Sri Lanka
Energy Empowered Nation
Research Findings

Ministry of Power and Renewable Energy

SRI LANKA
ENERGY EMPOWERED NATION
RESEARCH FINDINGS

Research Journal of the Ministry of Power and Renewable Energy

December 2015 Volume 01, Number 01

A Message from the Editorial Advisory Board

The International Energy Agency has projected that if the current policies continue, the world primary energy demand will grow by 47% between 2008 and 2035. Total world primary energy demand is estimated to increase from 514 Exajoules (EJ) in 2010 to 624 EJ in 2020 and to 756 EJ in 2035. Much of the growth in energy demand is expected to be from non-OECD countries, where demand is driven by strong, long-term economic growth. In Sri Lanka, the total primary energy demand which stood at 0.484 EJ in 2014is estimated to increase to rise up to about 0.756 EJ by year 2030 at an annual growth rate of 3%. According to the Sri Lanka Energy Balance 2014, 52.6% of the primary energy supply was from Renewable Energy sources and the balance from fossil fuels. In the year 2013, the country has imported fossil fuels worth USD 4.795 billion which is nearly quarter of the total import bill. This reliance on fossil fuels has posed a significant threat to economy in terms of draining foreign exchange, widening trade balance and pollution of the environment by emission of green-house gasses. Dependence on fossil fuel for energy also makes a threat to energy security since the fossil fuel prices are quite volatile. Furthermore, since it has been projected that the world fossil fuel resources will be depleted in the foreseeable future, heavy dependence on fossil fuels for electricity generation and transportation will also have a direct impact on the energy security of the country. Thus, a necessity has arisen to explore alternatives, which are more sustainable and environmentally benign for the country. In addition it is essential to rationalise the use of energy and minimise energy losses and find technologies which are more efficient in delivering necessary energy services.

In recognition of this need, the Ministry of Power and Renewable Energy has called upon all researchers and practitioners in the field of energy to come forward to find practical solutions for this dilemma faced by the country. As the first step towards this, *Energy Symposium 2015* was held on 26th and 27th of June under the theme ’Energy Challenges in the Knowledge Economy’. Of the large number of papers submitted, 86 were selected for presentation at the symposium. The findings from these papers were used to prepare a plan of action for the Ministry of Power and Renewable Energy. Fifty full papers were selected for publishing in the first volume of our Journal ’Research for an Energy Empowered Nation‘. Through these efforts, we intend to encourage and nurture this culture of research and development in the energy sector of the country. It is with great pleasure I introduce this first volume of the journal and take this opportunity to thank all those who have contributed to this endeavour.

Dr. B.M.S. Batagoda
Secretary
Ministry of Power & Renewable Energy

RESEARCH FOR AN ENERGY EMPOWERED NATION

Research for an Energy Empowered Nation is a peer reviewed international journal that publishes high quality original research articles related to the energy sector. This journal is published by the Ministry of Power and Renewable Energy, Sri Lanka and Center for Sustainability, University of Sri Jayewardenepura, Sri Lanka. This journal provides a multidisciplinary forum for discussion of issues and communication of research findings of wider interest to the community of energy professionals. Acceptance for publication is subject to a double-blinded peer-reviewing process.

Cover Design by:

Trishan Perera

Sponsored by:

Sri Lanka Sustainable Energy Authority,
Block 05, 1st Floor, 3G -17, BMICH, Bauddhaloka Mawatha, Colombo 7.

Publisher Information:

ISSN 2478-0669 Print
Center for Sustainability
Department of Forestry and Environmental Science
University of Sri Jayewardenepura
Nugegoda
Sri Lanka
Telephone: +94 11 2758414
Fax: +94 11 2802937
Email: sustainability@sjp.ac.lk

Printed in Sri Lanka

Table of Contents

Economics of Carbon Emission Reduction in Electricity Generation in Sri Lanka

S.W.S.B. Dasanayaka[1*], W. Jayaratne[2]

[1]*Management of Technology, University of Moratuwa, Sri Lanka*
[2] *Distribution Maintenance -WPS1, Ceylon Electricity Board*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

This paper discusses economics behind the reduction of carbon emission in electricity generation in Sri Lanka. This study shows that the present annual Green House Gas (GHG) emission with respect to the electricity generation is about 2.8 million metric tons. This is about 25% of the total national GHG emission in recent years. By year 2029, this level will increase to 26 million metric tons per year. The identified total GHG emission reduction potential in electricity generation in Sri Lanka is about 37GW. However, potentials for implementation within next 20 years are 3GW and it will cost 8.5 billion US$. The total reduction in GHG will be 16 million metric tons per year. If one ton of CO_2 is valued at 20 US$, then total earning potential only on reduction of GHG will be 320 million US$ per annum. Considering the savings on avoided fossil fuel combustion, total investment can be recovered within 6.5 years and this further confirmed with sensitivity analysis. In order to achieve these benefits broad policies and guide lines are needed for this sector as explained in this paper. In addition to the evaluation of present carbon emission situation in electricity generation in Sri Lanka, this paper explores possible GHG reduction methods and their economic feasibility. The methodology employed and the policy implications derived can be used as guides to similar types of research in other countries as well.

Keywords: economic cost benefits, technology policy, electricity generation, green house gases, GHG, kyoto protocol, clean development mechanism

1. Introduction

Sri Lanka became a party to the United Nations Framework Convention on Climate Change (UNFCCC) in 1993. Kyoto Protocol (KP) was formulated in 1997 in Kyoto and later in Bali, Copenhagen and Cancun forums where it was ratified. The protocol was adopted at the third conference of the parties (COP) to the UNFCCC in Kyoto in December 1997. Under the KP, the industrial countries are legally bound to reduce manmade GHG emissions by approximately 5.2% from the level of their emissions in 1990. Sri Lanka has no obligations to reduce GHG under KP as the overall emission level remains at lower level when compared to industrialized countries. KP has formulated three significant mechanisms to reduce GHG emission in the world. Only the Clean Development Mechanism (CDM) allows economical emission credit trading among developed and under-developed countries. CDM is one of the flexible mechanisms under KP which allows developed countries to invest in developing countries on projects to reduce GHG emission and thereby capture the carbon credit. As a signatory party to KP, Sri Lanka is eligible to obtain benefits coming under CDM. Under KP, there is a demand for GHG emission reduction as well as supply for carbon reduction mechanisms. According to UNFCCC, the total demand in the carbon market is around 5.5 billion tons of carbon dioxide equivalents (CO_2eq). The regulatory framework of this global carbon market has been established and the estimated market potential is around 350 million tons of CO_2 at an average price of 15-20 US$ per ton of CO_2. Accordingly, estimated money involvement in this market is 4200-6000 million US $ per annum. Sri Lanka's obligations under the UNFCCC and KP are to formulate policies and initiate measures that would mitigate emissions of GHG. The demand for electricity is rising and Ceylon Electricity Board (CEB) has to face this challenge with an economically feasible and sustainable solution. Use of available hydro power resources is getting saturated, the new power generation plans move on to thermal and high cost nuclear options which are capital intensive. The available thermal power generation options are coal, diesel, heavy fuel, residual oil, naphtha; furnace oil and LNG that all emit CO_2 as an end result after combustion. Therefore, reduction of CO_2 emissions has to be critically evaluated in terms of economic benefits granted

[*] *Correspondence: sarath.iba07@gmail.com*
ISSN 2478-0669 Print

from KP and UNFCCC. Non-Conventional Renewable Energy (NCRE) has become a prime potential source of energy for future due to the low impact on environment compared with conventional sources of energy.
This paper mainly focuses on following three objectives:

- To ascertain current situation of GHG emission in electricity generation in Sri Lanka
- To identify methods in reducing carbon dioxide emission in electricity generation in Sri Lanka and to assess the economic feasibility of such methods
- To derive some policies and broader guidelines in reduction of carbon emission in electricity generation in Sri Lanka

KP requires that countries limit or reduce their GHG emissions with main aim of reaching global consensus on mitigation of climate change as discussed in Bali, Copenhagen and Cancun forums. The marginal cost of emission reduction is estimated to around 15 to 100 US$ per metric ton of CO_2 equivalent for Annex I country (Zhang, 1999). The same emission reduction can be achieved in developing countries like Sri Lanka through natural alternate resources at a much lower cost. This makes CDM projects extremely attractive to both developing and the developed countries because the economic surplus of the transaction is highest when compared to other mechanisms proposed under KP (Sardana and Dasanayaka, 2010).

Previous studies conducted in Sri Lanka have explored the GHG emissions and CDM in power sector (Ranasingha, 2000; Kasturiarachchi, 2009; Fernando and Wijayatunga, 2000) Manthrinayake and Samarkkody (2004) have conducted studies on air emissions in power generation. Ramani (1998) has done a study on industrial pollution control programs. Other important research on these issues includes Yalegama and Senanayake (2004), Batagoda, Kularatne and Lokupitiya (1999), Anoja (2009), Ferdinando and Gunawardana (2007), Munasingha (1995). Priyantha, Wijayatunga and Shavindranath (2006) and Batagoda (2009) where they have presented strategies for the promotion of clean and energy efficient technologies. In the global context, World Resources Institute (2008) has presented a technical study on GHG while Farshid and Alang (2008, 2009) have carried out studies on Fuel and GHG reduction potentials in the Iran and Canada.

2. Methodology

Electricity demand data from year 1969 to year 2009 has been used to forecast demand for the next 20 years and thereby data of 40 years used to ascertain current situation of GHG emission. Electricity generation options were identified and the cost involvement, environmental impact ascertained to assess economic feasibility of reduction of CO_2 emission methods. Parameters of Net Present Value (NPV), Return on Investment (ROI), Benefits to Cost Ratio (B/C) and tangible and intangible benefits are considered. The existing regulations of Central Environmental Authority (CEA) and Ministry of Environment and Natural Resources (MOE&NR) in addition to the standards as specified by World Bank and World Health Organization (WHO) on environmental emission control are considered to formulate broad guide lines and policies in CO_2 reduction to achieve the third objective. Existing thermal plants of Ceylon Electricity Board (CEB) represent nearly 47% of total installed capacity. The forecast demand will help arrive at requirement of generator requirement, types of fuel and their economic feasibility based on the CO_2 emission reduction, cost effectiveness, and environmental friendliness.

2.1 Tier 1 approach

This method is fuel-based, since emissions from all sources of combustion can be estimated on the basis of the quantities of fuel combusted (usually from national energy statistics) and average emission factors.

2.2 Tier 2 approach

Emissions from combustion are estimated from similar fuel statistics, as used in the Tier 1 method, but country-specific emission factors are used. Emission factors might differ for different fuels, combustion technologies or even individual plants. Activity data is disaggregated to properly reflect sources.

2.3 Tier 3 approach

Fuel statistics, data on combustion technologies, technology-specific emission factors are used. Operating conditions, control technology, quality of maintenance and age of the equipment used to burn the fuel are other main input parameters.The annual emission values are calculated under, Tier 1, Tier 2 and Tier 3 approaches.

3. Results and Discussion

3.1 Values under tier 1 approach

The figures as depicted in Table 1 are arrived at by multiplying the combustion figures with the emission factors.

Table 1: Various Emissions per Annum

Emission Type	Average Emission	Annual Emission/MMT	% to Total
CO_2	75133.3	2.686	97.20%
SO_X	1218.0	0.043	1.60%
NO_X	893.0	0.032	1.20%

It is apparent that CO_2 is dominant while SO_X and NO_X percentages are very small when compared with CO_2 emissions. However, SO_X is not a GHG but it is a heavy environmental pollutant.

3.1 Values under tier 2 approach

In Tier 2, the quantities of consumed fuel from fuel statistics and country specific emission factors are used to estimate GHG emission. In order to calculate GHG emission using Tier 2 approach, all the emission factor values in Tier 1 approach will be replaced by Country specific emission factors.

Annual CO_2 emission is arrived at 3.053 Million Metric Tons. It is observed that, Tier 2 approach has given a higher value when compared to Tier 1 approach of was 2.7 million metric tons per annum.

3.3 Values under tier 3 approach

The IPCC methodology breaks the calculation of carbon dioxide emissions from fuel combustion in six steps;

- Convert to a Common Energy Unit
- Multiply by Emission Factors to Compute the Carbon Content
- Compute Carbon Stored
- Correct for Carbon Un-oxidized
- Convert Carbon Oxidized to CO_2 Emissions

Table 5 provides the Carbon Emission Factors (CEF) and Net Calorific Values (NCV) of mostly used fuel types. In Tier 3 approach, different types of plants operating with different types of fuels and technologies will be taken in to account. However, CO_2 emission is not dependent on technology but with the amount of carbon content in the fuel.

Table 2: Carbon emission factors and Calorific Values of various fuels

Fuel	Carbon Emission Factor(CEF)/TC/TJ	Net Calorific Values/ (TJ/1000tonnes)
Gasoline	18.9	44.80
Jet Kerosene	19.5	44.59
Other Kerosene	19.6	44.75
Shale Oil	20.0	36.00
Gas/Diesel Oil	20.2	43.33
Residual Fuel Oil	21.1	40.19
LPG	17.2	47.31
Ethane	16.8	47.49
Naphtha	20.0	45.01
Bitumen	22.0	40.19
Lubricants	20.0	40.19
Petroleum Coke	27.5	31.00
Refinery Feed stocks	20.0	44.80
Refinery Gas	18.2	48.15
Other Oil	20.0	40.19
Coking Coal	25.8	28.00

Source: Revised 1996 IPCC Guide lines for national GHG Inventories

Once the carbon emission values are calculated, same will be multiplied by 44/12, in order to convert them to actual CO2 emissions.

3.4 Calculation of GHG emission

The Tier 3 approach for estimating emissions is described by IPCC as one in which emissions from all sources of combustion of particular fuel are estimated on the basis of the total quantities of fuel consumed and average emission factors (IPCC 1997 b,c). As per Tier 3 approach calculations, the present CO_2 emission in electricity generation in Sri Lanka is 2.7 million metric tons per year.

$$\text{The average value of Tier 1, Tier and Tier 3} = \frac{(2.64 + 3.053 + 2.678)}{3} \qquad 1$$

Hence, Annual CO2 Emission in Electricity Generation = 2.798 million metric tons

Sri Lanka's total annual GHG emission as per the UNFCCC reports in year 2007 is about 11 million metric tons. Thus, the present contribution to total GHG emission from electricity generation is about 25%. This value will increase with the introduction of coal power stations by year 2012. The other 75% of GHG emission will come from vehicular transport, locomotives, air craft landing and taking off, ships, land and agriculture vehicles, waste dump site burnings etc.

3.5 GHG emission reduction methods in electricity generation and the economic feasibility

In order to identify potential projects and future electricity demand, existing generation mix, past energy demand in the country, population growth, GDP, GDP per capita , electricity sales, average electricity price, number of consumer accounts, during last 30 years will be evaluated and using regression techniques against each other and one with several of others. This regression analysis will be performed against different sectors like, domestic, industrial and others as there are different consuming habits within these categories.

3.5.1 Domestic sector

In regression analysis, it was found that GDP per capita and previous year sector electricity demands are the significant independent variables for the domestic sector electricity demand.

$$\mathrm{Domestic(t)} = (-73.988 + 0.005\mathrm{GDPPc(t)} + 0.976\mathrm{Domestic(t-1)}) \qquad 2$$

Where;

Domestic = Electricity demand for domestic category (GWh) in year (t)

GDPPc(t) = Gross Domestic Product Per Capita (MRs/Population) in year (t)

3.5.2 Industrial sector

Industrial sector is considered together with the commercial sector for the ease of evaluation. In this sector only significant independent variable for electricity demand is GDP.

$$DIndustrial(t) = (-349.72 + 0.004GDP(t)) \qquad 3$$

Where;

DIndusrtial(t) = Electricity demand for industrial and domestic sector in year (t)

GDP(t) = Gross Domestic Product in the year (MRs) in year (t)

3.5.3 Other sectors

In addition to Domestic Industrial and commercial sectors, there are certain demand for LECO and street lighting. LECO covers the coastal area which is known as the golden belt of the electricity distribution in the country. Specially, starting from Negombo to Galle including Nugegoda, Maharagama, Ethulkotte, and Kelaniya. However, Colombo city is not included to LECO. There is certain correlation in demand in other sector with GDP.

$$DOther(t) = 33.36 + 0.001GDP(t) \qquad 4$$

Where;

DOther(t) = Demand in LECO and Street Lighting

3.5.4 Cumulative demand

Total forecast for energy demand will be obtained by aggregating demands of these sectors. Alongside by using the forecasted system losses and load factors, with the GDP growth forecast by Central Bank of Sri Lanka, the expected system energy demand and peak power demand can be forecasted for the planning horizon. This forecast is referred as base load forecast.

3.5.5 Use of WASP software

Wien Automatic System Planning Package (WASP) is the tool use for optimization and analysis of present system together with national policy elements, implementing strategies, specific targets, milestones, institutional responsibilities, and economic factors for future demands. Each possible generation unit is evaluated based on the following constraints and the objective function (Bj) with respect to expansion plan j.

$$Bj = \sum_{t=1}^{T} \left\{ Ij,t - Sj,t + Fj,t + Lj,t + Mj,t + Oj,t \right\} \qquad 5$$

Where;

I	=	Capital investment costs
S	=	Salvage value of investment costs
F	=	Fuel costs
L	=	Fuel inventory costs
M	=	Non-fuel operation and maintenance costs
t	=	time in years up to maximum of T

Objective of running WASP software is to minimize cost function (*Bj*) while satisfying the constraints. Given *by* I, S, F, L and M matrixes.

4. Conclusion

4.1 Economics parameters

Following values display the cumulative net cash flow diagram to arrive at the payback period of the project. The graph meets time axis at which cumulative net cash flow become zero gives the exact payback period.

Total Cost	=	8590 Million USD
Net Benefits	=	31,383.05 Million USD
NPV	=	7809.04
ROI	=	3.65
Benefits/Cost Ratio	=	2.14
Payback Period	=	6.5 Years
Annual interest rate	=	10%

4.2 Policy implications

In this section, existing guide lines are evaluated in order to ascertain the conformity of the same to enhance the effectiveness. A set of new policies and broader guidelines are introduced in order to upgrade the existing guidelines. Major role remains with the government and CEB as the sole authority for electricity generation in the country. Certain contributions from private sector as well as the Central Environment Authority (CEA) and Sustainable Energy Authority of Sri Lanka (SEASL) is also vital in this effort.

4.3 National air quality standards

National air quality standards specify the limits on hazardous emission levels of different air pollutants. Table 10 provides a comparison with WHO limits.

Table 3: The National Air Quality Standards

Pollutant	Averaging timing	Maximum permissible limit(μg/m3)	WHO limit (μg/m3)
CO	8hrs	10000	10000
	1hr	30000	30000
NO_2	24hrs	100	-
	8hr	150	-
	1hr	250	200
	1yr	-	40
SO_2	24hrs	80	20
	8hr	120	-
	1hr	200	-
O_3	8hr	-	100
	1hr	200	-
Pb	1yr	0.5	0.5
	24hrs	2	-
SPM	1yr	100	-
	24hrs	300	-
	8hrs	350	-
	3hrs	450	-
	1hr	500	-

Source: Government Gazette Extraordinary dated 20/12/1994; WHO, 2006; and WHO, 2000

4.4 Local context

Carbon Dioxide emission in Sri Lanka's electricity generation sector is low in absolute values as well as per capita terms when compared with other countries in the region. Total CO_2 emission in electricity generation in Sri Lanka is 2.7 million metric tons per year, or per capita CO2 emission is 0.13. On the other hand annual national CO2 emission in all sectors including transport, electricity, industry and other anthropogenic activities is 11 million metric tons per annum (UNFCCC reports) and per capita national CO2 emission level at 0.6 tons. CO2 has not yet been identified as an environmental pollutant in Sri Lanka. The country is well placed in comparison to its neighbors as can be seen from the Table 4.

Table 4: Per-capita emissions

Country	Per Capita CO_2 Emission per annum/Metric Tons
Sri Lanka	0.60
Pakistan	0.76
India	1.02
Indonesia	1.55
China	3.65
France	6.22
Japan	9.52
Germany	10.29
USA	15.64
World	4.18

Source: IEA CO_2 database 2009

4.5 Recommendations for formulation of national policies on GHG emission reduction

Country obligations on policy implications identified in this paper include provision of a platform to address climate change issues at the national level, establishing the dedicated institutional mechanism on GHG emission and climate change responses. Further, establishing a mechanism to monitor GHG emission and subsequent impact on climate changes, liaising with UNFCCC to achieve Sri Lanka's obligation on global emission reduction issues are also vital policy implications. Establishment of GHG registry and GHG tax/reward system will create a register of GHG emission to create awareness. The use of economically viable, environmentally friendly, non-conventional renewable energy sources shall be promoted by providing a level playing field to both conventional and non-conventional energy sources. Concessionary financing will be sought for implementation of renewable projects which have been left out due to poor commercial aspects rather than environmental, social and economic viability. Biomass based energy projects need to be developed in rural areas in order to enhance the bare land usage, employment generation and industrial activities. Research and development activities on new technologies and practices on non-conventional renewable energy generation to suit the local conditions are to be promoted. Introduction of waste separation and purchasing policy within the local authority level desires to be introduced. Reduction of waste derivation volumes and utilization of environment-friendly materials for packaging, etc. are necessary.

References

Adam, N. 2008. Limiting the financial risks of electricity generation capital investments under carbon constraints: applications and opportunities for public policies and private investments, Carnegie Mellon University, Washington DC.

Anoja. H. 2009. Climate Change and Energy in Sri Lanka" to evaluate possible mitigation measures to be adapted to avert the situation using the different emission control mechanisms, Central Environmental Authority: CEA, Sri Lanka.

Arjun, M. 2009. The Technical and Economic Feasibility of a Carbon-Free and Nuclear-Free Energy System in the United States, USA.

Batagoda, B., Kularatne, K. and Lokupitiya, E. 1999. "Analysis of the emission trading potential in Sri Lanka for global green house gas market under the Kyoto Protocol", University of Sri Jayawardanapura, Sri Lanka.

Batagoda, B. 2009. "Strategic approaches to air quality management in Sri Lanka: an analysis of policy and legal options". University of Sri Jayawardanapura, Sri Lanka.

Constantine, S. and Meisterling, K. 2008. "Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy", Environmental Science and Technology, 42(9): 3170-3176.

Coelho, A., Varkulya, Jr., Paletta, C., Guardabassi, P. and Martins, O. 2007. Technical and economic feasibility of electricity generation from wood reforestation in Amazon.

Coninck, F., Haake, H. and Linden, V. 2007. Technology transfer in the Clean Development Mechanism identified under Kyoto Protocol.

Ceylon Electricity Board (CEB) .2008. Long Term Generation Expansion Plan (2009-2022), Colombo, Sri Lanka.

Ceylon Electricity Board .2008.Statistical Digest – 2009, Colombo, Sri Lanka.

Ceylon Electricity Board.1998. Environmental Impact Assessment Study Report, West Coast Coal Development Project, Ceylon Electricity Board, Sri Lanka.

Elisabeth, A. 2009.Integrating Comprehensive Air Quality Modeling with Policy Analysis: Applications for Distributed Electricity Generation.

Farshid, Z. and Alang, F. 2009. Estimation of Green House Gas Emissions in Iran‟s Electricity generation sector, in proceedings of the 22nd International Power Systems Conference, Tehran, Iran.

Farshid, Z. and Alang, F. 2008. Fuel and Greenhouse Gas Emission Reduction Potentials by Appropriate Fuel Switching and Technology Improvement in the Canadian Electricity Generation Sector.

Fernando, W. and Wijayatunga, P. 2000. Mitigating Emissions from Power Sector of Sri Lanka, Sri Lanka Energy Managers Association and University of Moratuwa.

