

**TECHNO-ECONOMIC ANALYSIS OF INTERMITTENT  
RENEWABLE ENERGY PENETRATION WITH THE  
PROPOSED INDIA-SRI LANKA HVDC  
INTERCONNECTION**

Madanakondage Dilini Vasana Fernando

(149281T)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

March 2018

**TECHNO-ECONOMIC ANALYSIS OF INTERMITTENT  
RENEWABLE ENERGY PENETRATION WITH THE  
PROPOSED INDIA-SRI LANKA HVDC  
INTERCONNECTION**

Madanakondage Dilini Vasana Fernando

(149281T)

Dissertation submitted in partial fulfillment of the requirements for the degree

Master of Science in Electrical Engineering

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

March 2018

## DECLARATION

“I declare that this is my own work and this dissertation 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 University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in 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).

.....

Signature

M.D.V. Fernando

.....

Date

The above candidate has carried out research for the Masters dissertation under my supervision.

.....

Signature of the supervisor

Dr. W.D.A.S. Rodrigo

.....

Date

## DEDICATION

*To my family*

## **ACKNOWLEDGMENT**

First, I wish to express my sincere gratitude to my supervisor Dr. W.D.A.S. Rodrigo for his continuous encouragement and guidance throughout my research work.

I extend my sincere gratitude to the all the lecturers of the Department of Electrical Engineering for the knowledge and wisdom provided during the course of the study period and for their valuable comments during the progress of the research in order to make it a success.

I would also like to mention that my work experience in the Generation Planning of CEB was immensely useful in conducting this research and in gaining access to required software.

I would also like to thank my friends and colleagues who assisted me in various manners by providing required material for the research work. Finally, I would like to thank my parents for their continuous support and my husband for his motivation throughout.

## ABSTRACT

This research is a techno-economic analysis carried out to identify the effect of level of intermittent renewable energy penetration in to the Sri Lankan power system with the proposed India-Sri Lanka HVDC interconnection. The focus on power generation using intermittent renewable energy gives rise to system operational issues leading to renewable energy curtailments. This research adopts a methodology to identify the level of RE penetration with the HVDC link compared to original power system planned with pump storage power plant.

Future power plant additions based on least cost principles are obtained using WASP software considering stage development of HVDC; 500 MW in 2025 and 1000 MW in 2028. This power plant schedule was input to long term dispatch simulation software SDDP in order to obtain the optimum hydro thermal generation mix for different seasons of the year namely, high wind and wet periods. Output of SDDP for each season was input to short term dispatch simulation software NCP in order to simulate the daily dispatch and obtain renewable curtailments to identify the RE penetration level. Renewable are modeled in detail with 30 minute resolution in the dispatch simulation software. This process was repeated to obtain the RE penetration level with 500 MW HVDC and 1000 MW HVDC for different scenarios assuming aggressive wind development, aggressive solar development and mix development.

The economic analysis was carried out to identify the cost impact of each scenario compared to the original power system. It was observed that the HVDC is economical for the initial RE capacities but the RE penetration can be increased with HVDC at an additional cost to the system. Therefore, sensitivity analysis was carried out to identify at what variable cost of HVDC the link would bring economic benefit to the country for each scenario. This methodology could be used when negotiating the pricing contract agreements with India to identify whether the HVDC link could bring economic benefit to Sri Lanka depending on the prevailing energy mix.

***Keywords: HVDC, Intermittent Renewable Energy***

## TABLE OF CONTENTS

	Page
Declaration	i
Dedication	ii
Acknowledgements	iii
Abstract	iv
Table of content	v
List of Figures	vii
List of Tables	xi
List of abbreviations	xii
1. Introduction	
1.1 Background	1
1.2 Objective	3
1.3 Organization of the dissertation	4
2. Literature Review	
2.1 HVDC technology	5
2.2 India-Sri Lanka HVDC Interconnection	6
2.3 HVDC Dynamic Performance in Sri Lankan Context	13
2.4 Renewable Energy	
2.4.1 Introduction	14
2.4.2 Sri Lankan context	14
2.4.3 Indian context	17
2.4.4 Renewable Energy Potential & Resource Estimation	17
2.5 System reserve requirement	22
3. Methodology	
3.1 Introduction	23
3.2 Optimization of Power Plant Schedule	25
3.3 Dispatch Simulation to Identify Optimum Renewable Penetration	
3.3.1 Long Term Dispatch	33
3.3.2 Short Term Dispatch	35
3.4 Scenario Selection	37
3.5 Assumptions	38
4. Simulation Results	
4.1 Introduction	40
4.2 Optimized Capacity Additions	40
4.3 System Comparison with PSPP and HVDC for Phase 1 of HVDC	41

4.4 Renewable Penetration with Development of 500 MW HVDC in 2025	48
4.5 System Comparison with PSPP and HVDC for Phase 11 of HVDC	62
4.6 Renewable Penetration with Development of 1000 MW HVDC in 2028	66
4.7 Summary of Results	73
5. Economic Analysis	
5.1 Methodology	75
5.2 Economic cost of the scenarios	76
5.3 Sensitivity analysis	78
6. Discussion	80
7. Conclusion & Recommendation	
7.1 Conclusion & Recommendation	84
7.2 Limitations	85
7.3 Future Work	86
Reference List	87

