DESIGN OPTIMIZATION OF A GRID SCALE HYBRID ENERGY STORAGE SYSTEM TO MAXIMIZE SOLAR PV INTEGRATION

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Master of Philosophy

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DECLARATION

I declare that this is my own 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. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date: 16/05/2025

The supervisor should certify the Thesis with the following declaration.

The above candidate has carried out research for the Master of Philosophy Thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Prof. D.P. Chandima

Signature of the Supervisor: Date: 16/05/2025

DEDICATION

This thesis is dedicated to my beloved parents and family, whose unconditional love, encouragement, and sacrifices have been the foundation of my achievements.

To my supervisor, who has guided and inspired me throughout this journey with his wisdom and patience.

And to my friends, who have stood by me through the challenges, providing support and motivation when I needed it most.

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ABSTRACT

The global utilization of renewable energy is increasing as an environmentally sustainable approach to reduce greenhouse gas emissions, which are major contributors to air pollution and climate change, by decreasing reliance on oil-fired thermal power generation. This research aims to minimize oil-fired thermal generation and maximize solar photovoltaic (PV) generation through a grid-connected Hybrid Energy Storage System (HESS) that integrates lithium-ion Battery Storage (BS) and Pumped Hydro Storage (PHS). Solar energy is prioritized due to its technological maturity and cost-effectiveness compared to other sustainable energy sources. The HESS is employed to optimize storage performance, utilizing high efficiency and energy management capabilities of lithium-ion BS and the large-scale energy storage potential of PHS. Both technologies are well-established, offering reliability and low investment risks.

A novel optimization algorithm, based on the Non-dominated Sorting Genetic Algorithm (NSGA-II), is developed to minimize total expenditures. This includes capital, operational, and replacement costs associated with solar PV, lithium-ion BS, and PHS systems, as well as expenses related to solar power curtailment and supplementary oil-fired thermal energy. The multi-objective optimization problem is solved using the open-source Python framework Pymoo (multi-objective optimization in Python), and Python code developed and executed on Google Colaboratory (Colab). The algorithm determines optimal capacities for lithium-ion BS and solar PV systems at short-term intervals throughout the project planning horizon. The capacity of PHS is identified through a feasibility study conducted for a specific region, considering geological constraints. An innovative energy management strategy is proposed to optimize solar energy utilization within the HESS. This strategy ensures the efficient utilization of solar energy, maintains grid stability, optimizes HESS operations within system limitations, and minimizes dependence on thermal power generation.

The research includes a case study of the Sri Lankan power system, supported by economic and environmental assessments to identify the most sustainable scenarios. Sensitivity analysis is conducted to evaluate capacity variations under fluctuating interest rates. A roadmap for solar PV and BS capacity expansions is developed for two-year intervals throughout the planning horizon, along with the optimal timeline for integrating PHS. The final results indicate minimal variations in total cost, ranging from -14.05 % to 56.69 %, and an increase in solar PV generation by 2.19 % at the lowest interest rate and 5.13 % at highest interest rate. The solar PV capacities determined from the optimization algorithm are compared with the projected capacities of solar power plants outlined in Sri Lankan generation expansion plan to evaluate their alignment with the renewable energy targets in the country. The results demostrats strong agreement with the national energy plan.

Keywords: Hybrid Energy Storage, Solar PV Generation, Genetic Algorithm, Techno-economic optimization

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
BS	Battery Storage
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
CEB	Ceylon Electricity Board
CSP	Concentrated Solar Power
DOD	Depth of Discharge
DRL	Deep Reinforcement Learning
EMO	Evolutionary Multi-Objective Optimization
FES	Flywheel Energy Storage
GA	Genetic Algorithm
GHG	Greenhouse Gas Emission
HESS	Hybrid Energy Storage System
IEA	International Renewable Energy Agency
IRR	Internal Rate of Return
JICA	Japan International cooperation Agency
LAES	Liquid air energy storage
LCOE	levelized cost of electricity
Li-ion	Lithium Ion
LNG	Liquefied Natural Gas
LR	Lower Reservoir
NaS	Sodium sulfur
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
NSGA	Non-dominated Sorting Genetic Algorithm
OPEX	Operational Expenditures
Pb-acid	Lead-acid
PHS	Pumped Hydro Storage
PSO	Particle Swarm Optimization
PUCSL	Public Utilities Commission of Sri Lanka
PV	Photovoltaic
Pymoo	Multi-Objective Optimization in Python
RE	Renewable Energy
REPEX	Replacement Expenditures

Abbreviation	Description
RFB	Redox flow battery
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
STC	Standard Test Conditions
UR	Upper Reservoir

LIST OF APPENDICES