Joseph, F. 2004. The Economics and Environmental Impacts of Large-Scale Wind Power in a Carbon Constrained World.

Joseph, I. 2007.A model to evaluate co2 emission reduction strategies in the US, The Ohio State University, USA.

Kasturiarachchi, K.A.K. 2009.Clean Development Mechanism in Sri Lanka, Global Affairs Division, Ministry of Environment and Natural Resources, Colombo, available at http://www.cd4cdm.org/Asia [accessed on 17 Dec. 2010].

Manthrinayake, M. and Samarkkody, R. 2004. Electricity and Air Emission, Air Resource Management in Sri Lanka.

Priyantha. P, Wijayatunga, D. and Shavindranath, F. 2006. Strategies for the Promotion of Clean and Energy Efficient Technologies: Sri Lanka Study, Energy Conversion and Management 44: 3247-3265.

Ranasinghe, A.R. 2000."Green House Gas mitigation options for the Sri Lankan power sector",University of Moratuwa, Moratuwa, Sri Lanka.

Ramani, E.1998. Implementation of Industrial Pollution Control Programs in Sri Lanka, Paper presented at the Fifth International Conference on Environmental Compliance and Enforcement, Workshop 4D, Setting up and Managing Compliance Assistance Programs and Information Outreach on Regulatory Requirements, Monterey, California.

Ram, M. and Chandrabhanu, O. 2005. Effect of carbon tax on power generation and energy security in Sri Lanka, The Online Journal on Power and Energy Engineering (OJPEE) Vol.1(4).

Sardana, G. and Dasanayaka, S. 2010. Carbon Emission Trading in India and Sri Lanka: A Review Perspective, Interdisciplinary Review of Environment (IRE),Vol.11 (2/3): 162-77.

World Bank, IBRD.2010. World Development Report - 2010, Washington, USA.

Yalegama, M. and Senanayake, N. 2004. "Air Pollution and Contributions of Particulate Matter from Different Types of Diesel Vehicles in Sri Lanka", Paper Submitted to the Better Air Quality Workshop 2004.

Zhang, Z.X. 1999.Estimating the Size of the Potential Market for All Three Flexibility Mechanisms under the Kyoto Protocol, Final Report Prepared for the Asian Development Bank under Contract TA-5592-REG.

Energy Policy Implementation Analysis for Electricity Sector Expansion Planning in Sri Lanka

D.C. Hapuarachchi*, M.D.V. Fernando, M.A.M. Rangana, T.L.B. Attanayaka, A.W.M.R.B. Wijekoon

Generation Planning Section, Transmission & Generation Planning Branch, Ceylon Electricity Board, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

The purpose of this paper is to analyze the Implementation of National Energy Policy Elements focusing on Electricity Sector Expansion Plan. National Energy Policy consists of nine Energy Policy Elements. Energy Policy Elements defined under Gazette No. 1553/10 on 10th June 2008 are, (1) Providing Basic Energy Needs, (2) Ensuring Energy Security, (3) Promoting Energy Efficiency and Conservation, (4) Promoting Indigenous Resources, (5) Adopting an Appropriate Pricing Policy, (6) Enhancing Energy Sector Management Capacity, (7) Consumer Protection and Ensuring a Level Playing Field, (8) Enhancing the Quality of Energy Services, (9) Protection from Adverse Environment Impacts of Energy Facilities. Out of these nine, five elements (1), (2), (3), (4) & (9) which have a significant impact on energy planning were chosen to analyze from the scenarios developed. The five selected scenarios were analyzed, considering Net Present Value, Emissions & Emission Reduction Costs, Primary Energy Sources, Levelised Unit Cost, and Primary Energy Share.

Keywords: national energy policy, electricity sector expansion planning

1. Introduction

As one of the three major sources for energy supply in Sri Lanka, electricity sector plays a major role in country's energy supply and economic development. The other two major energy sources are biomass and petroleum. There are no proven petroleum resources at present in the country. Therefore it is completely an imported primary energy source. Biomass is widely used as a household energy source with modest penetration for industrial sector and still not established as a commercial energy source. Electricity is an essential energy source considering the energy security, environmental impacts, convenience to consumers and contribution to national economy. It is essential to implement energy policies in this sector to drive the national economy in future. In this paper, the future electricity sector in Sri Lanka was analyzed under policies such as Providing basic energy needs, Ensuring energy security, Promoting energy efficiency and conservation, Promoting indigenous resources and Protection from adverse environmental impacts of energy facilities.

The analysis was done based on the study processes and results of Long Term Generation Expansion Plan (LTGEP), which was prepared by the Generation Planning Section, Transmission and Generation Planning Branch, Ceylon Electricity Board. The following scenarios were chosen to analyze in the study to compare the adherence of the above energy policy elements:

- Scenario 1: Baseline Scenario – Scenario which fulfill the forecast future electricity demand under least cost principle while absorbing optimum Non-conventional Renewable Energy (NCRE) to the system by year 2020
- Scenario 2: Reference Scenario– Scenario considering no future NCRE developments
- Scenario 3: Energy Mix Scenario – Scenario considering fuel diversification in to LNG and Nuclear
- Scenario 4: Demand Side Management (DSM) Scenario – Scenario considering Demand Side Management forecast by Sustainable Energy Authority (SEA)
- Scenario 5: Scenario with Natural Gas - Considering recoverable Natural Gas potential in Mannar Basin by 2020

* *Correspondence: eegp3@ceb.lk*
ISSN 2478-0669 Print

2. Methodology

Operating information and system limitations on the existing generating plants, details and costs of candidate thermal and hydro plants were used on computer models and a series of simulations were conducted to derive the feasible optimum generation expansion sequence for the 20 year planning horizon for the projected demand forecast. The above mentioned five Scenarios were chosen and the results of above scenarios such as Net Present Value cost for the planning horizon, environmental emissions and energy shares of indigenous, imported, conventional and non-conventional fuel were analyzed to see whether they are in line with the requirements of energy policy elements.

3. Results and Discussion

3.1 Providing basic energy needs

3.1.1 Fulfilling basic energy needs

Adequate electricity supply is required to fulfill the basic needs of the consumers, enhance their living standards and to economic development. Therefore, as an electricity utility, CEB has to generate or acquire sufficient amount of electricity to satisfy the demand. In, 2013 total electricity demand was 10,624 GWh, an increase of 1.4% compared to 2012. Whereas, in 2014 total electricity demand was 11,063 GWh, an increase of 4.1% compared to 2013. Therefore, forecasting of future electricity demand is important to make decisions on electricity generation and infrastructure development.

Long Term National Demand Forecast is a 25 year electricity demand forecast, which is a primary input for the Long Term Generation Expansion Plan (LTGEP). Econometric modeling, Time Trend projections and End User Projection methods are used to forecast the Electricity demand for 25 years. Econometric modeling is chosen for the future electricity demand forecast and the electricity sales figures of the past were analyzed against several independent variables such as population, GDP, per capita GDP, number of domestic consumer accounts etc. All the independent variables selected such a way that they represent economic factors, population and living standards of people.

To capture different consuming habits of various consumer categories, sector wise forecasts were prepared separately. Therefore, 'Domestic', 'Industrial', 'Commercial' (including General Purpose, Hotels and Government) and 'Other' (Religious purpose and Street Lighting) were analyzed separately to capture the different consuming habits within categories Figure 1 shows the past electricity demand and forecast total electricity demand for the planning horizon. Average per capita electricity consumption is an important factor which represents the electricity consumption per person and their living standard. Figure 2 illustrates the trend of per capita electricity consumption of past and forecast based on the population growth given by the Department of Census and Statistics.

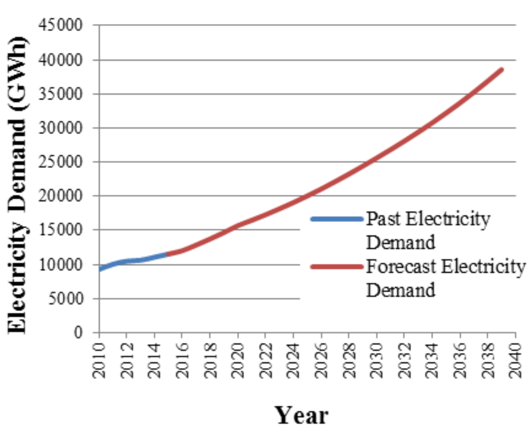


Figure 1: Electricity demand

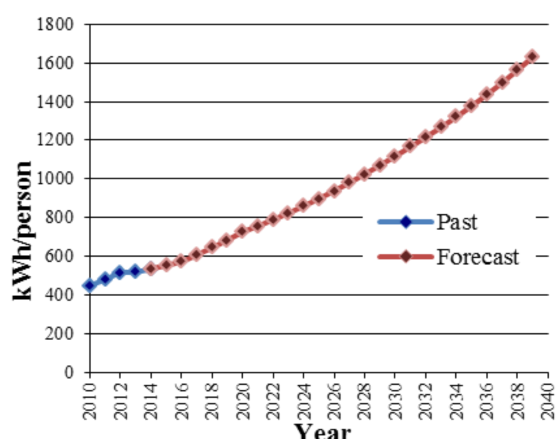


Figure 2: Per capita electricity consumption

3.1.2 Affordable price (Lowest possible cost)

It is important to supply electricity to the people with an affordable price. To supply the future electricity demand with lowest possible cost, it is important to select correct fuel options and technologies to optimize the whole electricity generation system. All the five scenarios were developed to supply forecast electricity demand while optimizing future generation options.

Considering the PV cost of all five scenarios for the 20 year period, a Levelised cost was calculated for comparison. The Levelised Costs of selected 5 scenarios are shown Table 1 below.

Table 1: Levelised Cost

Scenario	Levelised Cost (Rs/kWh)
Baseline Scenario	10.45
Reference Scenario	10.40
Energy Mix Scenario	10.51
DSM Scenario (including DSM implementation cost)	11.07
NG Scenario	9.58

3.2 Ensuring energy security

The present generation mix consists with hydro, oil, coal and renewable and the energy share in 2014 depicts in the Figure 3.

The least cost scenario was developed to optimize the future generation options adhering to the Government Policy framework. NCRE contribution share was increased up to 20% by 2020 and maintained the optimum share throughout the planning horizon. Coal power generation share has increased since it has been selected as a least cost base load generation option. Intermittency of NCRE is considered when developing this Scenario, and additional spinning reserve component allocated to maintain throughout the planning horizon. Electricity generation mix graph of Scenario 1 is given in the Figure 4 below.

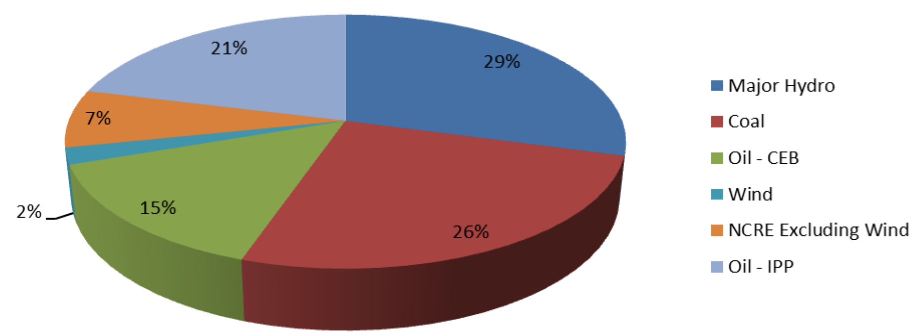


Figure 3: Electricity generation mix 2014

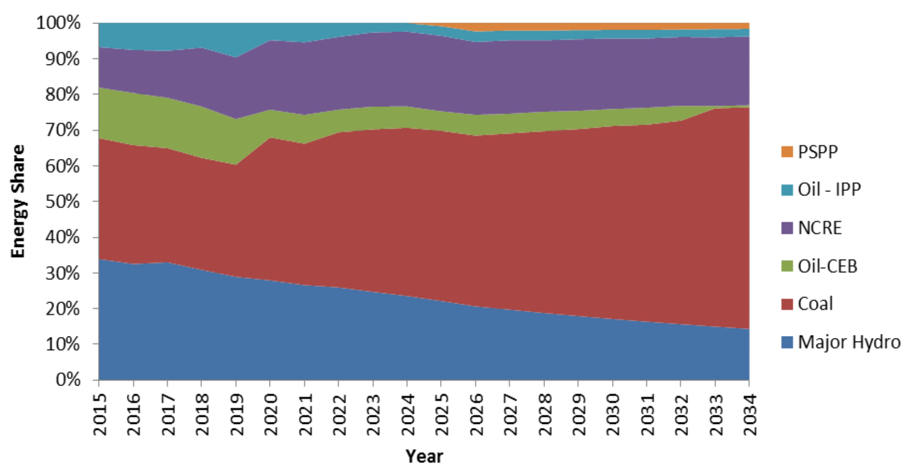


Figure 4: Energy share of scenario 1

In this scenario contribution of coal power generation is increased to around 60% share. It is essential to secure the fuel supply security through establishing multiple supplier portfolios. NCRE share has increased as an indigenous resource as well as environmental friendly electricity generation option which benefit the country. Pumped Storage Power Plants were introduced to the system to improve the operational efficiencies of base load coal power plants and replace the high cost thermal power plants in supplying the peak power demand. Hydro power has already been developed to a high level and it is essential to optimize the operation of major hydro power plants considering other main requirements like drinking and irrigation.

A separate scenario was carried out to identify the diversification of fuel options to enhance the energy security. However this scenario deviate from the least cost option. Energy mix Scenario (Scenario 3) gives a diversified fuel mix including Coal, LNG and Nuclear. The Figure 5 below depicts the energy share of Scenario 3.

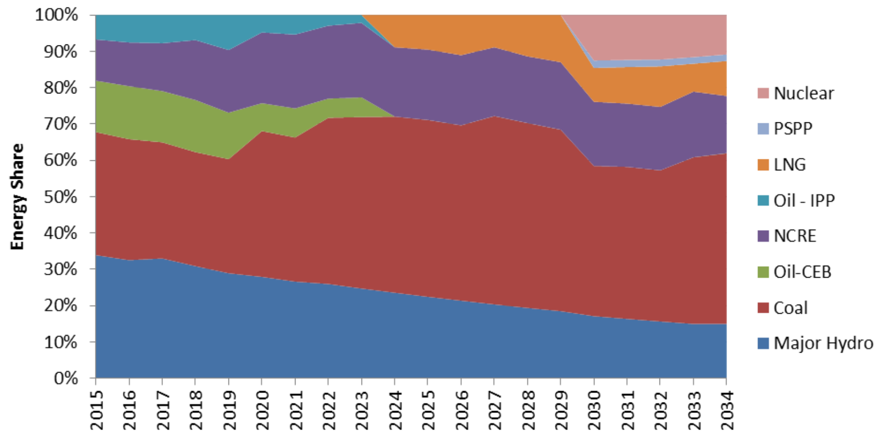


Figure 5: Energy Share of Scenario 3

The percentage energy share of selected five scenarios for the year 2030 is shown in Figure 6.

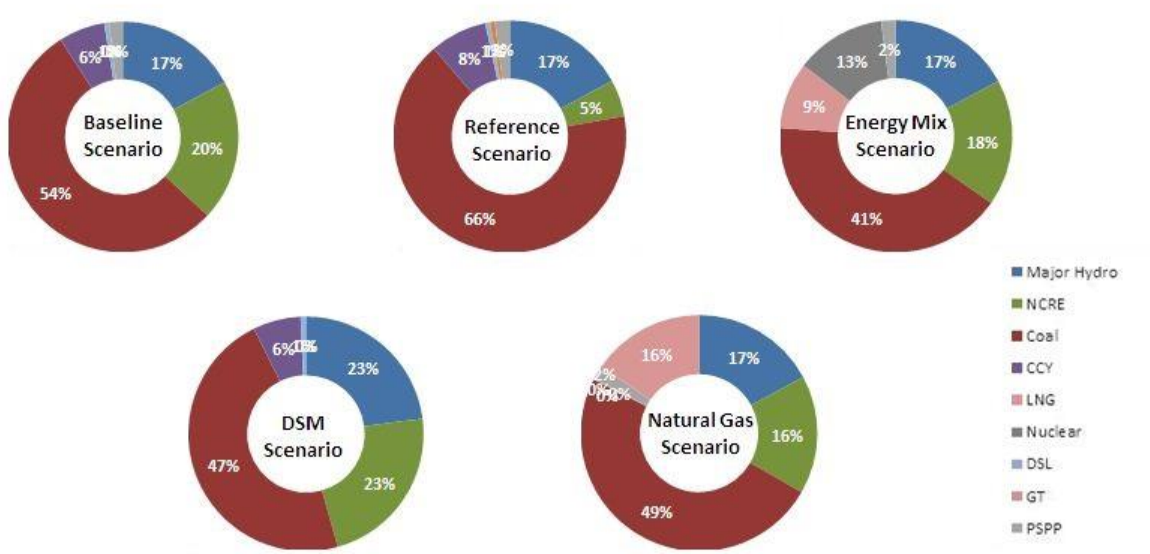


Figure 6: Energy share of each scenario - year 2030

3.3 Promoting energy efficiency and conservation

3.3.1 Supply side management

Supply side management is vital since it will determine the financial burden that will be on the consumer as electricity tariff. Efficient, Fast and minimum cost service to the consumer can be achieved by utilizing above policy on Electricity sector. Introducing high efficient Power Plants, Accurate forecasting of future demand and timely implementation of required Power plants, taking measures to loss reduction in Generation, Transmission and Distribution are major elements in supply side management in electricity sector.

After analyzing the past trend of the least cost generation Scenarios of LTGEPs, Generation Planning Section has identified that the Coal based power plants plays a major role in planning and has taken steps to introduce High Efficient Coal Power Plants as candidate power plants for future generation requirements. Table 2 shows the plant characteristic comparison.

Table 2: Coal plant characteristics comparison

	Conventional Coal Plant	New Candidate Coal Plant
Net Efficiency at Full Load (%) {using HHV}	33.3	38.4

Another major factor when considering supply side management is keeping Generation, Transmission and Distribution loss at a minimum level. Figure 7 shows the past total gross loss of the system and forecasted net system losses for twenty years. When analyzing the past trend of the system loss it can be clearly seen that country's electricity system is achieving a low system loss progressively.

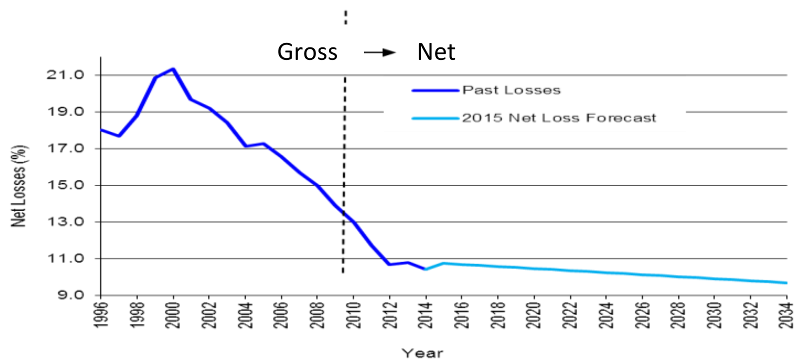


Figure 7: Past losses and forecast losses

3.3.2 Demand side management

DSM is required since it improves the load factor of the electricity system and the efficiency at consumer end. The saving potential from the DSM activities for the Industrial, General Purpose, Hotel and Domestic tariff categories were given by Sri Lanka Sustainable Energy Authority (SLSEA) with the cost for the implementation of such DSM actions. Scenario 4 was developed considering above estimation and results to the reduction of 10.1% in the total present worth cost of the Scenario 1 over the planning horizon. Figure 8 shows the existing future demand forecast and the demand forecast of Energy Management Plan (EnMAP) forecasted by SEA.

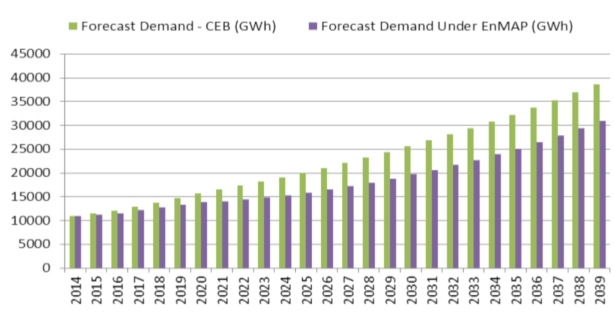
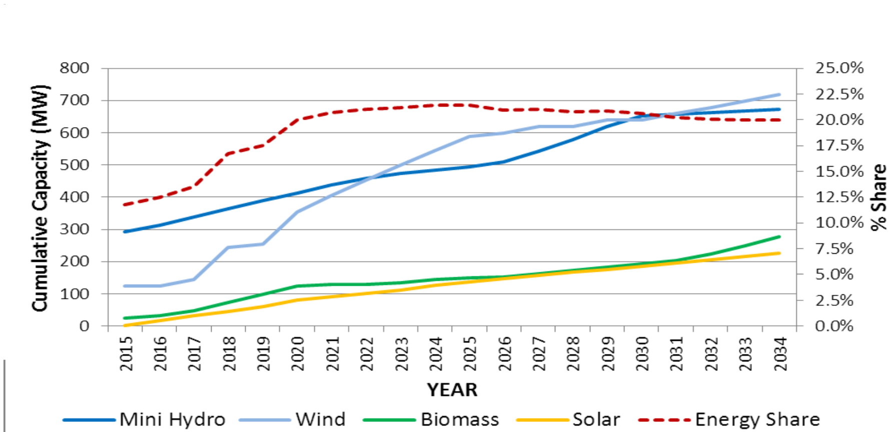


Figure 8: Demand variation with DSM

3.4 Promoting indigenous resources

Coal and Petroleum products which are used in the present electricity sector to generate the electricity are non-indigenous resources of energy and totally depend on import. So utilizing the indigenous energy resources which are readily available in the country is important in considering both fuel diversification and maximum use of available resources. Hydro is the main indigenous resource in the country at present and it is almost completely harvested. Most of the other indigenous resources are non-conventional (Wind, Solar and Biomass) and presently Sri Lanka is planning to extract Natural Gas in the near future.

Present energy contribution of non-conventional indigenous resources to the Sri Lanka's grid is more than 10% (major hydro projects have been considered as conventional and not included) and utility is planning to absorb 20% energy from non-conventional indigenous resources by 2020 and maintain it (Scenario 1). Extracting wind energy mainly from Mannar and Northern region of the country and higher penetration of biomass based electricity is highly expected in achieving the above target. Solar power mainly from Hambantota and Kilinochchi is expected and harnessing remaining mini hydro potential (hydro plants below 10 MW) is essential.
Figure 9 shows the future penetration of indigenous, non-conventional energy to the system.



When considering the oil and gas exploration at Mannar basin in Sri Lanka, recoverable gas reserves has been discovered and further potential is predicted. Explorations should further carry out to accurately quantify the recoverable gas potential. Approximate potential studies indicate the availability of natural gas for 15 years to cater for 1000MW power plant with middle load plant factors.

A scenario was analysed considering the natural gas availability after 2020. During the period of 2021 to 2023 1000MW natural gas combined cycle power plant capacity is assumed to be added to the power system. This would include the conversion of existing combined cycle power plants and the development of new plants to maintain approximately 1000MW during the planning horizon. This enables to maintain a 7% - 19% natural gas energy share in the system with an annual plant factor in the range of 30% to 60%. The cumulative NG requirement for this scenario is approximately 300bcf. The percentage energy share for the period from 2015 to 2034 is shown in Figure 10.