## LIST OF FIGURES

	Page	
Figure 1.1-	Capacity and energy mix of Sri Lanka 2016	2
Figure 2.1-	2x 250 MW bipolar interconnection configuration	11
Figure 2.2-	1x500 MW mono-polar interconnection configuration	12
Figure 2.3-	Historical Energy Contribution of Renewable Energy Sources 2005-2015	17
Figure 2.4-	Potential of Hydropower system from past 33 years hydrological data	18
Figure 2.5-	Per unit monthly average capacity of Mini Hydro plant	19
Figure 2.6-	Variation of Solar PV Plant Output	22
Figure 3.1-	Research methodology	24
Figure 3.2-	Demand Curve & LDC of a typical day in 2025 June	26
Figure 3.3-	WASP Optimization within Reserve Margin criteria	32
Figure 3.4-	Immediate and Future Cost Function Variation with Turbine Outflow	35
Figure 3.5-	Scenarios for simulation	38
Figure 4.1-(a)	Power plant dispatch with 200 MW PSPP in 2025 wet period weekday	42
Figure 4.1-(b)	Curtailments of Renewable Generation with 200 MW PSPP in 2025 wet period weekday	42
Figure 4.2-(a)	Power plant dispatch with 200 MW PSPP in 2025 wet period weekend day	43
Figure 4.2-(b)	Curtailments of Renewable Generation with 200 MW PSPP in 2025 wet period weekend day	43
Figure 4.3-	Power plant dispatch with 500 MW HVDC in 2025 wet period weekday	44
Figure 4.4-	Power plant dispatch with 500 MW HVDC in 2025 wet period weekend day	44

Figure 4.5-(a)	Power plant dispatch with 200 MW PSPP in 2025 high wind period weekday	45
Figure 4.5-(b)	Curtailments of Renewable Generation with 200 MW PSPP in 2025 high wind period weekday	45
Figure 4.6-(a)	Power plant dispatch with 200 MW PSPP in 2025 high wind period weekend day	46
Figure 4.6-(b)	Curtailments of Renewable Generation with 200 MW PSPP in 2025 high wind period weekend day	46
Figure 4.7-	Power plant dispatch with 500 MW HVDC in 2025 high wind period weekday	47
Figure 4.8-	Power plant dispatch with 500 MW HVDC in 2025 high wind period weekend day	47
Figure 4.9-(a)	Power plant dispatch with maximum solar penetration with 500 MW HVDC in wet period weekday	49
Figure 4.9-(b)	Curtailments with maximum solar penetration with 500 MW HVDC in wet period weekday	49
Figure 4.10-(a)	Power plant dispatch with maximum solar penetration with 500MW HVDC in wet period weekend day	50
Figure 4.10-(b)	Curtailments with maximum solar penetration with 500 MW HVDC in wet period weekend day	50
Figure 4.11-(a)	Power plant dispatch with maximum solar penetration with 500 MW HVDC in high wind period weekday	51
Figure 4.11-(b)	Curtailments with maximum solar penetration with 500 MW HVDC in high wind period weekday	51
Figure 4.12-(a)	Power plant dispatch with maximum solar penetration with 500 MW HVDC in high wind period weekend day	52
Figure 4.12-(b)	Curtailments with maximum solar penetration with 500 MW HVDC in high wind period weekend day	52
Figure 4.13-(a)	Power plant dispatch with maximum wind penetration with 500MW HVDC in wet period weekday	53
Figure 4.13-(b)	Curtailments with maximum wind penetration with 500 MW HVDC in wet period weekday	53
Figure 4.14-(a)	Power plant dispatch with maximum wind penetration with 500 MW HVDC in wet period weekend day	54
Figure 4.14-(b)	Curtailments with maximum wind penetration with 500 MW HVDC in wet period weekend day	54
Figure 4.15-(a)	Power plant dispatch with maximum wind penetration with 500 MW HVDC in high wind period weekday	55
Figure 4.15-(b)	Curtailments with maximum wind penetration with 500 MW HVDC in high wind period weekday	55

