

1.3 Energy Storage System 2

1.4 Problem Identification 3

1.5 Research objectives 4

1.6 Scope of study 4

1.7 Contribution to the country 5

2.0 LITERATURE REVIEW 6

2.1 Grid-connected solar PV system 6

2.2 Grid-connected solar PV System plus ESS 7

2.3 Research gap 12

3.0 RESEARCH METHODOLOGY 13

3.1 Option 1- Li-ion BESS plus PV systems 15

3.1.1 Project location selection 16

3.1.2 Metrological data 16

3.2 Option 2- PHPP plus Solar PV System 18

3.2.1 Project location selection 19

3.2.2 Metrological data 19

4.0 TECHNICAL FEASIBILITY EVALUATION OF THE SOLAR PV PLANT AND ENERGY STORAGE SYSTEM.. 22

4.1 Option 1- Li-ion BESS plus grid-connected PV plants 22

4.1.1 Sizing the Li-ion BESS for Option 1 22

4.1.2 Sizing the Ground-Mounted Solar PV Plant for Option 1 28

4.2 Option 2- PHPP with grid-connected solar PV plant...................................... 36

4.2.1 Sizing the Pump Hydro Power Plant for the Option2.............................. 36

4.2.2 Sizing the Ground-Mounted Solar PV System for the Option 2............... 41

5.0 ECONOMIC FEASIBILITY EVALUATION OF THE SOLAR PV PLANT AND ENERGY STORAGE SYSTEM.. 44

5.1 Economic Inputs.. 44

5.2 Present Cost... 44

5.3 Net Present Value.. 45

5.4 Internal Rate of Return.. 46

5.5 Levelized Cost of Energy.. 46

5.6 Payback Period.. 46

5.7 Economics Evaluation of the Solar PV with Li-ion BESS 46

5.7.1 Calculation for the Solar PV with Li-ion BESS....................................... 48

5.7.2 Grid-connected Solar PV with Li-ion BESS for Southern Province 49

5.8 Economics Evaluation for the Solar PV with PHPP 49

5.8.1 Economic Inputs to construction of 70 MW Pump hydropower plant 50

5.8.2 Construction of 100 MW grid-connected Solar PV power plant.............. 51

5.8.3 Calculation for the ground-mounted Solar PV plant plus PHPP 52

5.9 Environmental Benefits... 52

6.0 SUMMARY OF RESULTS AND DISCUSSION 53

7.0 CONCLUSION AND FUTURE WORK 58
7.1 Conclusion 58
7.2 Future work 58
REFERENCES 59
APPENDICES 63
A 1.1 Availabity of Solar and Mini hydro power plant in Sri Lanka 63
A 1.2 Tropology of Deniyaya 64
A 1.3 Whether report of Deniyaya 65
A 1.4 Required energy storage calculation 66
A 1.5 Requested specification for Li-ion BESS 67
A 1.6 Specifications and Quotation from BESS Supplier 68
A 1.7 Ambalangada - PC, NPV, and PP Calculation 76
A 1.8 Beliatta - PC, NPV, and PP Calculation 77
A 1.9 Deniyaya - PC, NPV, and PP Calculation 78
A 1.10 Embilipitiya - PC, NPV, and PP Calculation 79
A 1.11 Galle - PC, NPV, and PP Calculation 80
A 1.12 Hambantota - PC, NPV, and PP Calculation 81
A 1.13 Matara - PC, NPV, and PP Calculation 82
A 1.14 Southern Province – PV with Li-Ion BES (life Span 20 years) 83
A 1.15 Southern Province – Economic value calculation for PV plus Li-ion BESS (80-year life span) 84
A 1.16 Southern Province – Economic value calculation for PV plus PHPP (80-year life span) 89
A 1.17 Electrical generation price from a thermal oil power plant 95
A 1.18 References tables used to calculate the construction cost of the Pump Hydro Power Plant 96

A 1.19 Economic Evaluation summary of the proposed power plant used to calculate the construction cost of the Pump Hydro Power Plant 97