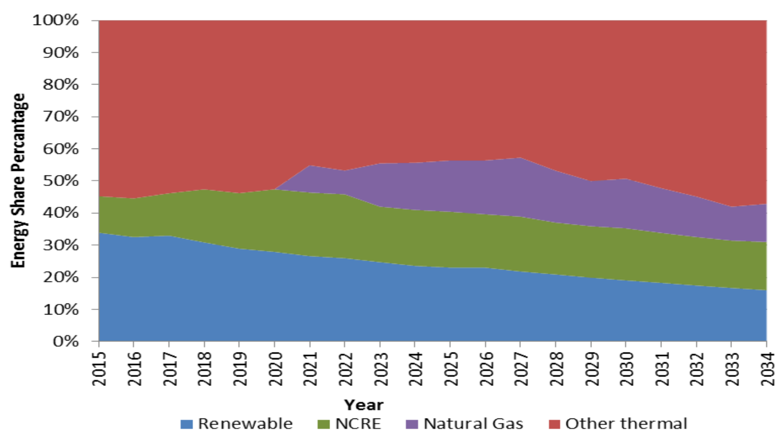


Figure 10: Energy share of scenario 5

3.5 Protection from adverse environmental impacts of energy facilities

Impacts on society and environment arising due to electricity sector developments should be given due consideration. Comparison of CO_2 emissions in different countries is shown in Table 3.

Table 3: Comparison of CO_2 emissions in different countries

Country	kg CO_2/2005 US$ of GDP	kg CO_2/2005 US$ of GDP Adjusted to PPP	tons of CO_2 per Capita 2011
Sri Lanka	0.41	0.10	0.78
Pakistan	0.99	0.20	0.77
India	1.41	0.35	1.58
Indonesia	1.02	0.22	1.76
Thailand	1.15	0.32	3.84
China	1.81	0.63	6.08
France	0.15	0.17	5.10
Japan	0.26	0.31	9.59
Germany	0.25	0.26	9.22
USA	0.36	0.36	16.15
World	0.58	0.38	4.51

Although Sri Lanka is far better compared with world standards for per capita emissions, high efficient power plants and penetration of indigenous resources has been considered in the planning process.

Figure 11 indicate the annual CO_2 emissions of each scenario. Reference Scenario has higher emissions compared to Baseline Scenario due to limitation of NCRE penetration to the system. DSM scenario shows the least emissions due to low electricity generation. Energy Mix scenario and the Natural Gas scenario has emission levels below the Baseline scenario and the rapid drop in the Energy Mix scenario in 2030 is due to the introduction of nuclear power plant.

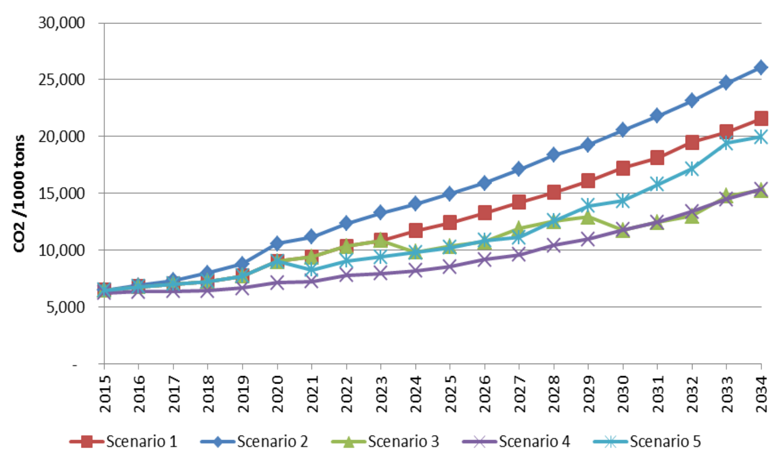


Figure 11: Annual CO_2 emissions

Figure 12 shows the total present value cost and the cumulative CO_2 emissions of each scenario for the 20 year period considered. Further, the incremental cost of each case was analyzed by comparing the cost differences and the reduction of CO_2 emissions in each case compared to base case. The impact is shown in Figure 13. Energy Mix case requires compensation for the CO_2 reduction achieved, while DSM and Natural Gas cases has a cost benefit for each unit of CO_2 reduced.

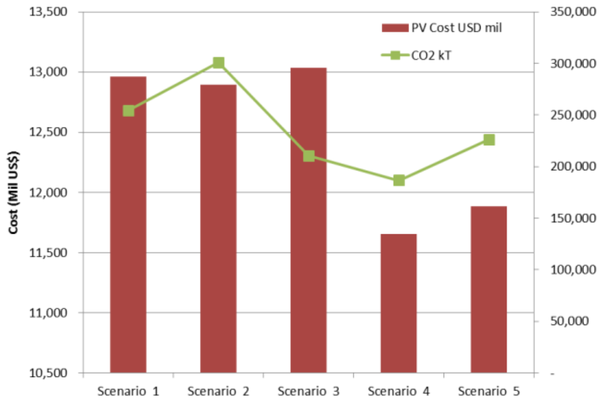


Figure 12: Scenario cost and CO_2 comparison

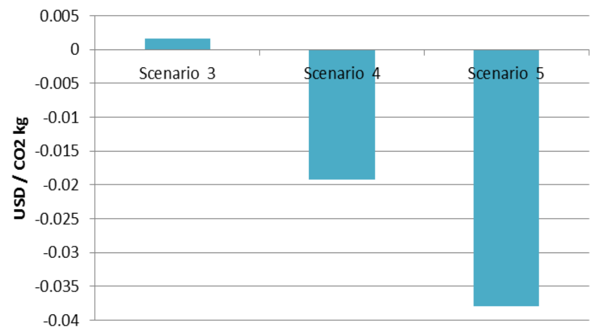


Figure 13: Cost/Benefit per CO_2 reduction

Baseline Scenario complied with the National Energy Policy Elements with realistic cohesiveness. Energy Mix Scenario enhances the energy security policy by diversifying the fuel mix further in to LNG and Nuclear, but it shows much higher PV cost at the end of the planning horizon.

In NG Scenario, economical extraction of NG from Mannar basin and the timeline of availability are still at the very initial stage without firm realistic quantities and price. Although it could be harvested and used in power generation as an indigenous resource, the sustainability of gas supply in future will be a concern. If the gas resources are exhausted, Sri Lanka will have to go for the Liquefied Natural Gas import option which will again lead to higher price and non-indigenous sources.

Implementation of DSM measures shows the considerable decrease in to total PV cost compared with the Baseline Scenario. But it shows the higher levelised cost due to higher implementation cost of DSM activities such as efficient lighting, efficient fans, efficient refrigerators, BMS, efficient pumps, efficient motors, efficient compressors etc.

4. Conclusion

Planners are expected to predict the future and they have to provide decision makers with information that would facilitate making sound decisions and decision makers should explore all the concerns with respect to the enhancement of the energy mix by giving due consideration to following but not limited to;

- Whether the diversification of present energy mix is not sufficient?
- Is it the diversification of fuel supply?
- Whether achieved through indigenous resources? (Eg. Hydro, Wind, Solar, Dendro, NG)
- Whether achieved through increasing imported fuels? (Coal, Oil, LNG, Nuclear)
- Whether look only in to the power sector?
- Is It Able to achieve without any incremental cost?
- Whether government has to bear incremental cost due to implementing policy?
- Whether People in the country willing to pay more?

References

CO_2 Emissions from Fuel Combustion (2014 Edition), International Energy Agency.Long Term Generation Expansion Plans, Ceylon Electricity Board.

Sri Lanka Sustainable Energy Authority, *Forecast of Energy Saving Potential and Cost 2014 – 2039.*

System Control Center, Ceylon Electricity Board, *System Controls & Operations Annual Report 2014*.

Energy Management in Hotel Sector in Sri Lanka: Adoption of Good Practices

K. Wickramasinghe*

Research Economist, Institute of Policy Studies of Sri Lanka

Date Received: 22-11-2014 Date Accepted: 29-04-2015

Abstract

Energy accounts for a major share of the operational costs in the hotel sector in Sri Lanka. For cost saving and environmental conservation aspects, proper energy management has become an important area that needs policy attention. The present paper aims to assess the level of adoption of energy management practices and to identify the determinants of such adoption. The analysis is based on primary data collected from registered hotels in the Western Province of Sri Lanka. The sample includes 78 hotels. The results indicate that, on average, hotels adopt 3.7 good energy management practices. The adoption of good energy management practices is determined by the hotel characteristics such as number of employees per room, age, chain affiliation, size and customer characteristics such as the origin and the purpose of visit. Policy attention should be particularly on motivating small hotels, independent hotels and newer hotels to adopt good energy management practices.

Keywords: energy, hotels, determinants, good practices

1. Introduction

Tourist arrivals to Sri Lanka have being showing significant increase after the end of the civil war in 2009. The tourist arrivals have increased by nearly 3.5 times in 2013 as compared with the before-the-end-of-war situation in 2008 (SLTDA, 2015). With the increased tourist arrivals, the demand for accommodation facilities is also increasing. The government aims to attract a total of 2.5 million tourists annually by 2016, and the number of hotels rooms is expected to increase to 50, 000 by 2016. In 2013, the total number of rooms in both hotels and supplementary accommodation units was 23,596 and the hotel rooms accounted for nearly 69 per cent of the total number of rooms.
Increasing demand for hotel accommodation leads to increased utilization of energy resources in the accommodation sector. The energy costs constitute 18 per cent of the total operational costs of the hotels (Miththapala, 2011). It is vital that hotels undertake good energy management practices in order to reduce the operational costs. Efficient energy management also brings in environmental benefits. Miththapala (2011) finds that there is a possibility of saving 20 per cent of energy consumption in the hotels in Sri Lanka, if they adopt good management practices.

However, studies in regard to adoption of good energy management practices are rare in the case of Sri Lanka. Given the fact that the Sri Lankan tourism industry is showing significant revival following the end of war, this becomes an important policy research need. Thus the paper attempts to find out the level of adoption of energy management practices in Sri Lanka and the determinants of such adoption.

2. Methodology

2.1 Data

The assessment is based on primary data collected from the hotels in the Western Province registered with the Sri Lanka Tourism Development Authority (SLTDA). Western Province is selected as the study area, as it shows the highest number of tourist hotels at provincial level in Sri Lanka. The number of registered hotels in the Western Province is 110 at the time of data collection. However, only 94 hotels were functioning during the survey period and the response rate is 83 per cent. Primary data for the study were collected through a survey and by conducting personal interviews using a pre-tested structured questionnaire. The respondents to the questionnaires are the officer in charge of the environmental management (energy, water and waste) of the hotel. The survey of hotels was undertaken during August 2013–March 2014.

* *Correspondence:*
ISSN 2478-0669 Print

Sample represents around 40 per cent of the small hotels, of which the number of rooms is less than 50. The rest of the hotels belong to large hotel category. The average number of rooms of the hotels in the sample is 85. Around 68 per cent of the hotels have star ratings from one to five and the rest (32%) are not classified. The percentages of hotels under one, two, three, four and five star ratings are respectively 10, 9, 14, 19 and 15 per cent, out of the total number of hotels in the sample. The size of the hotels (in terms of number rooms) increases as star rating increases. Hotels were asked to mention the luxury level as per the three options – luxury hotels, mid-range hotels and budget hotels. Accordingly, 42 and 40 per cent of hotels respectively are luxury and mid-range hotels. Location-wise, nearly half (49 per cent) of the hotels are beach hotels and about 35 per cent are city hotels.

2.2 Analysis

The study examines the present status in relation to energy management and identifies the factors that determine the level of adoption of good practices. Thus, the study focuses on assessing the hotel level efforts in terms of voluntary energy management. The probability of adoption of good energy management practices is assumed to be dependent on different characteristics pertaining to the hotel (*X*).

Energy-saving management practices include use of energy efficient lighting methods, solar power, key switches, efficient air conditioners, biomass boilers, LED TV and light timers. The contribution of each practice towards energy savings depends on the intensity of adoption. For instance, savings due to energy efficient lighting is dependent on the percentage of energy efficient bulbs used out of total number of bulbs used in a particular hotel. For some practices, for instance key switches, it entirely contributes to energy savings.

As there are a number of energy management practices, the number of practices was counted and a count data model was used for the assessment. Poisson regression model was used to find out the determinants of adoption of good practices.

$$Prob(Y = y_i / X_i) = \frac{e^{-\lambda_i} \lambda_i^{yi}}{y_i!} \qquad 1$$

In the above equation, y_i is the number of management practices (0, 1, 2,….) adopted by hotel *i*, and λ_i is the parameter representing both the mean and variance of y_i. The most common specification for λ_i is as follows:

$$E(y_i / x_i = \lambda_i = e^{x_i \beta} \qquad 2$$

where X_i denotes independent variables, which include hotel characteristics, characteristics of the respondent and the customer characteristics. The specific independent variables are: no of employees per room, age of the hotel, star classified or not, chain affiliation, size category, city hotel, number of years of experience of the responsible officer, percentage of local customers and percentage of customers for recreational purposes. The models were estimated using maximum likelihood estimation (MLE) method.

3. Results and Discussion

According to the assessment, the most commonly adopted energy management practices include use of energy efficient lighting methods (88 %), solar power (69 %), and key switches (60 %). The average number of energy management practices is 3.74. This may be due to the fact that savings due to adoption of energy management practices are significant in overall operational cost of the hotels. The histograms in Figure 1 show that energy management practices are more or less normally distributed and the most of number of hotels are having 4 energy management practices.

Results of the regression analysis are shown in the Table 1. Marginal effects of the Poisson regression are reported against each independent variable. The results show that number of employees per room is statistically significant at 1% or 5% percent level in the model. The Poisson regression results imply that when the number of employees per room increases by one unit, the number of energy management practices increases by 0.35.

Size category also shows a positive and statistically significant impact for adoption of good energy management practices. Size category is a binary variable, where it takes the value 0 when the number of rooms in a hotel is less than five and takes the value 1 when the number of rooms in a hotel is more than or equal to 50. When the hotel belongs to the ‘large hotel’ category, the number of energy management practices increases by 0.6.

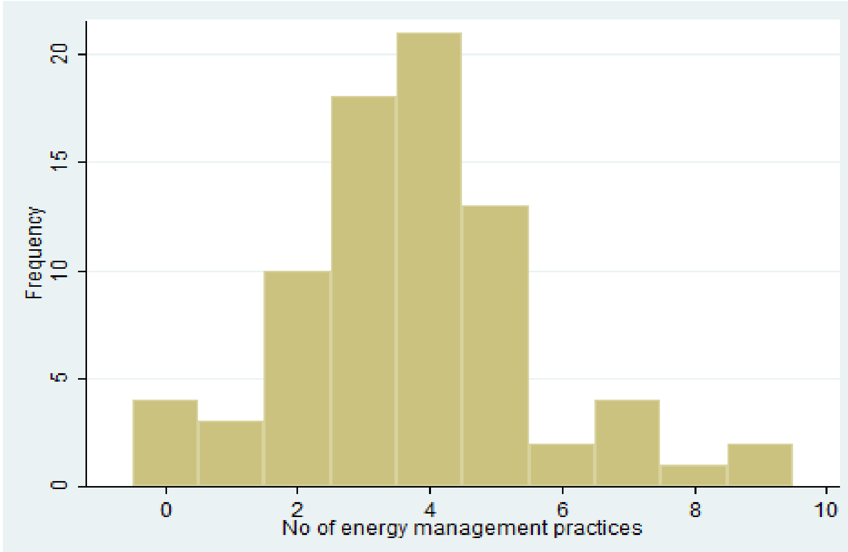


Figure 1: Frequency distribution of number of energy management practices

Size category also shows a positive and statistically significant impact for adoption of good energy management practices. Size category is a binary variable, where it takes the value 0 when the number of rooms in a hotel is less than five and takes the value 1 when the number of rooms in a hotel is more than or equal to 50. When the hotel belongs to the 'large hotel' category, the number of energy management practices increases by 0.6.

Table 1: Determinants of Adoption of Good Energy Management Practices

Dependent Variable	No. of Energy Management Practices
No of employees per room	0.353***
	(0.151)
Age of the hotel	0.010***
	(0.039)
Classified or not	0.367
	(0.334)
Chain Affiliation	0.726***
	(0.354)
Size Category	0.590**
	(0.295)
City hotel	-0.537
	(0.375)
Years of the respondent in the present post	-0.021 (0.236)
Percentage of local customers	-0.012***
	(0.061)
Percentage of customers for recreational purposes	0.010*** (0.045)
Number observations	78
Pseudo R^2	0.09

*Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Age of the hotel has also become a significant determinant for the number of energy management practices. When the age of a hotel increases by one year, the hotels tend to adopt 0.01 energy management practices. This may be because, over the years hotel learn to reduce their energy consumption and for that they adopt more number of energy management practices. The fact that energy cost is identified as a significant contributor to the total operational costs can also be attributed to this. Though the regression models attempted to see the impact of the characteristics of the officer responsible for environmental management on hotels' energy management, none of such variables become statistically significant.

Customer characteristics show a significant relationship to adoption of energy management practices. Accordingly, the percentage of local customers is negatively affecting the adoption of energy management practices. This implies that when the percentage of foreign customers is increasing, the hotels show a higher probability of adopting energy saving practices. The purpose of the customers is also significantly affecting the probability of adopting the energy management.

4. Conclusion

The average number of energy management practices adopted by hotels is around 3.7. The results show that certain hotel characteristics and customer characteristics play an important role in determining the adoption of good energy management practices. Accordingly, large hotels, chain affiliated hotels and classified hotels are more likely to adopt good practices. Hotels with more number of employees per room also show a higher tendency to adopt good energy management practices.

Therefore, from policy perspective, enough attention has to be paid in order to understand the constraints and issues faced by the small hotels in adopting good energy management practices. The support for small firms can be in terms of capacity building, awareness and financial assistance.

Also, the assessment showed that other hotel characteristics such as, chain affiliation have become significant determinants of energy management. Chain affiliated hotels are showing a higher tendency to adopt good energy management practices, when compared with the individual hotels. This calls for the need for creating proper awareness among independent hotels. Also, it is important to note that customer profile also playing a significant role. The hotels who are receiving more of customers for recreational purposes tend to perform better, in terms of their energy management.

Acknowledgement

This work has been undertaken with the financial support of the South Asian Network for Development and Environmental Economics (SANDEE) and its sponsors. Technical support and guidance has been provided by several SANDEE advisors and peers during the course of this research. The author also acknowledges the comments from the anonymous reviewer.

References

Sri Lanka Tourism Development Authority (SLTDA) (2015), Tourism Growth Trends - 1970 to 2014,[Online], Available, http://sltda.lk/sites/default/files/Tourism%20Growth%201970%20 %202014.pdf.

Miththapala, S. 2011, Good practice guidelines on environmental management for Sri Lankan hoteliers. Colombo: SWITCH Asia Greening Sri Lanka Hotels Project, C C Solutions.

Energy Demand and Dilemma of Forecasting: A study on Ceylon Electricity Board

P.J. Kumarasinghe*

Department of Business Economics, Faculty of Management Studies and Commerce, University of Sri Jayewardenepura

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Electrical energy has become a major form of energy for end use consumption in today's complex society. The influence of electricity is tremendous in all facets of human life. It has been recognized as a basic human need, without which almost all human activities will be paralyzed. It is a critical element of infrastructure on which the socio-economic development of a country depends. At present, the power sector of Sri Lanka faces two serious problems, viz. power crisis in terms of high electricity prices and the financial and liquidity crisis of Ceylon Electricity Board (CEB) due to non implementation of least cost generation plan in a timely manner. This situation needs a more accurate demand forecasting methodology. However, the demand forecasting model of the CEB National Forecast 2003 – 2023 for Planning Studies includes only a very few determinants. Therefore, this research was motivated by the requirement of a comprehensive and accurate long-run electricity demand forecasting model for Sri Lanka. This study has focused on the use of a comprehensive econometric model having six explanatory variables, viz. GDP, average electricity price, population, level of household electrification, energy intensity and implementation of rural electrification projects to estimate the long-run aggregate electricity demand for Sri Lanka. This is an in-depth empirical analysis because of inclusion of non-traditionally defined variables such as the level of electrification, energy intensity and implementation of rural electrification projects. The results of the study show that all the explanatory variables are statistically significant in explaining the long-run electricity demand. Hence the study concludes that the electricity demand model developed in this study has a better forecasting accuracy compared to the accuracy of the forecasting model of the CEB National Forecast 2003 – 2023 for Planning Studies.

Keywords: electricity demand, power forecast, demand determinants

1. Introduction

In 1895, electricity was introduced to Sri Lanka by a private company by setting up a power station and a distribution system in Colombo. Few years later, another power generation and distribution facility was established in Kandy. This can be regarded as one of the major historic events that happened in Sri Lanka as it facilitated development of industries in Sri Lanka (Asian Development Bank, 2007). Since then, Sri Lanka has been facing a continuously increasing electricity demand due to population growth, increase in electrification level, and socio-economic development. By end of 2013, 4.3 million consumers have been served by the Sri Lankan power sector and the total electricity demand of the country has grown to 8,232 Giga Watt hours (GWh) during 2013 compared to 587 GWh in 1969. The compound demand growth rate is about 8% per annum. The electricity consumers grew up to nearly 4.3 million in 2013 from 2.8 million in 2000 at an annual compound growth rate of about 6%. The overall annual electrical energy demand grew from 587 GWh in 1969 to about 8232 GWh in 2013 at an annual compound growth rate of about 8%. The annual demand growth rate is expected to remain around 8% to 9% in the foreseeable future.

Table 1 shows the number of consumers and electricity sales of the CEB and the LECO by major consumer groups for 2007. The total electricity sales of about 8232 GWh in 2007 has been contributed by the domestic and religious sectors (39.72%), the industrial sector (35.16%), the commercial sector (23.45%) and street lighting and other (1.68%) (Annual Report Ceylon Electricity Board, 2007).

* *Correspondence: pivithuru@sjp.ac.lk*
ISSN 2478-0669 Print

Table 1: Number of Electricity Consumers and Sales of CEB and LECO in 2013

Consumer Group	CEB		LECO	
	Number of Consumers	Electricity Sale in GWh	Number of Consumers	Electricity Sale in GWh
Domestic	3,409,440	2,728.0	376,469	491.0
Religious	22,804	43.0	2,135	8.0
Industrial	37,270	2,627.0	4,046	267
Commercial	397,435	1,626.0	53,043	304.0
Street Lighting and other	1	108.0	3,853	30.0
Total	3,866,950	7,132.0	439,546	1,100.0

(Source: Statistical Digest of Ceylon Electricity Board, 2014)

1.1 Problem of the Study

Electricity is a commodity that cannot be stored in the grid where demand and supply have to be continuously balanced (Al-Alawi, & Islam, (1996). Hence, a utility should have the ability to provide a continuous electricity supply which is adequate enough to meet the electricity demand at any point in time. During the recent past, the Government of Sri Lanka faced serious constraints on its ability to expand generating capacity fast enough to keep pace with the rising electricity demand. Therefore, accurate demand forecasting is very vital to the operation and planning of electric utilities. As pointed out by Campbell and Adamson (2006), the demand forecasting helps electric utilities to make important decisions such as decisions on purchasing and generating electrical energy, load scheduling and infrastructure development.

The econometric model prepared by the CEB for the National Demand Forecast 2003 – 2023 for Planning Studies is shown in Equation 1 below.

$$\begin{aligned} D(t) = & \left[-536.51 + 0.0358GDPPCi + 0.622Ddom(t-1)\right] \\ & + \left[-620.197 + -0.0199GDP(t-1)i + 0.006345GDPi\right] \\ & + \left[283.723(1+0.068)t\right] \end{aligned} \qquad (1)$$

Where;

D(t)	=	Total demand for electricity (GWh)
GDPPCi	=	Gross Domestic Product per Capita (Mn. Rs./cap)
GDP(t-1)	=	Gross Domestic Product in previous year (Mn. Rs.)
GDP	=	Gross Domestic Product (Mn. Rs.)
Ddom(t-1)	=	Demand in domestic consumer category in previous year (GWh)

According to Equation 1, the econometric demand forecasting model of the CEB used in the National Demand Forecast 2003-2023 included only few explanatory variables such as gross domestic product, gross domestic product per capita, and electricity demand in domestic customer category. However, other major variables such as population and electricity price have not been included in this model. It can therefore be stated that this model is not a comprehensive model for forecasting long term electricity demand for Sri Lanka.