Figure 4.16-(a)	Power plant dispatch with maximum wind penetration with 500MW HVDC in high wind period weekend day	56
Figure 4.16-(b)	Curtailments with maximum wind penetration with 500 MW HVDC in high wind period weekend day	56
Figure 4.17-(a)	Power plant dispatch with maximum renewable penetration with 500 MW HVDC in wet period weekday	57
Figure 4.17-(b)	Curtailments with maximum renewable penetration with 500 MW HVDC in wet period weekday	57
Figure 4.18-(a)	Power plant dispatch with maximum renewable penetration with 500 MW HVDC in wet period weekend day	58
Figure 4.18-(b)	Curtailments with maximum renewable penetration with 500 MW HVDC in wet period weekend day	58
Figure 4.19-(a)	Power plant dispatch with maximum renewable penetration with 500 MW HVDC in high wind period weekday	59
Figure 4.19-(b)	Curtailments with maximum renewable penetration with 500 MW HVDC in high wind period weekday	59
Figure 4.20-(a)	Power plant dispatch with maximum renewable penetration with 500 MW HVDC in high wind period weekend day	60
Figure 4.20-(b)	Curtailments with maximum renewable penetration with 500 MW HVDC in high wind period weekend day	60
Figure 4.21-(a)	Power plant dispatch with 600 MW PSPP in 2028 wet period weekday	63
Figure 4.21-(b)	Curtailments of Renewable Generation with 600 MW PSPP in 2028 wet period weekday	63
Figure 4.22-(a)	Power plant dispatch with 600 MW PSPP in 2028 wet period weekend day	64
Figure 4.22-(b)	Curtailments of Renewable Generation with 600 MW PSPP in 2028 wet period weekend day	64
Figure 4.23-	Power plant dispatch with 500 MW HVDC in 2025 wet period weekday	65
Figure 4.24-	Power plant dispatch with 500 MW HVDC in 2025 wet period weekend day	65
Figure 4.25-(a)	Power plant dispatch with maximum solar penetration with 1000 MW HVDC in wet period weekday	66
Figure 4.25-(b)	Curtailments with maximum solar penetration with 1000 MW HVDC in wet period weekday	66
Figure 4.26-(a)	Power plant dispatch with maximum solar penetration with 1000 MW HVDC in wet period weekend day	67
Figure 4.26-(b)	Curtailments with maximum solar penetration with 1000 MW HVDC in wet period weekend day	67

Figure 4.27-(a)	Power plant dispatch with maximum wind penetration with 1000 MW HVDC in wet period weekday	68
Figure 4.27-(b)	Curtailments with maximum wind penetration with 1000 MW HVDC in wet period weekday	68
Figure 4.28-(a)	Power plant dispatch with maximum wind penetration with 1000 MW HVDC in wet period weekend day	69
Figure 4.28-(b)	Curtailments with maximum wind penetration with 1000 MW HVDC in wet period weekend day	69
Figure 4.29-(a)	Power plant dispatch with maximum renewable penetration with 1000 MW HVDC in wet period weekday	70
Figure 4.29-(b)	Curtailments with maximum renewable penetration with 1000 MW HVDC in wet period weekday	70
Figure 4.30-(a)	Power plant dispatch with maximum renewable penetration with 1000 MW HVDC in wet period weekend day	71
Figure 4.30-(b)	Curtailments with maximum renewable penetration with 1000 MW HVDC in wet period weekend day	71
Figure 4.31-	Summary of renewable capacity addition	74
Figure 5.1-	Variation of PV cost of scenarios with HVDC variable cost	79

## LIST OF TABLES

	Page
Table 2.1- Present Status of Other Renewable Energy Sector	16
Table 2.2- Wind Plant modeling main parameters	20
Table 2.3- Results on Wind plant modeling	20
Table 2.4- Solar output plant factor	21
Table 3.1- Load Forecast	26
Table 3.2- Candidate Power Plant Characteristics	27
Table 3.3- Candidate Power Plant Cost Parameters	28
Table 3.4- ORE Initial Capacity	28
Table 3.5- Renewable Power Plant Cost Parameters	29
Table 3.6- Oil Prices and Characteristics for Analysis	29
Table 3.7- Coal Prices and Characteristics for Analysis	29
Table 3.8- PSPP Parameters	30
Table 3.9- HVDC Parameters	31
Table 4.1- Capacity additions of the system with initial renewable capacities	41
Table 4.2- Summary of results with 500 MW HVDC	61
Table 4.3- Summary of results with 1000 MW HVDC	72
Table 4.4- Summary of renewable capacities (MW)	73
Table 5.1- Capacity additions of the system for the scenarios	75
Table 5.2- Cost Difference of Scenarios	78
Table 7.1- Scenario summary & renewable capacities (MW)	84

## LIST OF ABBREVIATIONS

CEB	-	Ceylon Electricity Board
CSC	-	Current Source Converters
FIT	-	Feed-in-tariff
HVDC	-	High Voltage Direct Current
LDC	-	Load Duration Curve
LTGEP	-	Long Term Generation Expansion Plan
MMbtu	-	Million British Thermal Unit
O&M	-	Operation & Maintainance
ORE	-	Other Renewable Energy
PSPP	-	Pumped Storage Power Plant
PV	-	Present value
RE	-	Renewable Energy
SDDP	-	Stochastic Dual Dynamic program
SLSEA	-	Sri Lanka Sustainable Energy Authority
Solar_H	-	Solar Hambanthota
Solar_K	-	Solar Kilinochchi
SPPA	-	Small Power Purchase Agreement
VRE	-	Variable Renewable Energy
VSC	-	Voltage Source Converters
WASP	-	Wien Automation System Package
Wind_E	-	Wind Eastern
Wind_H	-	Wind Hill country
Wind_M	-	Wind Mannar
Wind_N	-	Wind Northern
Wind_P	-	Wind Puttalam