A 1.20 GHI and Clearness index of the Hambantota area 98

A 1.21 GHI and clearness index of Galle 98

A 1.22 GHI and clearness index of Ambalangoda 99

A 1.23 GHI and clearness index of Deniyaya 99

A 1.24 GHI and clearness index of Embilipitiya 100

A 1.25 GHI and clearness index of Beliatta 100

LIST OF FIGURES

Figure 1.1 power generation curve of Sri Lanka 2
Figure 2.1 Block diagram of Grid-connected PV System.. 6
Figure 2.2 Grid-connected AC coupled system 7
Figure 2.3 Grid-connected DC coupled system 8
Figure 3.1 Methodology flow of the study... 13
Figure 3.2 Schematic diagram of the seven ground-mounted Solar PV plus BESS in the Southern province 15
Figure 4.1 Daily Load curve of Ambalangoda Grid Substation 22
Figure 4.2 Daily Load Curve of Galle Grid Substation 23
Figure 4.3 Daily Load curve of Deniyaya Grid Substation 23
Figure 4.4 Daily Load curve of Matara Grid Substation 24
Figure 4.5 Daily Load curve of Embilipitiya Grid Substation.................................. 24
Figure 4.6 Daily Load Curve of Beliatta Grid Substation 25
Figure 4.7 Daily Load curve of Hambantota Grid Substation 25
Figure 4.8 Load curve of Ambalangoda GSS highlighting the peak hours 27
Figure 4.9 Simulated power system from Homer Pro to determine the capacity of a Solar PV plant in Ambalangoda.. 29
Figure 4.10 Power output of the proposed Solar PV plant in Ambalangoda............. 30
Figure 4.11 PV power output of the proposed Solar PV plant in Galle.................. 30
Figure 4.12 PV power output of the proposed Solar PV plant in Deniyaya 31
Figure 4.13 PV power output of the proposed Solar PV plant in the Matara 32
Figure 4.14 PV power output of the proposed Solar PV plant in Embilipitiya 32
Figure 4.15 PV power output of the proposed Solar PV plant in Beliatta................ 33
Figure 4.16 PV power output of the proposed Solar PV plant in Hambantota........ 34
Figure 4.17 Load curve of the Southern Province highlighting the peak hours 37
Figure 4.18 Power output of the proposed Solar PV plant in the Hambantota area .. 42
Figure 6.1 LCOE of the different energy storage options with the solar PV plant.... 53
Figure 6.2 Present Cost of the different energy storage options with the solar PV plant 54
Figure 6.3 IRR of the different energy storage options with the solar PV plant........ 54

Figure 6.4 Payback period of the different energy storage options with the solar PV plant.. 55

LIST OF TABLES

Table 1.1 Power Density and Energy Density of Storage Technologies 2
Table 3.1 Annual average of GHI in the selected area 16
Table 4.1 The calculated energy storage capacity Maximum power output of energy storage 27
Table 4.2 Output parameters of the proposed Solar PV plant in Ambalangoda 29
Table 4.3 Output parameters of the proposed PV plant in Galle 30
Table 4.4 Output parameters of the proposed PV plant in Deniyaya........................ 31
Table 4.5 Output parameters of the proposed PV plant in Matara............................ 31
Table 4.6 Output parameters of proposed PV plant in Embilipitiya 32
Table 4.7 Output parameters of the proposed PV plant in Beliatta 33
Table 4.8 Output parameters of the proposed PV plant in Hambantota 33
Table 4.9 Summary table of required battery capacity and Solar PV capacity.......... 34
Table 4.10 Output parameters of the proposed Solar PV plant in Hambantota area . 42
Table 4.11 Comparison of technical feasibility of Option 1 and Option 2 43
Table 5.1 Economic input parameters for Solar PV with Li-ion BESS 48
Table 5.2 The conclusive results derived from analysis of Solar PV with BESS 48
Table 5.3 Calculated Economic values of grid-connected Solar PV with BESS for Southern province 49
Table 5.4 Cost associated with the construction of a 70 MW pump hydro power plant 51
Table 5.5 Cost associated with grid-connected solar PV system with PHPP 51
Table 5.6 Economic parameters of grid-connected solar PV system with PHPP 52

LIST OF ABBREVIATIONS

Abbreviation	Description
BESS	Battery Energy Storage System
CEB	Ceylon Electricity Board
ESS	Energy Storage System
GHI	Global Horizontal Irradiation
GSS	Grid Sub Station
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
Li-ion BESS	Lithium-ion Battery Energy Storage System
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PHPP	Pump Hydro Power Plant
PV	Photovoltaic
PC	Net Present Cost
PP	Payback Period
O&M	Operation & Maintenance