Table Two: Differences between the actual and forecasted electricity demands

Year	Actual Electricity Demand (GWh)	Forecasted Electricity Demand (GWh)	Difference between Actual and Forecasted Demand (GWh)
2003	6209	6071	138
2004	6782	6453	329
2005	7255	6910	345
2006	7832	7414	418

(Sources: Ceylon Electricity Board National Demand Forecast 2003-2023 for Planning Studies, Statistical digests of Ceylon Electricity Board, 2003 - 2007 and the Sri Lanka Energy Balance – 2005 Database CD Rom of the Sustainable Energy Authority of Sri Lanka)

Table 2 shows the difference between the actual electricity demands and the forecasted demands indicated in the CEB National Demand Forecast 2003 – 2023 for Planning Studies. It clearly indicates that the actual demand is always higher than the forecasted demand, showing an under-forecasting scenario. This forecasting error varies from 138 GWh in 2003 to 418 GWh in 2006. This failure has resulted in closing the above demand gaps using costly thermal generation options to maintain the balance between electricity supply and demand, thus aggravating the current power and financial crises of the CEB. This clearly shows a gap and hence the following research problem arose:

Why the present long term demand forecasting model of the CEB fails to forecast demand accurately? The lack of accuracy of projecting electricity demand may be due to a limited number of explanatory variables that have been chosen for the current long-run demand estimation model of the CEB.

1.2 Significant and Scope of the Study

This is a macro level study, which uses aggregate data for the above variables. These determinants were identified through extensive literature surveys and expert opinions. The electricity demand used in this study is the total end use consumption of electricity (in GWh) by all customer classes of the CEB, Lanka Electricity Company (Private) Limited (LECO) and local authorities in Sri Lanka, viz. domestic, religious purpose, commercial and industrial. The effect of the planned and unplanned power interruptions on all the variables during the period of analysis was not taken into consideration.

Gross domestic product was considered as a proxy variable for the total national income of the country. The past GDP values at 1982 constant factor prices were available during the period of analysis, and therefore data on GDP values at 1982 constant factor prices. Average electricity prices were calculated as the weighted average of average electricity prices (the total revenue divided by the number of units sold) of the CEB, local authorities and the LECO, and then converted into US dollar terms using the respective exchange rates of the years. Population values used in this study were the total population of Sri Lanka for each year during the sampling period. The impact of electrical energy efficiency on electricity demand is worth studying due to the fact that various energy efficiency measures and energy efficient electrical equipment have been introduced to Sri Lanka during the recent past. The commercial energy intensity was used as a proxy variable for electrical energy efficiency. The energy intensities were calculated as the total consumption of commercial energy (petroleum and electricity) in tons of oil equivalent (toe) divided by real GDP (in Mn. Rs). The level of electrification in the country can be represented by percentage household electrified, i.e. the ratio of number of households electrified to the total number of households in the country as a percentage. The impact of implementation of rural electrification projects on electricity demand in Sri Lanka can be represented using a proxy variable, total number of rural electrification schemes completed during each year.

The study failed to find evidences in the local literature that the last three variables (i.e. energy intensity, percentage household electrified and number of rural electrification schemes completed) have been considered for electricity demand analysis for Sri Lanka. Thus, this study examines long-run electricity demand estimation for Sri Lanka by introducing these three new variables in addition to GDP, electricity price and population.

2. Methodology

Econometric approach which combines economic theory and statistical techniques is used to estimate the relationship between electricity demand and GDP, electricity prices, population, energy intensity, household electrified, and number of rural electrification schemes completed. The electricity demand is chosen as the explained variable and other remaining variables are chosen as explanatory variables. Using historical data from 1977 to 2013 pertaining to the above seven variables, this relationship is derived by employing the OLS technique using the Eviews 5.1 econometric package. However, prior to fitting the model, time series properties of data and the order of integration need to be investigated for stationarity.

The electricity demand considered in this study is the total consumption of electricity (in GWh) in Sri Lanka. This represents the total amount of electricity consumed by all electricity consumers which include domestic, commercial and industrial customers.

A long-run electricity demand function for Sri Lanka could be established mathematically as follows:

$$ED = f(GDP, P, POP, HHE, EI, RE) \quad or \qquad 2$$

$$ED = \beta_0 + \beta_1 GDP + \beta_2 P + \beta_3 POP + \beta_4 HHE + \beta_5 EI + \beta_6 RE$$

where;

ED	=	Electricity Demand
GDP	=	Real Gross Domestic Product in Rs. million at 1982 factor prices
P	=	Average Electricity Price in US$
POP	=	Total Population in thousands
HHE	=	Percentage Household Electrified
EI	=	Commercial Energy Intensity (Tons of Oil Equivalent (toe) per GDP Rs. million), which is used as a proxy to gauge the level of electrical energy efficiency measures implemented
RE	=	Number of Rural Electrification Schemes Completed. This is also a proxy variable to measure the level of rural electrification in Sri Lanka

The mathematical model is of limited interest as the relationships between variables are inexact. This is because other variables which have not been taken into account in the model are also likely to influence the dependent variable. To allow this inexact relationship, this mathematical demand function can be econometrically expressed as

$$ED = \beta_0 + \beta_1 GDP + \beta_2 P + \beta_3 POP + \beta_4 HHE + \beta_5 EI + \beta_6 RE + u \qquad 3$$

Where; β_0 is the intercept, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ *and* β_6 are the slope parameters and *u*, known as the disturbance or error term, is a random (stochastic) variable that has well defined probabilistic properties. Equation 3 is the population regression function (PRF), sometimes called the true model. The error term contains the factors other than above explanatory variables that affect the electricity demand.

Interpretation of coefficients is as follows:

$\beta_1 = \dfrac{\Delta ED}{\Delta GDP}$, while holding P, POP, HHE, EI and RE constant,

$\beta_2 = \dfrac{\Delta ED}{\Delta P}$, while holding GDP, POP, HHE, EI and RE constant,

$\beta_3 = \dfrac{\Delta ED}{\Delta POP}$, while holding GDP, P, HHE, EI and RE constant,

$\beta_4 = \dfrac{\Delta ED}{\Delta HHE}$, while holding GDP, P, POP, EI and RE constant,

$\beta_5 = \dfrac{\Delta ED}{\Delta EI}$, while holding GDP, P, POP, HHE and RE constant,

$\beta_6 = \dfrac{\Delta ED}{\Delta RE}$, while holding GDP, P, POP, HHE and EI constant, and

$\beta_0 =$ predicted value of ED when $GDP = P = POP = HHE = EI = RE = 0$.

With the above six regressors, the estimated OLS equation can be written as:

$$ED = \hat{\beta}_0 + \hat{\beta}_1 GDP + \hat{\beta}_2 P + \hat{\beta}_3 POP + \hat{\beta}_4 HHE + \hat{\beta}_5 EI + \hat{\beta}_6 RE \qquad 4$$

where $\hat{\beta}_0$ is the estimate of β_0, $\hat{\beta}_1$ is the estimate of β_1, $\hat{\beta}_2$ is the estimate of β_2, $\hat{\beta}_3$ is the estimate of β_3, $\hat{\beta}_4$ is the estimate of β_4, $\hat{\beta}_5$ is the estimate of β_5, and $\hat{\beta}_6$ is the estimate of β_6.

The method of ordinary least squares is used to estimate $\hat{\beta}_0, \hat{\beta}_1, \hat{\beta}_2, \hat{\beta}_3, \hat{\beta}_4$, $\hat{\beta}_5$ and $\hat{\beta}_6$. Equation 4 is called the OLS regression line or sample regression function (SRF). $\hat{\beta}_0$ is called as the OLS interpreted estimate and $\hat{\beta}_1$, $\hat{\beta}_2$, $\hat{\beta}_3$, $\hat{\beta}_4$, $\hat{\beta}_5$ and $\hat{\beta}_6$ are called the OLS slope estimates for the respective independent variables.

The parameter $\hat{\beta}_2$ related to the variable *P* is expected to have a negative sign, given the 'law of demand' which postulates an inverse relationship between electricity demand and price.

The parameters $\hat{\beta}_1$, $\hat{\beta}_3$, $\hat{\beta}_4$, and $\hat{\beta}_6$ related to variables *GDP, POP, HHE* and *RE* respectively are expected to appear with positive signs, since these variables and the electricity demand are expected to relate positively.

The parameter $\hat{\beta}_5$ related to the variable *EI* is expected to have a positive sign, as the electricity consumption will increase as a result of increase in energy intensity and vice versa.

Data were drawn from three sources for the study. The data for aggregate electricity demand in GWh, gross domestic product in Rs. million at 1982 factor prices, average electricity prices in US cents per kWh, percentage household electrified, and energy intensity in toe per GDP Rs. Million were obtained from the Sri Lanka Energy Balance database of the Sustainable Energy Authority of Sri Lanka and from the CEB statistical digests. The data on population (in thousands) and number of rural electrification schemes done per year were obtained from the Annual Reports of the Central Bank of Sri Lanka and the CEB statistical digests respectively.

3. Results and Conclusion

The first step of this analysis is to test stationarity of the variables using the Augmented Dickey-Fuller (ADF) unit root test. The results of the ADF unit root tests in levels and first differences are reported in the annexure 1. We estimate Equation (1) by using the first differences of the variables because all the variables are stationary in their first differences at the 5% level as pointed out above. The first differences of *ED, GDP, P, POP, HHE, EI* and *RE* are denoted as *DED, DGDP, DP, DPOP, DHHE, DEI* and *DRE* respectively. Annexure 2 shows the regression results of ordinary least squares (OLS) and first order autoregressive (AR1) process. In the OLS estimation, the Durbin-Watson statistic of 1.47, which is less than 2, indicates the evidence of serial correlation. Therefore, the AR (1) procedure is used to eliminate the serial correlation problem. In the regression results of AR(1) procedure, the Durbin-Watson statistic, which is close to 2, indicates that the serial correlation problem has been solved, which means that error terms associated with sample observations of different time periods are independent. Further, since there is no serial correlation problem associated with the sample data, the R^2 value obtained in the regression using AR (1) procedure is deemed to be realistic.

The fit of the estimated equation is pretty impressive for the AR(1) procedure as the coefficient of determination (R^2) is 0.983, which indicates that about 98.3% of the total variations in the first difference of the long-run electricity demand (i.e. *DED*) is explained by the explanatory variables *DGDP*, *DP*, *DPOP*, *DHHE*, *DEI* and *DRE* in the regression model. P- value for F-statistic of 89.1075 is zero. Therefore, we do not reject the null hypothesis that all the coefficients of explanatory variables are equal to zero. Therefore the six explanatory variables, *DGDP, DP, DPOP, DHHE, DEI* and *DRE* are highly significant jointly in explaining the long-run electricity demand for Sri Lanka.

Thus, GDP, population, percentage household electrified, energy intensity and rural electrification schemes implemented have positive effects on the long-run demand for electricity in Sri Lanka and on the other hand, average electricity price has a negative effect on the electricity demand. Since the Jarque-Bera statistic in annexure 3 falls in between 0 and 6, the AR (1) estimation does not have the problem of non-normality. In view of the test results discussed above, it is clearly evident that the all assumptions of regression are met in the AR (1) procedure.

As per regression results of AR (1) procedure shown below, the long-run electricity demand function for Sri Lanka (at first differences) can be written as:

$$\begin{aligned} DED = & -\underset{(0.0000)}{184.6361} + \underset{(0.0000)}{0.044918}DGDP - \underset{(0.0029)}{54.07402}DP(-2) \\ & + \underset{(0.0014)}{0.259840}DPOP(-6) + \underset{(0.0023)}{1959.126}DHHE(-3) + \underset{(0.0047)}{84.66129}DEI \\ & + \underset{(0.0023)}{0.076892}DRE(-8) \end{aligned} \qquad 5$$

Note: The probability values of individual coefficients are given in parentheses.

The above equation contains the lagged values of *DP*, *DPOP*, *DHHE,* and *DRE* so as to have the best fitted demand function with the intention of obtaining the expected signs for coefficients of explanatory variables and to make each individual explanatory variable statistically significant.

The explanatory variable *DP* (the first difference of electricity price) is lagged for 2 years in and the coefficient of *DP* has the expected negative sign. The negative sign implies an inverse relationship between average electricity price and the electricity demand, which is consistent with the law of demand in economic theory. The reason as to why we get 2 year lagged period for *DP* in the demand equation is that in the short run, most of the electricity consumers have few options to reduce their electricity consumption in response to electricity price increments. But over a larger period, i.e. may be around 2 years as per the regression results of this study, they may switch to other energy options such as gas, go for improved energy efficiency measures or adopt energy conservation practices. In summary, electricity consumers do not quickly respond to electricity price changes, and they take a considerable time of about 2 years to change their consumption pattern. It can therefore be said that electricity demand is more elastic in the long run.

The explanatory variable *DPOP* (the first difference of population) is lagged for a period of 6 years in the equation, which indicates that the annual population during a particular year may exert an impact on the long-run electricity demand after a period of about 6 years. The *DPOP* has the expected positive sign as it is assumed that the demand for electricity is positively correlated with the population.

The variable *DHHE* is also lagged for 3 years in the demand function, which indicates that the level of households' electrification during a particular year would take about 3 years to impact the electricity demand. The *DHHE* has the expected positive sign in the demand equation as it relates positively with the demand for electricity.

Finally, it is noted that the *DRE* has the expected positive sign because it is obvious that the electricity demand is positively correlated with the number of rural electrification schemes added to the power system. It is also noted that the explanatory variable *DRE* (the first difference of number of rural electrification schemes implemented per year) is lagged for 8 years (which is quite a long period) in the electricity demand function as shown in the equation. This result clearly indicates that it would take about 8 years for a rural electrification scheme to reach a consumption level which is large enough to impact the electricity demand of Sri Lanka. According to various studies carried out by the ADB Resident Mission of Sri Lanka, on average it takes about 8 to 10 years for a rural electrification scheme to reach average electricity consumption level of Sri Lanka. This result is in line with Ringwood, Bofelli, & Murray, (2001). This information was also verified by the rural electrification branch of the CEB. It takes about 10 years on average to become a rural electrification scheme to the normal average consumption level in Sri Lanka. Almost all the rural electrification schemes are implemented in the rural areas of Sri Lanka where the income level of people is very low and these people meet most of their energy requirements from naturally available energy sources such as firewood, natural sunlight etc. Therefore, after commissioning a rural electrification scheme, a very few people can afford to get the benefit of electricity, while leaving a majority unelectrified for a long time. Even after getting the electricity supply, they use electricity mainly for lighting purposes while meeting their other energy needs with naturally available energy options. Another reason may be that the electricity prices in Sri Lanka are one of the highest in the region and therefore the poor people in villages may not have a sufficient proportion of their income to pay for their electricity consumption. This may encourage them to bring down their level of electricity consumption. The equation shows that the explanatory variables *DGDP* and *DEI* will have direct impacts on the demand for electricity in Sri Lanka. The explanatory variables, *DGDP* and *DEI* have the expected positive signs in as the demand for electricity is positively correlated with the gross domestic product and the energy intensity.

References

Al-Alawi, S. M. and Islam, S. M. 1996. Principles of electricity demand forecasting: Part 1 methodologies. *Power Engineering Journal*. 139-143. Retrieved September 29, 2014, from http://ieeexplore.ieee.org.

Asian Development Bank. 2007. *Sri Lanka country assistance program evaluation: Power sector*. Retrieved October 12, 2008, from http://www.adb.org/Documents/Evaluation/CAPES/SRI.

Bose, R. K. and Shukla, M. 1999. Elasticities of electricity demand in India. *Energy Policy. 27.* 137-146. Retrieved October 12, 2008, from http://www.sciencedirect.com.

Campbell, P. R. J., and Adamson, K. 2006. *Proceedings of 3rd International IEEE Conference Intelligent Systems*. 800-806. Retrieved March 31, 2014, from http://ieeexplore.ieee.org.

Central Bank of Sri Lanka. 2004-2014. *Annual reports*. Colombo: Central Bank of Sri Lanka.

Ceylon Electricity Board. 1980-2014. *Statistical digests*. Colombo: Ceylon Electricity Board.

Ceylon Electricity Board. 1999-2014. *Annual reports*. Colombo: Ceylon Electricity Board.

Ceylon Electricity Board. 2003. *National demand forecast 2003-2023 for planning studies*. Colombo: Ceylon Electricity Board.

Ringwood, J. V., Bofelli, D. and Murray, F. T. 2001. Forecasting electricity demand on short, medium and long time scales using neural networks. *Journal of Intelligent and Robotic Systems, 31.* 129-147. Retrieved April 1, 2008, from *http://www.ingentaconnect.com.*

Sri Lanka Sustainable Energy Authority. 2005. *Sri Lanka Energy Balance – 2005. Colombo: Sri Lanka Sustainable Energy Authority.*

Sri Lanka Sustainable Energy Authority. 2005. *Electricity data and energy-economy indicators. Sri Lanka Energy Balance – 2005, [CD-ROM].*

Statistics New Zealand. 2007. *Energy and the economy 1997-2005*. Retrieved October 13, 2008, from *http://www.stats.govt.nz/*

Taylor, D. 1975. *The demand for electricity: A survey. The Bell Journal of Economics. 6(1). 74-110.* Retrieved October 20, 2008, from http://www.jstor.org/

Wang, H., Tian, P. and Jin, P. 2005. *Electricity consumption and economic growth in China. Proceedings of the 2005 International Conference on Services Systems and Services Management. 2.* 1331-1334. Retrieved April 14, 2008, from http://ieeexplore.ieee.org/

Wijayatunga, P. D. C. and Attalage, R. A. 2002. *Sri Lanka electricity industry: Long term thermal generation fuel options*. (Research Studies: Energy & Environmental Economics Series No. 10. Colombo, Sri Lanka: Institute of Policy Studies.

Annexure

Annexure 1: Results of the ADF tests for unit root in levels and first differences

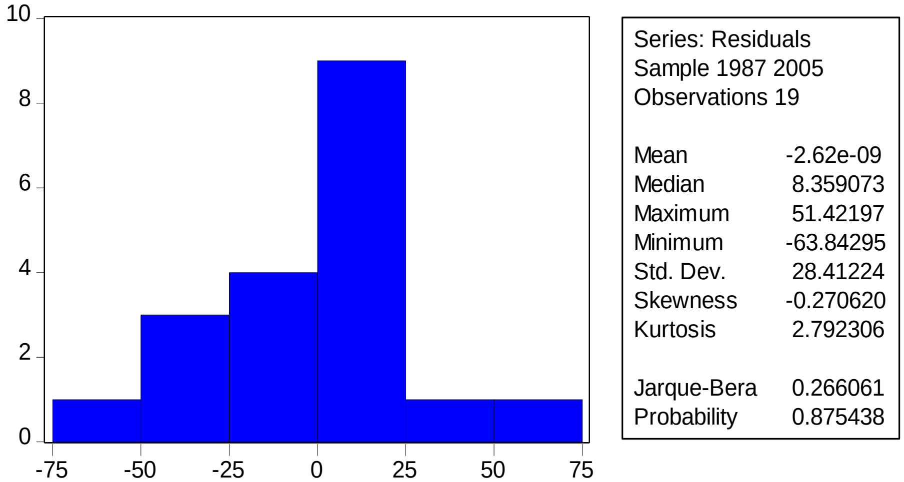
Variable	Levels for Testing Unit Roots	Trend	Constant	Number Of Lags	ADF Test Statistics	Test Critical Value at 5% Significant Level
ED	Level	Yes	Yes	0	0.3138	-3.5806
	1st difference	Yes	Yes	0	-5.6340	-3.5875
GDP	Level	Yes	Yes	0	0.3727	-3.5806
	1st difference	Yes	Yes	0	-4.5857	-3.5875
p	Level	Yes	Yes	0	-2.2201	-3.5806
	1st difference	No	No	0	-4.3896	-1.9539
POP	Level	Yes	Yes	0	-1.6908	-3.5806
	1st difference	No	Yes	0	-4.9056	-2.9763
HHE	Level	Yes	Yes	5	-3.6939	-3.6220
	1st difference	Yes	Yes	2	-4.8162	-3.6032
EI	Level	No	No	0	-1.4907	-2.9718
	1st difference	No	No	0	-5.8287	-1.9539
RE	Level	No	No	0	-3.7148	-2.9718
	1st difference	No	No	1	-6.7678	-1.9544

Note: The null hypothesis of the ADF test is that the variable has a unit root.

Annexure 2: Regression results of the determinants of the long-run electricity demand for Sri Lanka

Variable	OLS Method		The AR(1) Method for correcting serial correlation problem	
	Coefficient	Probability	Coefficient	Probability
C	-180.8922	0.0000	-184.6361	0.0000
DGDP	0.044892	0.0000	0.044918	0.0000
DP(-2)	-52.60212	0.0032	-54.07402	0.0029
DPOP(-6)	0.278361	0.0003	0.25984	0.0014
DHHE(-3)	1839.366	0.0027	1959.126	0.0023
DRE(-8)	0.078761	0.0039	0.076892	0.0023
DEI	72.60355	0.0070	84.66129	0.0047
AR(1)	-	-	0.29683	0.3314
R-squared		0.980192		0.98267
Adjusted R-squared		0.971049		0.971642
Durbin-Watson star		1.466518		2.085933
F- Statistic		107.2142		89.1075
Prob (F- Statistic)		0.000000		0.000000

Annexure 3: Jarque-Bera statistic for residuals for long-run electricity demand estimation for SriLanka


10
8
6
4
2
0
-75
-50
-25
0
25
50
75
Series: Residuals
Sample 1987 2005
Observations 19
Mean -2.62e-09
Median 8.359073
Maximum 51.42197
Minimum -63.84295
Std. Dev. 28.41224
Skewness -0.270620
Kurtosis 2.792306
Jarque-Bera 0.266061
Probability 0.875438

Promoting Building Energy Efficiency through Performance-based Standards: Is it a Challenge?

R.M.P.S. Bandara[1], R.A. Attalage[2*]

[1]*Department of Mechanical Engineering, General Sir John Kotelawala Defence University, Sri Lanka*
[2]*Department of Mechanical Engineering, University of Moratuwa, Sri Lanka*

Date Received: 22-11-2014 Date Accepted: 29-04-2015

1. Background and Issues

Buildings account for nearly 40% of the global energy consumption, 16% of the world's fresh water, 25% of the forest timber while emitting almost 70% of oxides of sulphur and 50% of carbon dioxide gas annually (Ghiaus and Inard, 2004). Buildings could last for decades and hence the decisions made on them today have a long lasting impact on the future global energy consumption and emissions. Also it is found that people spend almost 90% of their time inside buildings and as a result the indoor pollutant levels may reach 2 to 5 times higher than outdoor levels (Mumovic and Santamouris, 2009).

The built environment is booming all over Asia with China constructing almost half of the world's new buildings. The buildings in India have doubled from 2000 to 2005 (Mumovic and Santamouris, 2009). It is recorded that buildings in Asia are consuming more energy and producing more Green House Gas (GHG) emissions and it is predicted that this will rise at a rapid rate during the next decade. In the present context, great emphasis is imparted to minimize, or more specifically optimize the energy efficiency and the Carbon footprint related to buildings. In an overall perspective, building performance encompasses energy performance, indoor environment and air quality for human comfort and health, environmental degradation and economic aspects. This paper intends to highlight the potential of performance-based building standards over the widely used prescriptive standards for building energy performance and the challenges posed in establishing the same for promoting energy efficiency. It further attempts to quantify the energy efficiency gains in adopting performance-based standards compared to those with prescriptive elements through a suitable case study. Furthermore, the current status of the application of such standards, their evolution in the recent past, key benefits that they have brought about into the sector of building performance, and the challenges in adopting the same in the local building sector are highlighted.

2. Trend towards Energy Efficient Buildings

Building performance standards have played a very significant role and in particular, in view of pushing the sector above a globally acceptable minimum energy performance level since the first petroleum crisis in 1973. This trend subsequently evolved to other aspects of building performance such as indoor air quality, comfort etc. There have been several major government initiatives for promoting the concept of energy efficient buildings globally. Some of them are the Directive on the Energy Performance of Buildings implemented by the European Union in 2003, G8 Gleneagles Program on Building Energy Efficiency in 2005 and European Commission Green Building Program of 2005 (Wagner, 2007). Also there are market driven programs such as Leadership in Energy and Environmental Design (LEED) developed by the US Green Building Council in 1998 and ENERGY STAR originated in the United States by the Environmental Protection Agency and the Department of Energy in 1992 (Reeder, 2010). *LEED* consists of a suite of rating systems for the design, construction, operation and resource utilization of energy efficient buildings. *ENERGY STAR* is an international standard for energy efficient consumer products (Reeder, 2010). A growing market for energy services has been established with the emergence and growth of Energy Service Companies (ESCOs). A trend of mushrooming *Green Building Projects* around the world is also observed. Furthermore, there are clear evidences of a transformation that envisaged a change of the market prices of the building industry.

Energy efficiency policy measures related to buildings can be broadly categorized as fiscal, financial and regulatory. Fiscal policy measures are mainly concerned with granting tax credits, tax reduction on equipment

* *Correspondence: rattalage@hotmail.com*
ISSN 2478-0669 Print

appliances, tax reduction on energy tax and implementation of tax schemes on inefficient appliances. Financial measures establish and implement policies related to granting of subsidies or soft loans for energy efficient buildings and systems. Also it promotes the concept of *Energy Auditing* for enhancing the energy performance of systems and processes. Regulatory measures emphasize on Minimum Energy Performance Standards (MEPS) and Energy Performance Labelling for buildings, which has become a newly rising trend.

Lighting, HVAC, and office equipment consume most of the energy in a typical commercial building as shown in Figure 1. Most savings can be achieved by implementing energy efficiency measures around these elements. High-impact measures can significantly reduce energy consumption and cost.

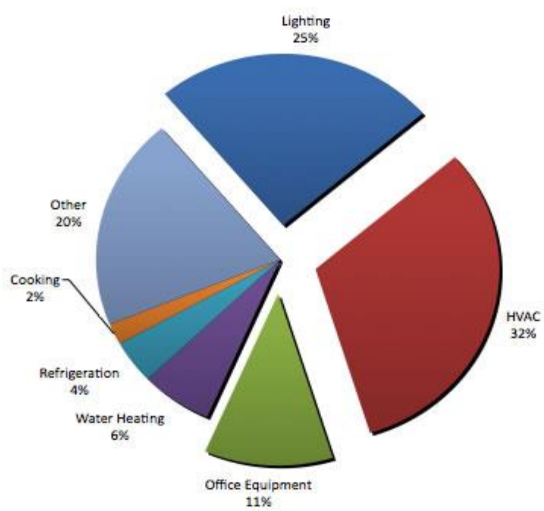


Figure 1: End use energy consumed by components of the building
Source: Building Energy Data Book, US Department of Energy, 2006

3. Building Performance Standards / Codes

Building performance standards have been introduced mainly for the purpose of establishing the regulatory minimum level for building performance. They also offer a level playing field for relevant stakeholders and ensure the elimination of non-conforming products. Building performance standards which are either of mandatory or voluntary nature have traditionally played an important role in building regulations. As of now, building performance standards have been established and adopted by many countries irrespective of whether they are in the developed or developing world as shown in Figure 2 (WEC, 2009). Energy performance labeling makes the energy performance "visible" to the public and consumers.

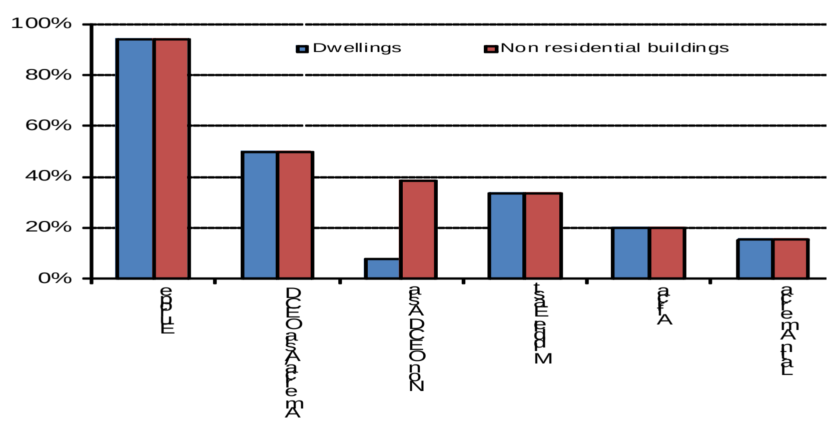


Figure 2: Existence of building regulations
Source: WEC, ADEME Survey 2009

Building performance standards fall into two generic categories, namely, prescriptive and performance based. In the prescriptive category, the standard stipulates mandatory and prescriptive criteria for generic building elements, equipment and energy supply conditions to be complied by the user. This includes building envelope, HVAC equipment, lighting system, hot water system, power supply and auxiliary equipment. The system analysis approach adopted in this regard is illustrated in Figure 3.

In case of performance based standards, the compliance is based on stipulated performance metrics that have to be established by pre-determined methods. This approach mainly utilizes design tools and building performance modelling techniques. Modelling for performance based approach considers Peak (usually) design loads estimation, Lighting and receptacle power allowance calculation, Annual energy consumption estimation, parametric analyses and Energy efficiency measures.

4. A case study on building energy performance

An energy performance case study of a two-story building which has an automobile repair work shop and office spaces is considered. It has 6846 sq. ft of conditioned area with Window-to-Wall Ratio (WWR) of 24.5%. This building is located in the climate zone of 1 A as per the ASHRAE classification (ANSI/ASHRAE/IESNA, 2007). The computational model of the building is shown in Figure 4. Table 1 gives the prescriptive and performance-based standards for the building. Table 2 provides a comparison of the energy performance of the office building when the prescriptive and performance-based standards are applied separately.

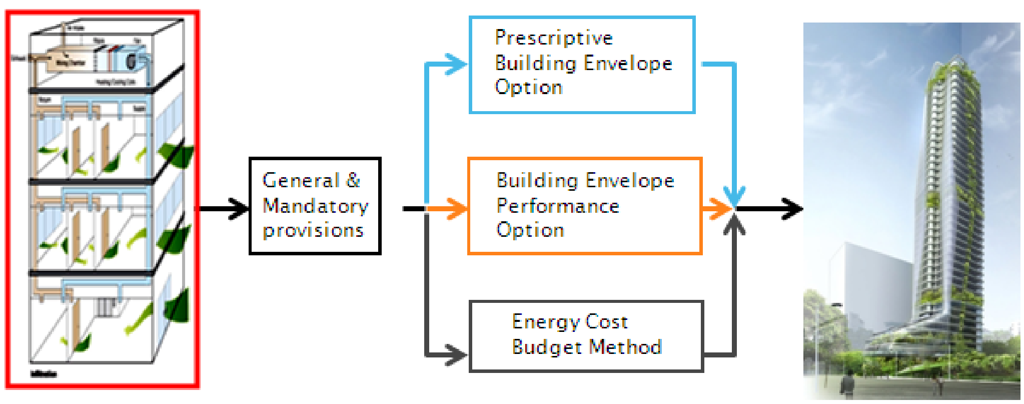


Figure 3: Designing for Energy Performance – System Analysis Approach
Source: Extract from ASHRAE documentation

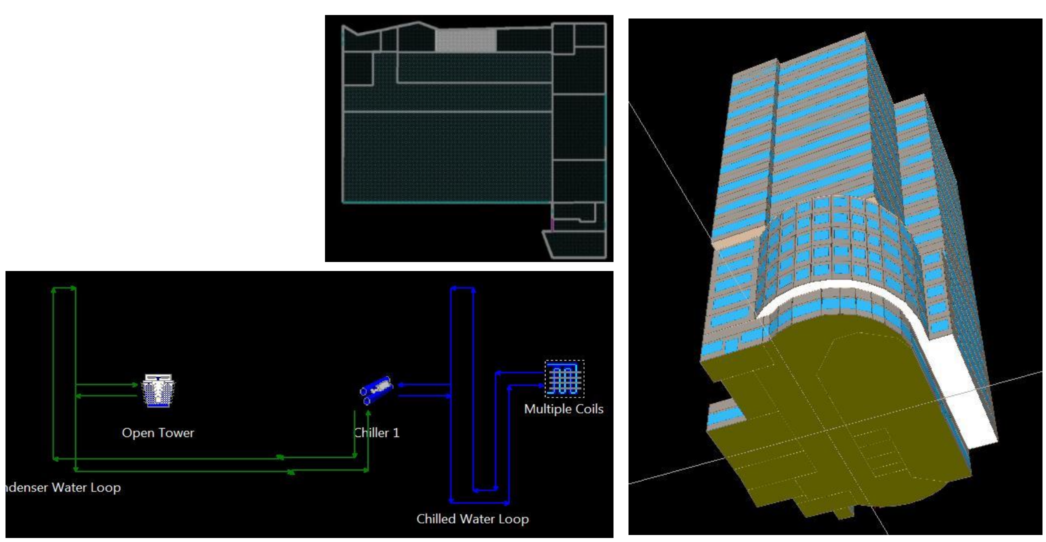


Figure 4: Computational model of the office building

Table 1: Extract of information of prescriptive and performance-based standards

Building Element / System		Prescriptive	Performance Based
Envelope	Wall	U-0.705 W/m^2.K, R-2.3 m^2.K/W	Not specific
	Roof	U-0.360 W/m^2.K, R-2.6 c.i. m^2.K/W	Not specific
	Floor	U-1.986 W/m^2.K	Not specific
	Glazing	U-6.81 W/m^2.K, SHGC-0.25 all	Not specific
Lighting	Interior	Space by Space Method	Through Lighting system simulation
HVAC System		Minimum Equipment efficiencies	Through HVAC system Simulation

From Table 2 it is observed that by applying performance-based standards instead of the prescriptive standards, substantial energy savings can been achieved through interior lighting, space cooling and interior fans without sacrificing the design intent. Hence the total annual energy saving for the building through the application of performance-based standards amounts to 28%. This clearly shows the potential of the performance-based building standards over the widely used prescriptive standards.

Table 2: Comparison of energy performance of the building

End Use	Energy Consumption per Annum [kWh]		Percent Energy Savings per Annum (%)
	Prescriptive Method	Performance Rating Method	
Interior Lighting	48,474	29,611	39
Task Lighting	1,430	1,430	0
Receptacle Equipment	131,461	131,461	0
Space Heating	0	0	-
Space Cooling	92,890	53,506	42
Heat Rejection	0	2,740	-
Pumps and Auxiliary items	0	12,531	-
Fans - Interior	53,377	2,435	95
Exterior Usage	2,935	2,935	0
Total	330,566	236,649	28

References

Alvarez, E., Duque, A., Saldarriaga, J., Cabrera, K., de las Salas, G., del Valle, I., Lema, A.,Moreno, F., Orrego, S. and Rodríguez, L. 2012. Tree above-ground biomass allometries for carbon stocks estimation in the natural forests of Colombia. *Forest Ecology and Management*, 267: 297-308.

Baker, T.R., Phillips, O.L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Higuchi, N.,Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Lloyd, J., Monteagudo, A., Neill, D.A., Patino, S., Pitman, N.C.A., Silva, J.N.M. and Vasquez Martinez, R., 2004. Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology*, 10(5): 545-562.

Basuki, T.M., van Laake, P.E., Skidmore, A.K. and Hussin, Y.A. 2009. Allometric equations for estimating the above ground biomass in tropical lowland Dipterocarp forests. *Forest Ecologyand Management*, 257: 1684-1694.

Brown, S., Gillespie, A. and Lugo, A.E. 1989. Biomass estimation methods for tropical forest withapplications to forest inventory data. *Forest Science*, 35(4): 881-902.

Cannell, M.G.R. 1984. Woody biomass of forest stands. *Forest Ecology and Management*, 8: 299-312.

Chambers, J.Q., dos Santos, J., Ribeiro, R.J. and Higuchi, N. 2001. Tree damage, allometric relationships, and above ground net primary production in central Amazon forest. *Forest Ecology and Management*, 152: 73-84.

Chave, J., Condit, R., Lao, S., Caspersen, J.P., Foster, R.B. and Hubbell, S.P. 2003. Spatial and temporal variation in biomass of a tropical forest: results from a large census plot in Panama. *Journal of Ecology*, 91(2): 240-252.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F.,Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B. and Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145: 87-99.

Chave, J., Muller-Landau, H.C., Baker, T.R., Easdale, T.A., ter Steege, H. and Webb, C.O. 2006.Regional and phylogenetic variation of wood density across 2,456 neotropical tree species. *Ecological Applications*, 16(6): 2356-2367.

Clark, D.A. 2007. Detecting Tropical Forests' Responses to Global Climatic and Atmospheric Change: Current Challenges and a Way Forward. *Biotropica*, 39(1): 4-19.

Dawkins, H.C. 1961. Estimating total volume of some Caribbean trees. *Caribbean Forester*, 22: 62–63.

Dixon, R.K., Brown, S., Solomon, R.A., Trexler, M.C. and Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystems. *Science*, 263: 185-190.

Henry M., Bombelli A., Trotta C., Alessandrini A., Birigazzi L., Sola G., Vieilledent G., Santenoise P., Longuetaud F., Valentini R., Picard N. and Saint-André L. 2013. Glob Allome Tree: international platform for tree allometric equations to support volume, biomass and carbon assessment. *iForest - Biogeosciences and Forestry,* 6: 326-330.

Litton, C.M. and Kauffman, J.B. 2008. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Biotropica*, 40(3): 313-320.

Luizão, F., Meir, P., Monteagudo, A., Neill, D., Núñes-Vargas, P., Peñuela, M.C., Pitman, N., Priante Filho, N., Prieto, A., Panfil, S.N., Rudas, A., Salomão, R., Silva, N., Silveira, M.,Soares de Almeida, S., Torres-Lezama, A., Vásquez-Martínez, R., Vieira, I., Malhi, Y. and Phillips, O.L. 2009. Branch xylem density variations across the Amazon Basin. *Biogeosciences*, 6: 545-568.

McMahon, T.A. and Kronauer, R.E. 1976. Tree structures: deducing the principles of mechanical design. *Journal of theoretical Biology*, 59(2): 443-466.

Nelson, B.W., Mesquita, R., Pereira, J.L.G., de Souza, S.G.A., Batista, G.T. and Couto, L.B. 1999.Allometric regressions for improved estimate of secondary forest biomass in the central Amazon. *Forest Ecology and Management*, 117: 149-167.

Sandeep, S., Sivaram, M., Henry, M. and Birigazzi, L. 2014. Inventory of volume and biomass tree allometric equations for South Asia.KFRI, Peechi, India. *UN-REDD Programme MRV report,* 15, Food & Agriculture Organization of the United Nations, Rome, Italy.

Sierra, C.A., del Valle, J.I., Orrego, S.A., Moreno, F.H., Harmon, M.E., Zapata, M., Colorado, G.J.,Herrera, M.A., Lara, W., Restrepo, D.E., Berrouet, L.M., Loaiza, L.M. and Benjumea, J.F. 2007. Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. *Forest Ecology and Management*, 243: 209-309.

Steege, H., Pitman, N.C.A., Phillips, O.L., Chave, J., Sabatier, D., Duque, A., Molino, J.F.,Pr´evost, M.F., Spichiger, R., Castellanos, H., von Hildebrand, P. and Vásquez, R. 2006. Continental-scale patterns of canopy tree composition and function across Amazonia. *Nature*, 443: 444-447.

Wang, X., Fang, J., Tang, Z. and Zhu, B. 2006. Climatic control of primary forest structure and DBH height allometry in Northeast China. *Forest Ecology and Management*, 234: 264–274.

West, G.B., Brown, J.H., Enquist, B.J., 1999. A general model for the structure and allometry of plant vascular system. *Nature*, 400: 664-667.

Zianis, D. 2008. Predicting mean above ground forest biomass and its associated variance. *Forest Ecology and Management*, 256: 1400-1407.

Benchmarking of Electricity Distribution Licensees Operating in Sri Lanka

L. Neelawala*, K.T.M.U. Hemapala

Department of Electrical Engineering, University of Moratuwa

Date Received: 27-06-2015 Date Accepted: 5-11-2015

Abstract

Electricity sector regulators are practicing benchmarking of electricity distribution companies to regulate the allowed revenue. Mainly this is carried out based on the relative efficiency scores produced by frontier benchmarking techniques. Some of these techniques, for example Corrected Ordinary Least Squares (COLS) method use econometric approach to estimate efficiency scores, while a method like Data Envelopment Analysis (DEA) uses Linear Programming. Those relative efficiency scores are later used to calculate the efficiency factor (X-factor) which is a component of the revenue control formula. In electricity distribution industry in Sri Lanka, the allowed revenue for a particular distribution licensee is calculated according to the allowed revenue control formula as specified in the tariff methodology of Public Utilities Commission of Sri Lanka (PUCSL). This control formula contains the X-factor as well, but its effect hasn't been considered yet just kept it zero, since there were no relative benchmarking studies carried out by the utility regulators to decide the actual value of X-factor. This paper focuses on producing a suitable benchmarking methodology by studying prominent benchmarking techniques used in international regulatory regime and by analyzing the applicability of them to Sri Lankan context, where only five Distribution Licensees are operating at present.

Keywords: data envelopment analysis, corrected ordinary least squares, distribution licensees

1. Introduction

There are five Distribution Licensees operating in Sri Lanka. The Distribution Allowed Revenue (DAR) is the revenue that a Distribution Licensee (DL) is allowed to collect from the distribution users due to the use of the distribution system. For each DL, the DAR shall be calculated based on the Tariff Methodology published by PUCSL. This includes efficient operational expenditure (OPEX). A relative OPEX efficiency score obtained from a benchmarking study is an input to formulate X-factor. At present PUCSL take X-factor as zero due to the fact that there is no benchmarking study has been done on DLs to obtain the relative OPEX efficiency scores. The regulator can set differentiated price limits based on the companies' efficiency performance estimated from a benchmarking analysis (Farsi, 2007). And also it can decide which companies deserve closer examination, so that scarce investigative resources are allocated efficiently (Shuttleworth, 2005). There are different benchmarking techniques used by international regulators (Shuttleworth, 2005), and following techniques were considered in this paper.

2. Selection of variables

In regulators point of view, following factors such as quality, availability, relevance and ease of collection of the data, has to be considered when selecting variables. Importantly the selected variables must be able reflect the scale of operation and should have major influence on the cost of operation. Selecting non redundant variables with high discriminating power are advantageous since we are comparing only five DLs (small sample). Therefore the regulator must take care to keep the number of variables to minimum while those variables are strong cost drivers (i.e. OPEX). Relevant data should be accurate and importantly be practical to collect from the DLs timely.

When analyzing the available information with the regulator it was found that Energy Sold, Total number of consumers, No. of new connections provided, No. of employees, Total distribution lines length, No. of substations, Operational Expenditure and Authorized operation area (This is a constant for each licensee) are meeting above mentioned criteria in Sri Lankan context. Note that, in international benchmarking practices, the use of supply/service quality as a variable is rare. Most of the countries reviewed separately run a quality-of-service reward/penalty regime (ACC/AER, 2012). In Sri Lanka, the supply/service quality is to be determined according to the drafted Electricity Distribution performance regulations, where penalties have been introduced for underperformance (PUCSL, 2012).

* *Correspondence: udayanga@elect.mrt.ac.lk*
ISSN 2478-0669 Print

Table 1: Benchmarking techniques

Benchmarking Technique	Remarks
Partial Performance Indicators (PPIs)	Used to compare the ratios of single output to a single input of firms (eg. Energy sold per OPEX). They are often significantly affected by the capital substitution effects (Chung, 2011).
Data Envelopment Analysis (DEA)	Involves linear programming to determine the efficient firm(s) from a sample relative to the other firms in the sample. In this technique, the ratio of weighted outputs to the weighted input a firm is maximized subjected to constraints (require to solve individual linear programming problems for each firm in the sample).
Corrected Ordinary Least Squares (COLS)	A regression technique that most efficient firm or the frontier is estimated. From the Ordinary Least Squares (OLS) technique the cost function of the business is estimated. This OLS line (line of best fit) is then shifted to the efficient firm by adding the absolute value of the largest negative estimated error. This is therefore a 'corrected' form of OLS.

3. Selection of benchmarking techniques and models

DEA, COLS, and PPI fulfill the desirable characteristics such as easiness to compute and understand transparency and ability to implement in smaller samples. If a benchmarking method requires higher number of data points then it will be harder to implement with a smaller sample like five, as in the case where only five DLs in Sri Lanka. DEA can be easily implemented with five DLs, but care has to be taken to verify the results with other methods. A rule of thumb (from international practices) is that for *m* number of inputs and *n* number of outputs, there has to be *n* x *m* number of DLs (Talluri, 2000). Otherwise all the DLs would get closer to 100% efficiency and discrimination could be difficult.

COLS method with Cobb-Douglas cost function with same set of variables (as used in DEA) can be implemented, and also COLS implementation can be used to verify the results from DEA. To verify the results (efficiency scores) at least two different benchmarking methods must be used. Selected methods should have different characteristics so that the regulator can convince the DLs about the efficiency scores. In this case DEA and COLS are feasible to implement.

4. Implementation of benchmarking techniques using DEA

Following variables were selected when implementing DEA.

Table 2: Selected variables

Variable	Remarks
Energy sales	Amount of energy (GWh) distributed to the consumers by DL during the year concerned. This was taken as the main output variable, since the energy sales is the main production of the electricity distribution business.
No. of new connections given	That is the number of new service connections provided by the Dl during the year concerned. This is an output of the distribution business.
No. of employees	Total number of employees employed by the DL. This is taken as an input to the distribution business
OPEX	The operational expenditure is taken as the main input to the distribution business.
Total network length	This is the total route length of the electrical distribution lines. In one hand this can be taken as an output, because this amount of line length has to be maintained by the DL. On the other hand this can be taken as input, because this is a capital input to the distribution business.
No. of substations	In one view this is taken as an output, as it consumes input resources by DL to maintain. In another view this can be taken as an input as it is a capital input to the distribution business.
Area per consumer	This variable is an indication of the extent of dispersion of the consumers. Generally if the dispersion is greater, then the input resource requirement would be greater per consumer. Hence this is taken as an output to the DEA model.
Network line length per consumer	This is the electricity distribution route length per consumer. Lower value for this indicates higher concentration of consumers. Further, this is an indication of the extent of rural electrification. To implement this factor in DEA model, it is taken as an output to the DEA model.

Note that every possible input output configurations (models) were taken into consideration when obtaining results. Energy Sales and OPEX present in each model (Refer table 3) since those are the main output and input variables respectively. If a variable to a model is taken as output then it is indicated as 'O' while inputs represented as 'I'.

Table 3: DEA efficiency scores of 3 input/output variables models

Model	Energy sales	New connections given	Area per consumer	Network line length per consumer	Total network length	No. of substations	No. of employees	OPEX	DL 1	DL 2	DL 3	DL 4	DL 5
1	o	o						I	100	77.3	100	77.7	100
2	o		o					I	100	77	92.1	77.7	100
3	o			o				I	100	76.8	100	100	100
4	o				o			I	100	77.4	100	100	100
5	o					o		I	98.8	76.6	91	77.3	100
6	o				I			I	98.8	76.6	91	76.9	100
7	o					I		I	100	77.5	91.5	76.9	100
8	o						I	I	100	77.8	91	76.9	100

In DEA 3- variable technique we have used 8 different input/output combinations (8 models) and relative efficiency scores calculated under each model. For example, in the model-4 (Refer Table 3)' Energy Sales' and 'Total Network Length' are taken as outputs of the electricity distribution business while OPEX is taken as the input. In this aspect we look at how efficiently (relatively) a DL has used its OPEX to provide electrical energy to its consumers and also to maintain the total network length owned by that DL. In that case all DLs except DL2 have obtained relative efficiency score of 100%. DL2 has obtained a score of 77.4%. This means only relative to each other, DL2 is efficient only about 77.4%. This does not imply that all other DLs are 100% efficient in are strictly efficient. It is possible that DLs with 100% score could be operated more efficiently.

5. Implementation of benchmarking techniques using COLS

Variables in 'benchmark cost function' should represent; Output produced by the business, Input prices paid and the Environmental conditions that effect the production cost. In Sri Lanka, OPEX of DLs mainly consists of expenses for human resource. Therefore cost per employee must be used as the main input price of the cost function. Energy Sold (GWh) reflect the main output produced. The consumer density has to be included in the cost function in order to capture the heterogeneity dimension of the distribution business (Fillippini, 2002). The table 4 indicates the extent of heterogeneity. Note that to estimate the coefficients of the cost function we have only five data points. Therefore only one variable from each category, i.e. output, input prices and environmental conditions were used. Cost functions used and the efficiency scores are given in table 5 and table 6 respectively.

Table 4: Consumer density

Licensee	Consumers per Unit Length of Network (Cons./km)	Customer Density (Consumer Accounts per km^2)
DL1	32.48	47
DL2	42.71	94
DL3	34.66	76
DL4	31.97	126
DL5	113.14	1375

Table 5: Cost functions used with three variables

Model No.	Cost function
1	*ln (OPEX) = a + b. ln (Energy Output) + c. ln (Cost of employee)*
2	*ln (OPEX) = a + b. ln (Energy Output) + c. ln (Cust. per line length)*
3	*ln (OPEX) = a + b. ln (Energy Output) + c. ln (Cust. Per area)*
4	*ln (OPEX) = a + b. ln (Energy Output) + c. ln (Total network length)*

Table 6: COLS with three variables

Model	Energy sales	Network length-Total	Consumer Density-line	Consumer Density-area	Cost per employee	Efficiency scores				
	GWh	km	Cons/ km	Cons/ sqkm	LKR'000	DL1	DL2	DL3	DL4	DL5
1	X				X	100.0	76.6	94.6	85.4	88.8
2	X		X			100.0	74.8	93.5	81.6	90.3
3	X			X		100.0	74.7	93.4	79.7	91.9
4	X	X				100.0	76.4	96.1	84	89.8
					Average	100.0	75.6	94.4	82.7	90.2
					Maximum	100.0	76.6	96.1	85.4	91.9
					Minimum	100.0	74.7	93.4	79.7	88.8

6. Implementation of PPI

PPIs were calculated for each DL by taking the OPEX and number of employees as inputs. Line lengths and number of substations were not taken into account, since those can be considered input or output either. On the other hand OPEX and number of employees can only be considered as inputs to the system while energy delivered to consumers, number of consumers can only be taken as outputs from the system. Table 7 depicts the results from PPIs.

Table 7: Efficiency scores from PPIs

Partial performance indicator		DL1	DL2	DL3	DL4	DL5
Energy sales/OPEX	kWh/LKR	0.763	0.592	0.703	0.594	0.773
No. of consumers/OPEX	Nos/LKR Mil	345	310	425	397	321
Energy sales/employee	MWh	976	760	740	625	816
No. of consumers/employee	Nos/LKR	442	398	447	417	338
Corresponding relative efficiencies						
Energy sales/OPEX	%	98.8	76.6	91.0	76.9	100.0
No. of consumers/OPEX	%	81.2	72.9	100.0	93.3	75.4
Energy sales/employee	%	100.0	77.8	75.8	64.0	83.6
No. of consumers/employee	%	98.7	88.9	100.0	93.2	75.6
Average	%	94.7	79.1	91.7	81.8	83.6

Efficiencies obtained by PPIs are not used to directly conclude the relative efficiency score of a particular DL but to qualitatively verify the results obtained from DEA and COLS.

7. Discussion

Robustness of the Results - The models selected must be robust to changes in techniques implemented. In particular, the ranking of firms, especially with respect to the 'best' and 'worst' performers, and the results must show reasonable stability and the different approaches should have comparable results. COLS and DEA are the main two different techniques used to measure the overall efficiency. Therefore robustness of the results obtained using those two techniques has to be analyzed. It can be seen from the table 8 that the results produced by DEA and COLS are robust for DL1, DL2, DL3 and DL4 as the differences are very low.

Table 8: Average efficiency scores

	Average efficiency score				
	DL1	DL2	DL3	DL4	DL5
DEA (3-variables)	99.7	77.1	94.6	82.9	100
COLS (3-variables)	100	75.6	94.4	82.7	90.2
Difference	-0.3	1.5	0.2	0.3	9.8

Ranking of DLs According to Overall Efficiency - Table 9 depicts the ranking of each DL according to each technique used and also verification by using PPIs. DL2 is lowest and DL4 is second lowest in each case. Average efficiency results shown in table 17 indicate that DL2 and DL4 are having efficiency scores of nearly 76% and 83% respectively, while all other DLs are having scores greater than 90%.

Table 9: Ranking of DLs

Ranking			
Rank	DEA	COLS	PPI
1	DL5	DL1	DL1
2	DL1	DL3	DL3
3	DL3	DL5	DL5
4	DL4	DL4	DL4
5	DL2	DL2	DL2

DL2 is the lowest performer while DL5, DL1, DL3 and DL4 are ranked highest to lower according to the average efficiency scores. Therefore it can be recommended that DL2 deserve closer supervision while DL4 also require close supervision of the electricity regulator (i.e. PUCSL) as they are under performing relative to other three DLs.

Influence on X- Factor -The regulator can decide on how to determine the X-factor, and the method of determining the X-factor may vary among the regulators (Jamasb et al, 2004; ACCC, 2012). For example X-factor can be calculated as (1-Efficiency Score). In such method and according to the average efficiency scores obtained under DEA 3-variable models, the X-factor of DL2 is (1-0.771) i.e., 0.229 as the average efficiency score of DL2 is 77.1% (refer table 8). While DL1, DL3, DL4, DL5 are having X- factors of 0.003, 0.054, 0.171 and 0.00 respectively. On another hand, if the regulator wants DL2 to catch up 20% of the frontier (100% efficient firm, i.e. DL5) over next year then it would be required to catch up, (1-0.771) x 0.2 = 0.0458. Thus the X-factor would be 0.0458 per year (Coelli and Lawrence, 2007).

8. Conclusion

The relative efficiencies of five Distribution Licensees operating in Sri Lanka were analyzed using prominent benchmarking techniques. Techniques like DEA, COLS and PPI method were utilized with several input output models in order to assess the efficiency in several angles. Care was taken to address the heterogeneity of the operating conditions such as consumer density, authorized area of operation of each DL which is out of the management control.

The efficiency scores obtained with respect to various possible models were scrutinized and came up with a suitable methodology to obtain efficiency scores considering the data availability and low number of distribution licensees. The proposed methodology use DEA with 3 input/ output variables and get the average efficiency scores as the final score. That is to have higher discrimination in the efficiency scores. In parallel these efficiency scores verified by the average results obtained by COLS method (3 variables including OPEX). Further, the ranking of Distribution Licensees are also verified with respect to DEA, COLS and PPIs.

Considering the fact that Sri Lanka is in its early stage in regulatory implementations, it is recommended to persuade underperforming DL. These efficiency scores would make a strong platform to the regulator when making the decision on X-factor in order to control the allowed revenue of Distribution Licensees.

References

ACCC/AER. 2012. Benchmarking Opex and Capex in Energy. Working Paper 6.

Chung, W. 2011. Review of building energy-use performance benchmarking methodologies. *Applied Energy, 88*(5): 1470-1479.

Coelli, T. and Lawrance, D.A. 2007. Performance Measurement and Regulation of Network Utilities.

Coelli, T. P. 2005. An Introduction to Efficiency and Productivity Analysis (2 ed.). Springer.

Farsi, M. F. 2007. Benchmarking and regulation in the electricity distribution sector .

Filippini, M. F. 2005. Benchmarking analysis in electricity distribution. CEPE Working Paper, CEPE ETH, Zurich.

Fillippini, M., Hrovatin, N.H. and Jelena, Z. 2002. Efficiency and Regulation of the Slovenian Electricity Distribution Companies. CEPE Working Paper No. 14.

Geoffrey Smith, B. W. 2004. Performance benchmarks for electricity distribution companies in South Asia. Concept Paper, USAID SARl/Energy Program.

GmbH, W. C. 2011. Cost Benchmarking in Energy Regulation in European Countries. Final report study for the Australian Energy Regulator.

Jamas, T. 2007. Incentive Regulation and Benchmarking of Electricity Distribution Networks: From Britain to Switzerland. Faculty of Economics, University of Cambridge.

Jamasb, T. 2000. Benchmarking and regulation: international electricity experience. *Utilities Policy,* 9(3): 107-130.

Jamasb, T., Nillsen, P. and Politt, M. 2004. Strategic behavior under regulatory benchmarking. *Energy Economics, 26*: 825-843.

PUCSL, 2011. Tariff Methodology, Distribution allowed revenue.

PUCSL, 2012. Electricity Distribution Performance Regulation – Final Draft.

Shuttleworth, G. 2005. Benchmarking of electricity networks: Practical problems with its use for regulation. *Utilities Policy. 13*: 310-317.

Talluri, S. 2000. Data envelopment analysis: Models and extensions.

Managing Lighting for Roads and Public Spaces in Sri Lanka

S. Jayasinghe*

Public Utilities Commission of Sri Lanka

Date Received: 27-06-2015 Date Accepted: 29-04-2015

1. Introduction

Lighting for Roads and Public Spaces consume 1.5% of total energy sold in distribution areas of Ceylon Electricity Board (Survey on Street Lighting, CEB, 2012) [†]. Why should it worry about 1.5% of consumption which seems an insignificant amount of energy? When energy conservation programs are implemented the rational consumers tend to ask a question of "while the street-light near to the house is lighting during the 'day time' why should curtail energy use during the "night time". Irrational use of lighting in roads and public places gives negative incentive on energy conservation.

Hence the objective of this paper is to propose a system to streamline the management of lighting for roads and public places. This paper proposes a community driven management solution. There are several state agencies that have empowered to perform different obligations in terms of lighting the roads and public spaces. Community empowerment on consumer bargain is an essential element to succeed the proposal. Ultimate objective and recommendation is to give a "voice to the citizen" "light to the darkness" and "specification to the lamp".

2. Methodology

The author examined the international best practices available in literature for providing lighting for roads and public spaces. The methodology implemented was that review the status-quo of the Sri Lankan practice in line with the international best practices. Recommendation dealt with replication of the best practices in Sri Lanka. Stakeholder interview conducted as facts finding measures and provisions in relevant legislation also referred to understand the status-quo of the problem. Street lighting Survey Date was available in region wise, however related other data such as locality, ownership and management of lamps were not available with the survey data.

3. Existing mechanism to manage road lighting in Sri Lanka

The guideline, circular No. PE 01/01, issued by the Ministry of Power and Energy (MOPE) is still enforced except the section on pricing of energy. The section 1.1 and 1.2 of the MPOE circular caped the energy uses for street lighting. Municipal and Urban Council areas (developed areas) total electricity consumed by the street lights installed should not exceed 2% of the total energy consumed at retail rates by Domestic and General Purpose Customers. In Pradeshiyasaba areas (rural areas) the cap limits to a 3% of the same. Though the correlation is obvious, existing mechanism does not provide sufficient incentives to introduce innovative management systems into the street lighting.

4. Challenges of providing lighting for roads and public spaces in Sri Lanka

- Provide the service in absent areas: According to the survey on Street lighting conducted by Ceylon Electricity Board (CEB) in year 2012 there are only 404,600 street lamps available in the entire country. According to the estimate there is 110,503 km (Kumarage A. 2012) distance of road which comprises of road manage by Road Development Authority (RDA), Provincial Road, Urban Access Roads (Street), Rural Access Roads, in the entire country. The simple calculation indicates only 4 road-lights available within a one kilometer of distance which is not sufficient.

* *Correspondence: shantha@pucsl.gov.lk*
ISSN 2478-0669 Print

- Specific standard for Lighting for Roads and Public Spaces: The Annex 1 attached to the MOPE circular on Street lighting (PE 01/01) provides general guideline. However, specific minimum values of luminance and illuminance[‡] to be
- determined before recommending the luminaries. The sub-optimal design may lead to either under lit streets, or over lit streets resulting in wasting energy.

- Legal Ambiguity: The provisions in Sustainable Energy Authority (SEA) Act enable Sri Lanka Sustainable Energy Authority to specify and enforce standards on Lighting for Roads and Public Spaces. However, local authorities also have the powers to make by-laws Lighting for Roads and Public Spaces. For example, according Section 157, Urban Councils Ordinance, the council has powers to make by-laws on 'cleaning, watering, and lighting of streets'.

- Political Influences: Local Authority members are of the view that, streetlight is one of the basic services that could be provided to the people under the purview of Local Authorities. There is, perhaps inevitably, a strong political influence on street lighting, because politicians who represent the local community are also live with the issues relating to the Street lighting.

- Cost Recovery: Lighting for Roads and Public Spaces has the basic features of a Public Goods[§]. Hence, there is no incentive for end consumers to make direct payments on usage. However there are provisions in local authorities to meet expenses from revenue of the Council by levying a special rate upon the area benefited by such service.

5. Proposal on management of lighting for roads and public spaces

Following are the key points in the proposal to streamline the management of Lighting for Roads and Public Spaces in Sri Lanka.

5.1 Standards on lighting for roads and public spaces

Under the Section 35 (2) (g), of SEA Act, the Authority has empowered to specify and enforce standards, norms, codes, measurement and verification protocols and building codes, for the efficient use of energy and for reduction of wastage of energy in buildings. Under the Section 36 (1) of SEA Act authority may from time to time by regulations made in that behalf, establish specific energy consumption benchmarks to be complied by all energy consumers. Standards for Lighting for Roads and Public Spaces also could be considered under the same provisions. SEA is fairly equipped in terms of powers and functions and technical capacity to deal with preparing standards on Lighting for Roads and Public Spaces.

Based on the research, certain standards have been developed in different parts of the world. Code of Practice for the design of road lighting, the Street lighting Standard Britain, BS 5489 and joint Australian/New Zealand Standard As/NZS 1158 could be considered as references for the design of Standard for Lighting for Roads and Public Spaces.

Table 1: Comparison between SEA and local authority to design and enforce standards.

SEA	Local Authorities
Central Authority	Devolved Authority
Technically equipped	Technically to be improved
Core function	Function among others
No access to Community	Access to Community through representatives
Strong in design	Strong in implementation.
Jurisdiction is all Island	Jurisdiction is limited to a particular geographical area
Professional environment in decision making	Political environment in decision making

Taking into account the pros and cons of SEA and Local Authorities the proposed mechanism to manage Lighting for Roads and Public Spaces is given in figure 1.

The "light" is the name given to electromagnetic radiation that can evoke a human visual response. In case of providing lighting the criteria measure the brightness of a surface (luminance) or the amount of light incident on an area (illuminance) are designed to match as nearly as possible the spectral response of the average human eye.

[§] In economics, a public good is a good that is both non-excludable and non-rivalrous: individuals cannot be effectively excluded from use and where use by one individual does not reduce availability to others.

5.2 Responsibilities

- Ministry of Power and Energy (MOPE)

  The responsibility of the Ministry of Power and Energy is to issue Government Policy directives with regard to providing Lighting for Roads and Public Spaces. The policy decisions should not be overlapped with technical criteria given in the ‘standard”. Policy deals with the direction that the lighting of Roads and Public spaces should move during a particular time period. However standards deals with how should it be implemented. Hence the scope of policy and standards should not overlap and extended to the boundaries of each other.
- Sustainable Energy Authority (SEA)

  SEA conducts basic research on lighting requirements in difference road categories. SEA prepares and issues the standard for Lighting Roads and Public Spaces. It is proposed to use AS/NZS 1158, BS 5489 as guidance for the preparation of standards. Awareness programmes for Area Engineers and Members of Local Authorities, technical Staff of Local Authorities and community in general to be conducted by the EA. Further, SEA should directly deal with approving the applications submitted by RDA and UDA.
- CEB and Lanka Electricity Company Ltd (LECO).

  Area Engineers of CEB and LECO requires approving the applications submitted by the Community with recommendations from local authorities whether it is in line with standards. Provide Technical Support to implement the approved lighting programs i.e. provide dedicated line, metering, billing etc. also vest with the Area Engineers of CEB and LECO. It is more appropriate of signing an agreement with the Local Authority identifying the responsibilities of CEB/LECO and Local Authority over installations, maintenance and cost sharing.

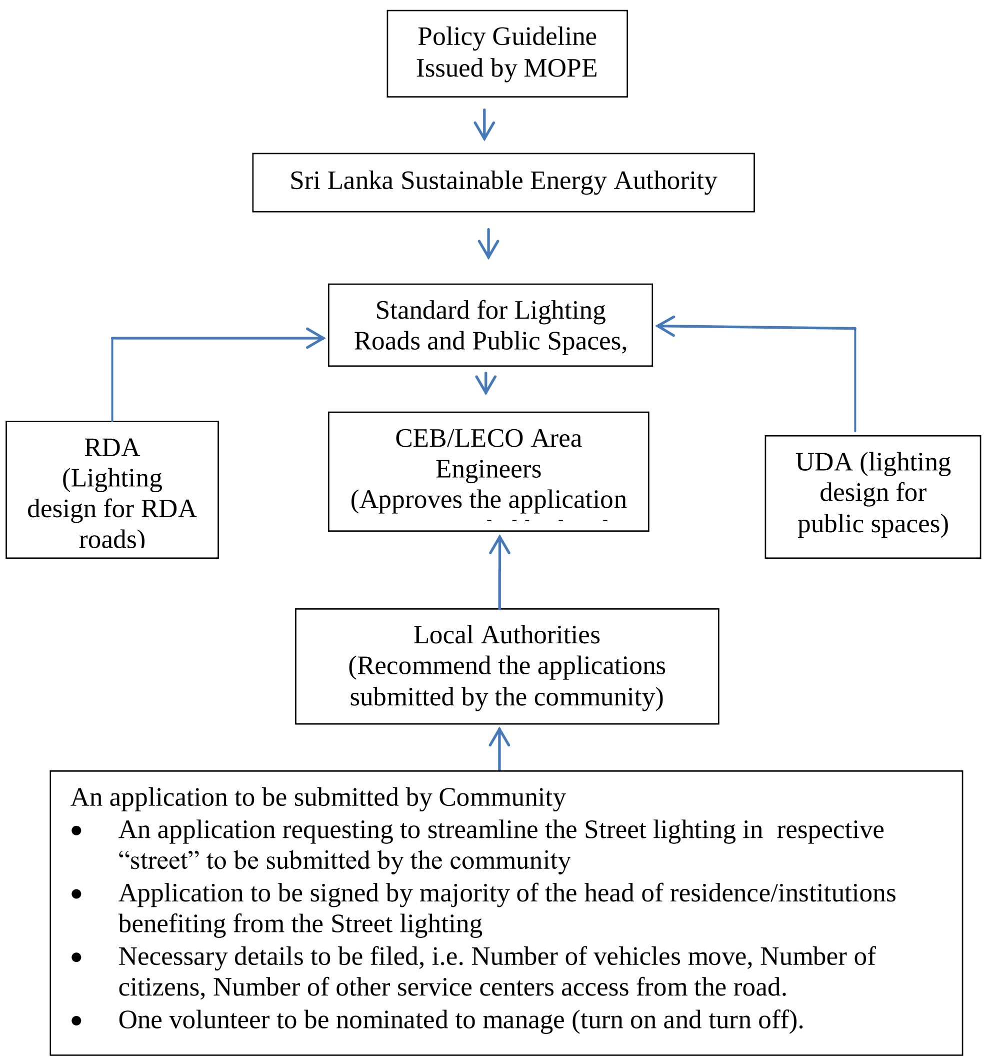


Figure 1: Proposal to streamline the management of lighting for roads and public spaces

- Local Authority
  The local authority requires implementing the standards issued by the SEA. Recommend the application submitted by the Community confirming that it is in line with the standards issued by the SEA. It is required to do a field visit to the particular road/street where the application is submitted. The appropriate Lamps, Luminaires: Bracket Arms and Poles are to be recommended by the local authority considering the provisions in the 'Standards" and cost of them. The cost of the equipment to be borne by the local authority. The settlement of any other expenses could be negotiated between the electricity service provider CEB/LECO and local authority and make provisions in the agreement.

- Community/ Community Base Organizations:
  Community empowerment to negotiate appropriate service delivery is the "silver lining" in the recommendation. In Sri Lanka local authority legislations includes provisions to recover the cost of utility services provided by them. All most all the cost of utility services is finally borne by the citizens who reside in the respective local authority area. Hence there is a direct responsibility between the citizens and the local authority in providing services and paying for such services. When there is a financial commitment there is a natural tendency to bargain for a better service. If there is mechanism to establish a contractual relationship between citizens and the local authority, a bargain process will eventually develop. Most important point here is to demarcate a small physical area where the focal point for such bargaining. 'Street' would be an area which citizen can organize and enter into the bargaining with the local authority. This mechanism should not be limited only for lighting of street, could be extended to bargain for other public goods such as defense, transport, water supply etc. A similar activity is conducting in other countries one of such program is in Seattle, where Seattle City Light is a publicly owned utility created by the citizens of Seattle in 1902.

- Cost of Services
  Energy used for lighting for Roads and Public spaces by Local Authorities, Urban Development Authority, and Road Development Authority to be measured and paid by the respective agencies. The Public Utilities Commission of Sri Lanka determines the tariffs applicable in this regard. Cost of maintaining the lamp, luminaries, lamp fixtures and voltage control system shall be borne by the Local Authority. The agreement between local authority and the area electricity service provider CEB/LECO shall address a mechanism to conduct the maintenance work.

6. Conclusion

It is required reaching consensus on proposed conceptual framework by all stakeholders and agreed to a framework which is the outcome of a consultation process. Preparation of standards by SEA in consultation with stakeholders, pilot project in a local authority area and fine-tune the conceptual framework if necessary are the subsequent actions. Capacity building at Lighting Center, Local Authorities, Area Engineers of CEB/LECO, also to be implemented. Finally inform the public through a properly design media campaign to send the message across the society.

References

A framework for producing a street lighting maintenance management plan. London's Transport Assets Management Board. British Standard: Code of Practice for the design of road lighting. BS 5489-1: 2013: http://shop.bsigroup.com/en/ProductDetail/?pid.

Dan SIMHAS, Claudiu POPOVICI, A Smart Grid Application: Street Lighting Management System U.P.B Sci. Bul. Series C. Vol. 75 iss. I http://www.scientificbulletin.upb.ro/rev_docs_arhiva/fullef2_736218.pdf.

Demand Side Management for Municipal Street Lighting, Asian Development Bank, Ministry of Power and Energy (TA No. 7267 Sri) Mid Term Report, Rev. 2, Feb. 25th 2010.

Energy Efficient Public Lighting Charges- Victoria Final Decision – Feb 2009. Australian Energy Regulator available at: http://www.aer.gov.au/sites/default/files/Final%20decision%20%20Energy%20efficient%20public%20lighting%20charges%20-%2027%20February%202009.pdf.

Estimates 2013, Ministry of Power and Energy Sri Lanka.

Guidelines Energy Efficient Street Lighting USAID/India.

Kumarage A. S. "Land Transport in Sri Lanka, University of Moratuwa, 04th January 2011.

Public Lighting Design Requirements Guidance Manual, Cork City Council. UK.

Report from the public lighting taskforce March 2009, Victorian Local Sustainability Accord. http://www.sustainability.mav.asn.au/content/upload/files/publications/FINAL_PUBLIC_LIGHTING_REPORT_29023.pdf.

Street Lighting Design Guide, 4th edition. Street Lighting Section. Hampshire County Council. Available at: http://www3.hants.gov.uk/street_lighting_design_guide__4th_edition_.pdf.

Standards, Lighting for Roads and Public Spaces Part 1.2: Vehicular Traffic (Category V) lighting – Guide to design, installation, operation and maintenance: Council of Standards Australian.

Standards for Integrated Street Lighting Project for Delhi, Delhi Transco Limited. Available at: http://www.delhitransco.gov.in/EnergyEfficiency/lighting%20standards_rev_1.pdf.

Interview Conducted, Deputy Director (Electrical Engineer) Colombo Municipal Council, Technical Officer, Kuliyapitiya Urban Council. Director, Lighting Center, Sustainable Energy Authority.

Policy Guideline for Energy Optimization during Planning and Design Stages of Water and Waste Water Pumping Systems in Sri Lanka

M. Abeyesekera*, B.G.A. Dinesh, L.K. Bogahapitiya

National Water Supply & Drainage Board, Galle Road, Ratmalana

Date Received: 27-06-2015 Date Accepted: 05-11-2015

1. Introduction

National Water Supply & Drainage Board (NWSDB) is acknowledged as the largest electricity consumer in Sri Lanka, consuming 237 million kWh annually. In the recent past, NWSDB was made aware of the possible energy wastages in the pumping systems due to recent legislations on energy efficiency and other related developments in the energy & environment areas. As a result NWSDB embarked on an energy efficiency improvement programme consisting of energy audits, taking remedial action when energy efficiencies were identified.

The results on the energy losses of the pumping systems were bordering on 30% level of the power consumption which the NWSDB was not aware of at all. Causes for the energy losses were unearthed after every energy audit, and main reason almost always was the mismatch of the pump/s with connected system thus causing the pump/s to operate at suboptimal efficiency levels. This invariably results in excessive energy consumption for pumping well over the bare minimum required.

Mismatch of pump/s was the result of many causes. One primary cause was the faulty design practices. On most cases, pumps had been selected causing excessive flows when operated on the system. In our systems variable speed drives or other similar means of flow controls for the motors are not employed commonly. Under the circumstances, O&M staff tends to throttle the pump delivery valves. Throttling of valves causes large power losses in our systems as our pumps are of substantial sizes, ranging from 1 kW to 850 kW.

Another common cause is the faulty design of parallel pumping systems. Acceptable parallel pumping systems squarely depend on the characteristics of the pumps as well as the characteristics of the system which is connected to the pumps. When designs are carried out without regard to these constraints, resulting system will be highly energy in efficient during operation.

Less commonly designers tend to employ variable speed drives in pumping systems in the belief that this automatically results in energy efficiency improvement. Rather employability again depends on the characteristics of the pump/s and the characteristics of the system which is connected to the pumps.

To the same degree, decisions made at the planning stage do much harm to the energy efficiency of the pumps during operation. Usually the larger the pump sizes the higher the achievable optimal operating efficiency of the pumps. Therefore, it should be the policy to supply the same water using largest possible pumps sizes rather than a number of smaller pumps. Employing smaller pumps adds the complication of the parallel pumping which again causes inefficient operation in the field. Planning decision to construct scattered pump houses in integrated systems also contributes to this situation. Therefore every effort must be made to reduce the number of pumping stations in order to employ large size pumps.

In the pumping systems audited, there are a large number of systems that generates unduly large friction heads due to the unduly small sizes of pipes designed. This cause cannot rectify in almost all operational pumping systems due to financial, social, etc. constraints. These are faulty design decisions having a great bearing on the energy wastages in the pumping systems requiring policy in the future.

In this guideline, NWSDB has formulated a screening procedure based on the energy efficiency of the system designed for construction and operation. Systems capable of complying with these guideline requirements will result in

* *Correspondence: nwsdblog@sltnet.lk*
ISSN 2478-0669 Print

systems with optimally energy efficiency with minimum wastage of energy. During the planning & design stage, planners and designers have to weigh in appropriate options of types, sizes, combinations etc. until they come up with an energy optimized solution.

2. Methodology

The methodology is based on comparison of the energy efficiency between different suitable options and reiteration with modified options and/or configurations until the most optimal energy efficient option is identified.
A typical water supply system could consist of;

- Water Intake Pump Station
- Water Treatment Plant
- High Lift Pump Station
- Transmission piping system
- Pressure Boost Pumping Stations
- Storage Towers and Ground Reservoirs
- Distribution Piping System

Therefore, all above systems should be optimized in combination during the planning and design stages.
For the energy efficiency optimization of the intake pumps, planning decisions include;

- Types of suitable intake options
- Number of intakes needed and their types
- Configurations of selected intake options
- Types, sizes and numbers of pumps for selected intake options.

(General criteria for the above are beyond the scope of this paper).
After finalizing the above options, data necessary for the selection of pump options are determined, as follows;

- How much water need to be pumped and how much can be conveyed by gravity requiring no energy
- Water source details
- Intake source water levels
- Source raw water quality

At the end of this stage, Energy efficiency optimized pump/s type is finalized.

Water Intake Pumps, High Lift Pumps, Pressure Boost Pumps are the heavy consumers of electrical power to the extent of more than 90% of the total consumed at a typical installation.
Transmission piping system, Distribution piping system, Tower/Ground reservoirs etc. are energy dissipaters.

Next the energy efficiency optimization step is carried out. This has to be done in combination with the connected system of the Intake water transmission pipe, because they interact with each other hydraulically.

A tentative transmission pipe is taken initially, emanating from the planning stage earlier. The following are the data needed for the initial analysis;

- Pipe type & material, Pipe size, pipe length.

A tentative pumps configuration is taken initially, emanating from the planning stage earlier. The following are the data needed for the initial analysis;

- Total number of pumps for the station (duty & standby), type of operation (single/parallel), maximum number of pumps run parallel.

The following analysis follows for optimal energy efficiency solution of the intake.
Friction head generated by the pipeline directly relates to the velocity in the pipeline, hence the velocity is calculated at all different pump running combinations. From this the head required by the piping system can be calculated.

From the below piping system, head and the planned flow capacity of few matching pumps in the market with the highest efficiency are selected. Using an average efficiency value from these specific energy consumption (SEC) is calculated.

This is the end of the initial analysis, which is followed by different options and iterations until optimal solution is reached.

Next a justification of the above SEC value is analyzed.

It is well known that the larger the pipe size the lesser the head required by the system hence requiring lower head pumps. The lesser head required, the lesser the SEC and the power required.

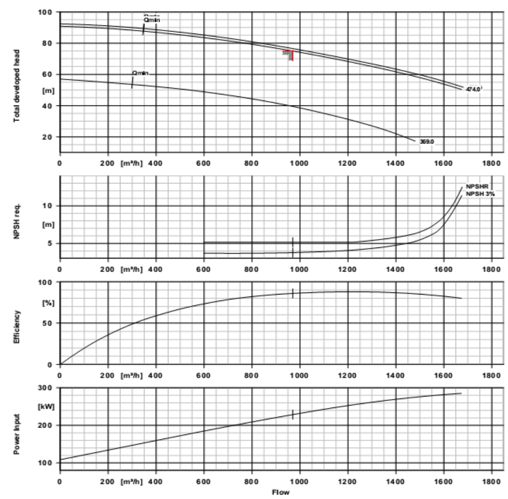


Figure 1: Typical pump characteristic curve

Therefore, the next larger size pipe is selected for this to find out the new energy requirement which is lower than that of the initial analysis.
Following data will be used in the analysis;

- Pipe type & material, Pipe size

In the analysis, total head required by the system with the larger pipe is calculated. This system will need a pump with a new different head value. An average high efficiency value is obtained using the data of compatible pumps from the market, as was done in the initial analysis.
This results in a new lower SEC value for the water pumped by the intake.

But we have to check the effect of the larger size of the pipe on the increase of the capital cost. This increase must be compared with the energy benefits of the change of pipe size.

Finally the economic analysis is done. Following factors consists of the factors determining this analysis.

Increase of capital cost due to increase of the pipe size, additional costs, if any, due to the change of pump to suit the larger pipes, Total additional cost resulting from first iteration, total energy saving savings attributable to the increase of pipe size and the same in monetary terms.

From these simple payback period of the additional cost is calculated compared to the energy savings. If this is acceptable the iteration will be the optimal solution at this stage. But the designers must carry out reasonable number iterations to narrow down the solution to the economically possible optimal energy efficient solution.

An exactly similar analysis is carried out for the high lift and booster pumps because the pump/system configuration is quite comparable. A major variation from the above configurations results when the pumps are decided to be run by Variable Speed Drives (VSD). This becomes necessary when the pressure and flow rate variations vary due to complicated distribution networks etc. There are two main typical cases of VSD applications for analysis for optimal energy efficiency.

- Variation of system head causing pump operating point to change
- Variation of system head and flow rate of systems directly connected to the pumps

In the analysis for the case 1, the following factors will be taken for the analysis,

- Head variation during operation, effect of the head variation on the maximum and minimum capacity of the pump/s, need for throttling to maintain flow variations.

If flow variations cannot be achieved without throttling the valves, then designers must decide to install VSD's. But this decision shall be subject to the validation of the system characteristics with the iso-efficiency curves of the pump. The check to be done is whether relevant head and flow rate operating points of the pump/s are falling between the iso-efficiency lines of the pump. If so, VSD will result in high efficiency at all operating points thus achieving optimal energy efficiency at all operating points.

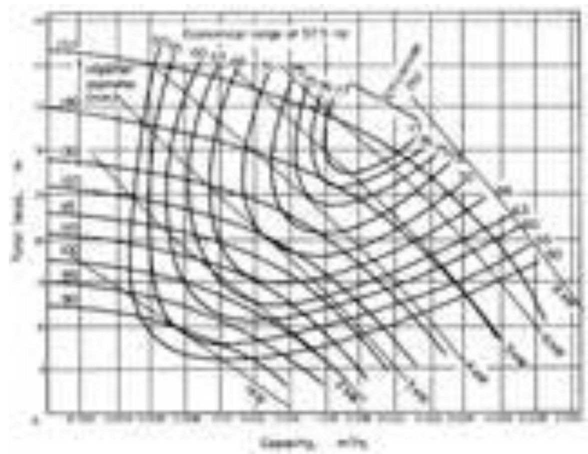


Figure 2: Typical Iso-efficiency curves of VSD operation

3. Discussion

The implementation of the guideline is still in the early stages and it has borne fruit by pushing the designers to screen for economically feasible energy optimization, which was absent earlier. Obviously, already a lot of potential energy losses have been averted at the design stage.

Designers have a precise tool which they can use with concrete quantitative data derived from calculations for the determination of the economically feasible optimal energy efficient solutions. When it is mandatory for the designers to go through all these technical and economic analyses before recommending pumping systems there is no room for energy inefficient pumping system designs to creep through.

Once energy inefficient systems are designed and built, it is impossible to effect the rectifications necessary for the eliminations of energy wastages. This involves replacement energy wasting small size pipes, complete changes to the pump configurations, layouts etc.

4. Conclusion

This guideline ensures to a great extent that pumping systems are built with energy wasting aspects greatly reduced with economically feasible and technologically updated solutions.

It is highly desirable to implement energy screening guidelines of this nature wherever energy consumption is involved. However, NWSDB is still in the early stages of implementation of this guideline and there may be refinements needed this guideline in the future. Also, this guideline needs to be expanded further with the addition of other factors and areas which may give rise to energy inefficiencies in left unchecked at various stages of the lifecycle.

References

Ebara Pump system Engineering Handbook: Ebara Corporation, 2001.
Garr M. Jones , PE : Pumping Station Design – Third Edition , 2006.
Hydraulic institute Standards for Centrifugal, rotary and reciprocating pumps: fourteenth edition –1983.
Igor J. Karassik , Joseph P. Messina , Paul Cooper , Charles C. Heald (2004) : Pump Hand Book Fourth Edition , 2008.
Pumping Station Engineering Handbook: Japan Association of Agricultural Engineering Enterprises Tokyo , 1991.

Biomethane as Fuel for the Transport Sector in Sri Lanka

P.G. Joseph[1*], P.G. Ratnasiri[2]

[1]*Sri Lanka Carbon Fund*
[2]*Department of Chemical & Process Engineering, University of Moratuwa*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

This concept paper investigates the feasibility of introducing biomethane as a transport fuel in SriLanka. There is an urgent need for introducing renewable fuel sources to ensure energy security, to conserve foreign exchange, to reduce carbon emissions, to mitigate climate change and to improve air quality as well. Anaerobic digestion (AD) has been widely accepted as a sustainable technology due to benefits such as waste management, low GHG emissions and renewable energy production. Current utilization pattern of petroleum fuel in the transport sector is first analysed. Due to availability of varieties of biodegradable organic materials, AD is identified as the best option for bioenergy production for this sector. Results from Pilot scale AD plant and its application to a motor vehicle developed at University of Moratuwa are presented. Several test runs were conducted using purified compressed biomethane and confirmed the applicability to three wheelers as an alternative fuel. Emission test further confirmed the quality of combustion products. It is proposed to establish large scale AD plants to generate biomethane with required quantity and quality and also develop infrastructure facilities needed with the view of introducing this technology to buses used the transport sector.

Keywords: transport fuel, pilot plant, biomethane, GHG emission

1. Introduction

The transport sector in Sri Lanka consumes around 29% of the total national energy consumption in the year 2013. This trend has been on the increase as shown in Figure 1 below. 100% of the transport sector demands are met by petroleum products. Foreign exchange spent on the import of petroleum fuels has been imparting severe strain on the national economy. In the year 2010, the foreign exchange bill on fuel for the transport sector has been over US$ 2 billion (Guneruwan, 2014).

The energy demand for the transport sector for the future years, as predicted by Janaka Ratnasiri (2014) is given in Figure 2 below.

From the point of view of national energy security, these alternatives need to be indigenous in nature. Moreover, the technology of adopting it in Sri Lanka should not adversely affect the local environment. As Sri Lanka is moving towards a low carbon economy, these technologies should not emit Greenhouse gases. As resources such as land, water etc are very limited in the country, the use of these resources for the utilization of these technologies should not be very minimum.

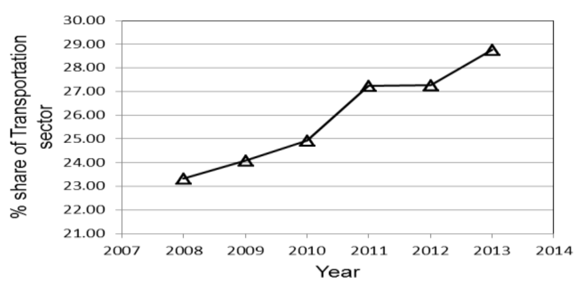


Figure 1: Share of energy consumed in the transport sector expressed as % of total energy consumption (Sri Lanka Sustainable Energy Authority, Energy Balance 2013)

[*] *Correspondence:pgjoseph@gmail.com*
ISSN 2478-0669 Print

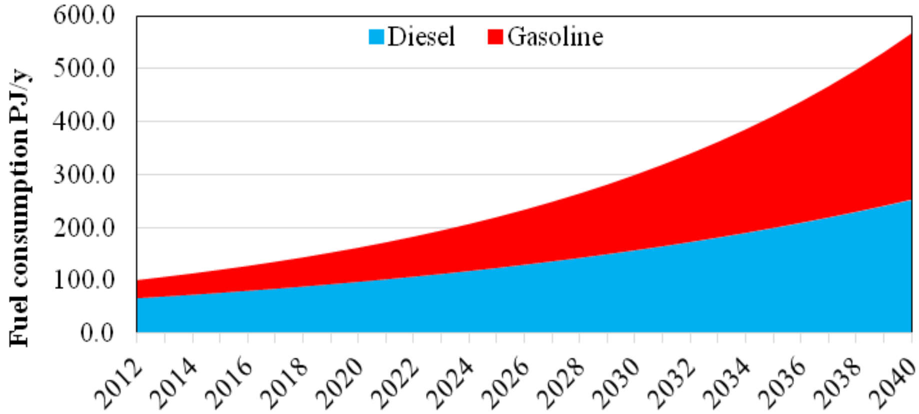


Figure 2: Forecasted growth of fuel consumption in the transport sector
(Natural Gas-New Energy Resource: Janaka Ratnasiri, 2014)

2. Vehicle types and share of load

Figure 3 below shows the share and the numbers of different types of vehicles used in the passenger transport sector.

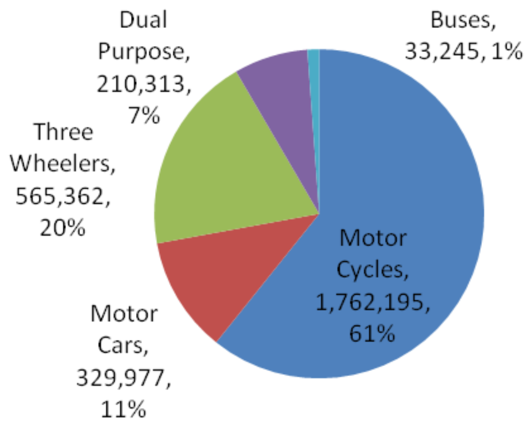


Figure 3: Numbers and % share of Vehicle Types Used for passenger transport
(Sugathapala (2013), Sri Lanka Sustainable Energy Authority)

Figure 4 below shows the share of passenger kilometres handled by the different types vehicle in Sri Lanka.

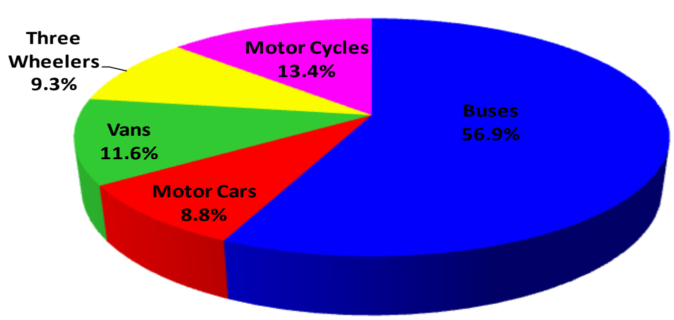


Figure 4: Share of passenger kilometers covered by vehicle types.
(Sugathapala, (2013))

An examination of Figures 3 and 4 above clearly shows that busses accounting for a mere 1% of the total number of vehicles in our roads, account for over 50% of the passenger kilometres covered. Moreover, Table 1 below gives the energy intensity of some of the vehicle types used in Sri Lanka.

Table 1: Fuel consumption according vehicle types (Diandas, 1999).

Vehicle Type	Passenger Miles/Gallon of Fuel
Bus	403
Train	357
Car	42
Motor Cycle	200

Figures 3, 4 and Table 1 above show that, when finding an alternative fuel for our transport sector, priority should be given to busses and trains.

3. Present approach

At present the only serious proposal submitted so far to meet the energy needs of the transport sector is electrification of railways, introduction of electric cars and busses. According to the Long Term Generation Expansion Plan (LTGEP) prepared by the Ceylon Electricity Board, the bulk of the future power plants will utilize coal as the fuel. According to this expansion plant nearly 300 MW of coal power plants will be added annually to the grid for the rest of the foreseeable future. A summary of the LTGEP is given in Table 2 below.

Table 2: Long term generation expansion plan (LTGEP) by CEB

Capacity (MW)	Plant type	Year
1x75	Gas Turbine	2015
1x105	Gas Turbine	2015
1x105	Gas Turbine	2017
3x250	Trinco Coal	2018
1x27	Moragolla HPP	2018
1x250	Trinco coal	2019
1x300	Coal	2020
1x300	Coal	2021
1x300	Coal	2022
1x300	Coal	2023
1x300	Coal	2024
1x300	Coal	2025

Utilizing electricity generated mostly from coal based power plants for transport application would not address any of the adverse impacts mentioned earlier. In fact coal is a much dirtier fuel than petrol or diesel. As we do not have indigenous coal, we need to import all our requirements. By switching from petrol or diesel to coal based electricity would result in shifting the pollution from our urban areas to the rural areas where coal power plants are going to be located. Although renewable resources such as wind and solar could be used to generate electricity, the LTGEP has provision to absorb only 12% of the total generation from such new renewable energy sources.

The use of off-grid or net metering based solar PV technology to charge electric vehicles needs careful study as these systems are manufactured in foreign countries, large scale adaptation of this technology is bound to increase the strain on foreign exchange reserves.

An attempt is being made to popularize the use of hybrid vehicles in Sri Lanka. In the short term the introduction of hybrid vehicles have reduced the consumption of fuel almost by halve. But life-cycle cost-benefit analysis should be carefully carried prior to large scale introduction.

4. A novel proposal

The agricultural, industrial and household sectors in Sri Lanka annually generate 12 million tonnes of easily biodegradable materials such as leaves of trees, liquid effluents, food wastes, vegetable market garbage etc. Presently a small portion of this is collected as part of Municipal Solid Waste (MSW). The major part is either heaped and combusted or simply allowed to decay or gets washed away with rain water finally into the sea. If these materials are digested in anaerobic digesters, we could annually generate the equivalent of 3 million tonne oil equivalent of methane gas. This is more than the present annual oil consumption of 2.5 million tonne oil equivalent of oil used in the transport sector.

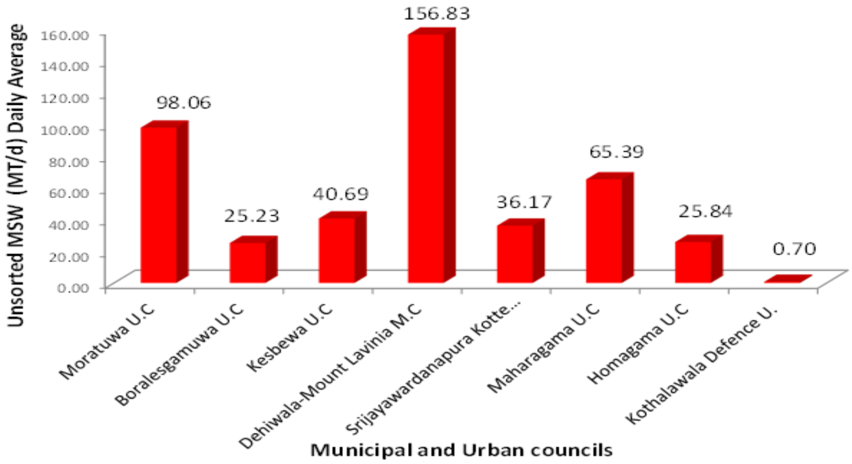


Figure 5: Daily MSW generated from municipalities and urban councils
(Feasibility report: Rathnasiri and Charith 2014)

Generation and open dumping of MSW are happening at an alarming rate and data from few municipalities are shown in Figure 5. By suitably segregating the organic fraction of these MSW, preferably at source, it can be anaerobically digested and produce biomethane required for transportation activities.

5. Present status

5.1 Pilot scale studies and biomethane as a transport fuel for three wheelers

To investigate the feasibility of utilizing purified compressed biomethane firstly in three wheelers, Ministry of Science and Technology funded a project in 2007 and implementation agency was Department of Chemical & Process Engineering, University of Moratuwa. The main objective of this project was to find feasibility of using upgraded bio-gas as a transport fuel. Construction of pilot plant was completed in the middle of 2009. Thereafter commissioning and operational activities of the pilot plant (Figure 6) were started. In this project, anaerobic co-digestion technology was conducted using canteen food waste as the main substrate and co substrates were Gliricidia leaves, water hyacinth and straw. Before start up, series of lab scale experiments were conducted and according to these experiments, it was found that the highest cumulative biogas production was observed when Gliricedia was used as co substrate. Total COD removal efficiency was between 61- 79%. The gas volume and rate increased with the increase of glirecidia composition in the feed mixture.

Figure 6: Picture of the pilot plant developed at Department of Chemical and Process Engineering, University of Moratuwa. Reactor system (left), feed pretreatment (right)

In this process, firstly, source separated organic fraction of canteen food waste from canteen waste were crushed in a crusher and mixed with co-substrate in the presence of water. Feed slurry is then prepared according to the required solid content. Then it is pumped into continuously stirred tank reactor (CSTR) which is operating under anaerobic conditions. Biogas is produced in this reactor and effluent removed from reactor is used as an organic fertilizer. Biogas Produced was upgraded into Synthetic Natural Gas (SNG) by removing CO_2 through a scrubbing process and subsequently removing the moisture. The upgraded Synthetic Natural Gas (SNG) was compressed into cylinders and used as a transport fuel.

Figure 7: Conducting test runs using compressed biomethane

Test runs were conducted using purified compressed biogas and results obtained are shown in Table 3.

Table 3: Test runs conducted using biogas produced from pilot plant

Name of test run	Date	Remarks
Run 1	19th Nov 2009	Ignited from biogas (60% CH_4)
Run 2	23nd Dec 2009	Continuously run 2.6 km without stopping
Run3	14th July 2010	5.3 km 320 liter upgraded biogas (85% CH_4)
		16.5 km from 1m3 of (85% CH_4)
Run 4	3rd and 4th March 2011	20 km from 1m3 of biogas (85% CH_4)

In order to investigate the composition of the emission, test was conducted and given in Table 4.

Table 4: Emission test results from biogas operated three wheeler.

Items	Limits	Biogas		Petrol
		High Idle	Low Idle	
HC PPM vol	9000	756	1621	137
CO % Vol	6	0.215	0.102	0.54
CO_2 % vol		9.44	8.010	14.5
O_2 % vol		7.32	9.06	0.83
Lambda		1.488	1.678	NA
RPM		2523	1025	NA

Emission test data reveals that quality of combustion products is competitive with petrol.

6. International experience

According to Natural Gas Vehicle Association (NGVA) Europe, About 60% of the gas used in Sweden's 38,500 natural gas vehicles is Renewable Natural Gas (RNG). RNG is an an alternative name given to biomethane. In Germany, 25% of the public compressed natural gas stations dispense 100% RNG (U S Dept of Energy : Alternative fuel data center).

Sweden has a fleet with 36,520 light duty vehicles, 1,530 buses and 550 heavy duty trucks. At the end of year 2011 there were over 130 public filling stations. This was accomplished by establishing decentralized plants for the production of biomethane which accounts for over 60 % of the total methane used in Swedish NGVs. There is currently only one standard adopted within an EU member state for the use of Biogas as a transport fuel. Sweden has a published standard - SS 15 54 38 : “Motor fuels – Biogas as fuel for high-speed otto engines”. The standard deals with specific characteristics relevant to the use and storage of biogas produced by anaerobic digestion for use as a motor fuel (NSCA, 2006).

The energy content of biogas is dependent on its methane composition. The energy content for biogas with a methane content of 65 %, and for when it is upgraded to 97 % methane are given in Table.(Wladysaw, 2011).

Table 5: Energy content of biogas and other fuels

Fuel	Energy content (kWh)
1 Nm^3 biogas (65% methane)	6.5
1 Nm^3 biogas (65% methane)	9.7
1 litre petrol	9.1
1 litre diesel	9.8

7. Conclusion

It is proposed to segregate the easily biodegradable materials such as leaves of trees, food wastes, and vegetable market garbage etc. from other wastes and transport to suitable locations. At these locations, anaerobic digesters are constructed to digest these materials generating biogas consisting of approximately 65% methane and 35% carbon dioxide and other trace gases. Carbon dioxide and other trace gases are removed by scrubbing with water under a pressure of about 5 bar. Water used for scrubbing could be recycled. The scrubbed gas consisting of methane – known as bio-methane, can be compressed to a pressure of about 200 bar into steel cylinders as Compressed Natural Gas (CNG). Petrol and diesel operated land vehicles could be converted to operate on CNG.

At this stage, we are not in a position to give accurate values of the costs and benefits of this proposal. However, as most of the processing activities are carried out with in the country, this proposal merits consideration from the point of view of energy security and foreign exchange savings.

References

Biogas as a road transport fuel. An assessment of the potential role of biogas as a renewable transport fuel, National Society for Clean Air and Environmental Protection, England. 2006.

Biomethane as a transport fuel, Project completion report. University of Moratuwa, 2011.

Diandas, J. 1989. *SLEMA Journal*, Vol 3, No. 1&2.

Gunaruwan, T.L. 2014. Energy and Environment: Transport Policy Perspectives.

Jayaweera, D. S. 2008. Energy efficiency in the transport sector in Sri Lanka, , Economic Review.pp:38-42.

Natural Gas vehicle Association (NGVA), Europe, http://www.ngvaeurope.eu/

Rathnasiri P.G. and Abeywarna, C. Feasibility Report on Proposed Large Scale Anaerobic Digestion Plant to Treat MSW Collected at Karadiyana Open Dump Site, 2014.

Sri Lanka Energy balance, An analysis of energy sector performance. Sustainable energy authority, Sri Lanka, 2013.

Sugathapala, A.G.T. 2013. Current Status and Issues of Sustainable Energy Domain in Sri Lanka.

Wladysaw, P. 2011. Biogas as vehicle fuel, *Journal of KONES Powertrain and Transport*. 18(1).

Energy Potential of Municipal Solid Waste (MSW) and Sewer Generated within Colombo Municipality

P.G. Rathnasiri[1], M. Rajaratne[2*]

[1]Department of Chemical and Process Engineering, University of Moratuwa
[2]Triple A Management Consortium Pvt Ltd, Nedimala Dehiwela

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

The objective of this study is to quantify the energy potential of Municipal Solid Waste (MSW) and Sewer generated within Colombo municipality and by applying sustainable waste management techniques. Anaerobic digestion process is considered due to its ability of handling high organic loading rates and low sludge production, and its potential for production of energy by generating methane. Engineered Landfill Bioreactor is found to be the best option for treatment of MSW. The "First Order Decay Model" is identified as the model for prediction of methane from MSW in landfills. Chemical composition of MSW is determined by applying an ultimate analysis and using a stoichiometric based approach. Anaerobic co-digestion of sewer and organic fraction of MSW (OFMSW) is conducted using CSTR. The "Anaerobic Digestion Model No.1" is applied for prediction of methane from sewer and OFMSW. Input parameters are determined based on information collected and standard kinetic parameters are used in the model. The study determines the energy potential of MSW collected in the Colombo City is nearly 7.03 x 10^4 GJ per annum and that from anaerobic co-digestion of sewer and food substrates around 3.04 x 10^5 GJ per annum. If parameters could be determined for the wastes generated locally the accuracy of the methane generation potential could be further enhanced.

Keywords: anaerobic co-digestion, landfilling, ADM1, energy potential

1. Introduction

This study is confined to the Municipal Solid Waste and Sewer Wastewater generated within the Colombo municipal limits.

The objective is to characterize the waste generated within the Colombo Municipal Limits. Secondly to develop an appropriate bioconversion process to generate energy. Finally to estimate energy generation of the processes identified.

According to the survey on Solid Waste Management in the city of Colombo, the per capita waste generation in Colombo is 85 kg per day in 1998 (Asian Productivity Organisation, 2007). CMC collects 700 tons/day of MSW (Premachandra, 2006).

A report by UNEP (2001) estimates that each day in the Colombo Metropolitan Region, 428 MT of sewage are released into the ground through septic tanks and pit latrines and 138 MT of sewage are released to the waterways. (Sudasinghe, Galagedera and Gunewardena, 2011)

2. Materials and Methods

2.1 Properties of MSW

The organic matter in the waste generated in Colombo is 85% as shown above. The moisture content of the MSW too is relatively high and as a result the calorific value becomes low. (Asian Productivity Organisation, 2007).

The results of a more recent study on the MSW carried out on six different local bodies by the Waste Management Authority of Western Province (appendix A) gives more accurate and detailed analysis of MSW in the western province.

* *Correspondence: wmahesr@sltnet.lk*
ISSN 2478-0669 Print

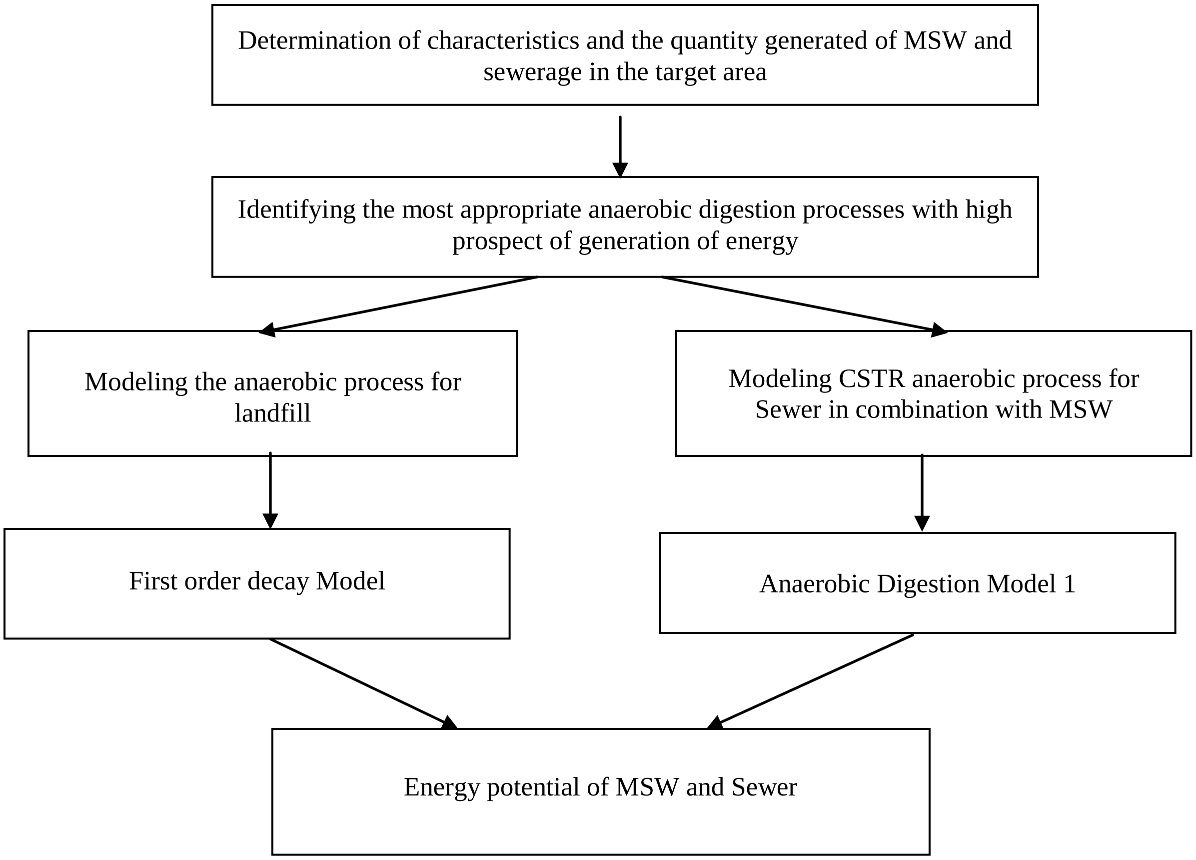


Figure 1: Proposed methodology

2.2 Properties of Sewer

According to ADB Technical Assistance Consultant's report (Lanka Hydraulic Institute Ltd, 2009), new pumping station has been operated since December 2007 at Madampitiya for Mutwal outfall. (Lanka Hydraulic Institute Ltd, 2009).

There are two sewerage systems complete with treatment plants; JaEla/Ekala scheme and the Moratuwa/Ratmalana scheme. The Feasibility study report for the Moratuwa/Ratmalana scheme (Sri Lanka Consultancy Engineering Sciences Inc, 1981) gives two options of collecting and disposal of waste water. This paper considers parameters of option 1 related wastewater.

3. Bioconversion of waste

Aerobic digestion activates on availability of dissolved oxygen. The main products are carbon dioxide, water, nitrates, sulphate and biomass. Anaerobic process initially, a group of microorganisms converts organic material to a form that a second group of organisms utilizes to produce organic acids (The Encyclopedia of Alternate Energy). The main products of anaerobic process are biogas, sludge and water. Due to its propensity to generate energy producing biogas anaerobic digestion process is preferred.

3.1 Sustainable anaerobic waste management technologies

3.1.1 MSW

The normal method of disposal of MSW is to use it for landfill. The bioreactor technology has evolved from relatively smaller Biocells to Landfill Bioreactors and to the more advanced Anaerobic Bioreactor Controlled Landfill.

The primary function of the bioreactor landfill is to accelerate the degradation of MSW by liquid recirculation.

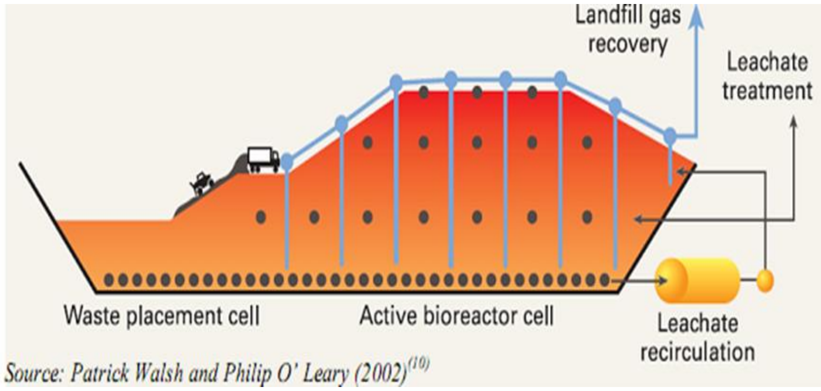


Figure 2: Anaerobic bioreactor controlled landfill

The composition of waste is one of the main factors influencing both the amount and the extent of CH_4 production within Solid Waste Disposal sites. (Reinhart, 2010). Moisture promotes bacterial growth and metabolism, as well as for transport of nutrients within the Solid Waste Disposal Site (SWDS). Landfill temperatures are generally between 25-40 $^{\circ}$C which is in the Mesophilic range.

3.1.2 Sewer

For low solids slurries, continuous flow reactors CSTR where the feedstock is continuously charged and discharged is used. (Verma, 2002). The high water content and the low solid content of sewer suits this type of reactor and the digest process perfectly.

According to IPCC reference manual (IPCC, 1966), handling of wastewater and its residual solids by-product (sludge) under anaerobic conditions results in CH_4 production. The extent of CH_4 production depends primarily on the amount of degradable organic material, a temperature higher than 15 $^{\circ}$C, retention time.

Co-digestion of organic wastes simultaneous treatment of several solid and liquid organic wastes together which improves methane yield because of the supply of additional nutrients. Anaerobic co-digestion of source separated organic fraction MSW was optimized with many other substrates (Neves , Ribeiro, Oliveira, and Alves, 2004); bio solids (Zhang, et al., 2007) with sewerage sludge etc. Some of the most popular co-digestion treatment are combining the organic fraction of the municipal solid wastes (OFMSW) and agriculture residues, organic solid wastes with sewage sludge or more specific wastes (Fernandez, Font, and Sanchez, 2005).

4. AD modelling for landfilling

4.1 First Order Decay Model

The IPCC (1966) defines a first order decay model be used to model the rate of CH_4 generation over time.

$$Q_{TX} = k\, L_0\, R_x\, e^{-k(T-x)} \qquad 1$$

Where;

Q_{TX}	=	The amount of methane generated in current year T by the waste R_x (m^3/yr)
L_0	=	methane generation potential (m^3/Mg of refuse)
R_x	=	the amount of waste disposed in year x (Mg)
k	=	methane generation rate constant (1/yr)
T	=	current year
x	=	year of waste input

4.1.1 Parameters for first order decay model

The methane generation potential (L_0) represents the potential of a waste stream to generate a specific amount of methane per unit mass. Consequently, it is mainly a function of the waste composition.

Other important information required for computation of the chemical formula of waste are the Ultimate Analysis of the waste, the biodegradable fractions of various components of MSW and the moisture content of each components of MSW. Typical ultimate analysis data obtained from literature is used.

According to computations neglecting sulphur which is negligible and rounding off to the nearest integer, the molecular formula of MSW generated within the Colombo Municipal Council is $C_{21}H_{31}O_{12}N$.

4.1.2 Methane Generation Potential - L_0

Buswell gives the stoichiometric equation of conversion of organic matter to methane and carbon dioxide elemental composition of waste as shown in equation below. At standard temperature and pressure gas will occupy 22.4 m^3 per kilo mole. Therefore with the identification of the molecular formula of the MSW, L_0 is determined.

$$C_aH_bO_CN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \Rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \quad (2)$$

4.1.3 Gas generation rate constant k

The gas generation rate (k) is a value that ultimately defines the time span of methane generation from a waste stream under specific site conditions. The suggested default value by US EPA is 0.04 yr^{-1} for areas receiving 63.5 cm (25 inches) or more of rain per year. (US EPA AP-42, 1997; US EPA, 2008a) (Reinhart, 2010) The rainfall in Colombo exceeds 65 cm per year, and suggested value for k, 0.04 yr^{-1}.

4.2 Anaerobic digestion modelling for sewer and MSW

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Under the same conditions, wastewater with higher COD, or BOD, concentrations will generally yield more CH_4.

ADM1 built in Aquasim 2.1f simulator is used for modeling and simulation of combined waste stream. Sewage by itself does not have the highest potential for anaerobic digestion. Therefore, Co-digestion with two or more types of feedstock is used to increase the biogas yield.

4.2.1 Characteristics of food waste and sewer

The AQUASIM 2.1f is used to estimate the methane potential of sewer together with food waste. It is assumed that HRT is 20 days and headspace of the reactor is 10% of total reactor size. The sewer is continuously fed to the reactor while food waste is fed intermittently. Six scenarios are considered and in each scenario food waste input are varied from 0 to 50 ton but sewer input is kept as constant.

Table 1: Input data of sewer and food waste characteristic

Type of Input Waste	Sewer – kg COD/ m^3			Food Waste – kg COD/ m^3			Q_sewer - m^3 /day	HRT - days
	X carb	X pr	X lip	X carb	X pr	X lip		
Value	0.1365	0.1713	0.2946	104.95	41.58	20	23,884	20

5 Results and Discussion

5.1 Methane generation from MSW

It is assumed that the landfill is closed after five years of opening. The estimated methane yield for twenty years is given in Fig 3 below. L_0 = 93 m^3/Mg of MSW, k = 0.04/yr. The daily MSW generation within Colombo City 700 Mt per day 340 days of the year. Therefore R_x = 238,000 Mg per year.

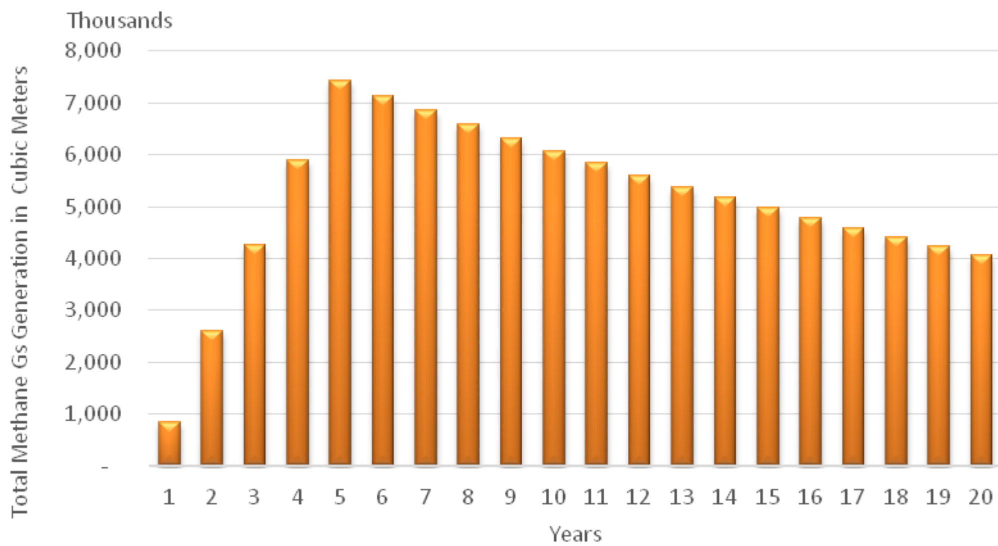


Figure 3: Total methane generation from MSW using computed average L_0

From the computations, maximum generation of methane occurs at the end of fifth year the period where the landfill is kept open. The generation peaks at approximately 3.93 m^3 at the end of year 5.

5.2 Methane generation from co-digesting of sewer and food waste

The methane generation potential of sewer, alone or co-digested with food waste, is modeled using ADM1 built in AQUASIM 2.1f.

Biogas production is modeled by using AQUASIM 2.1f for six different set of input feeding scenarios. The sewer input of all scenarios was kept as a constant and amount of food waste was changed. The reactor sizes were designed under each scenario based on Hydraulic Retention Time (HRT) of 20 days. Headspace was taken as 10% of reactor volume. Reactor sizes, food waste and sewer input flow data and input data of carbohydrates, protein and lipid of both sewer and food waste are given in Appendix E.

It was observed that the total gas production rate is higher when increasing amount of food waste in the feed stream. Scenario 06, where the addition of food waste is highest, gives the highest gas production. The total gas production within the first 10 days of scenario 06 is approximately $3.25x10^5$ m^3 and scenario 01 $2.5x10^5$ m^3 the others varying between these two scenarios.

It is observed that the highest volume of methane is produced from protein, followed by fats and the lowest from carbohydrates. Therefore if protein and lipid (fat) is higher in the sample of a substrate more methane can be generated.

Table 2: Comparative methane yields of Scenario 01 and Scenario 06

Period (Days)	CH_4 Gas production - m3	
	Scenario 01	Scenario 06
First 10 Days	259,000	307,000
Next 30 Days	139,000	292,000
Total for 40 Days	398,000	599,000

Total methane production of scenario 06 for 40 days is 599,000 m^3 and annual methane production is 4.49 x 10^6 m^3. In the alternative if every 10 days the reactor is reactivated with a fresh load the annual methane yield per annum is 9.2 x 10^6 m^3. This is twice more than the methane production of a single plant operating on a 40 day reactivation cycle.

6. Conclusion

This study identified disposal of the MSW in a landfill bioreactor and co-digestion of sewer with food waste in CSTR as the appropriate bioconversion process that gives energy producing Methane. For MSW it appears a 10 year life cycle could optimize methane generation. Similarly for sewer/wastewater the optimum point appears to be 10 days. The

ADM1 model for co-digestion of sewer and food waste predicts 9.2 x 10^6 m^3 of methane generation per annum on a 10 day reactor reactivation cycle.

The First Order Decay model for MSW predicts 21.3 x 10^6 m^3 per annum after ten years in a ten year reactor reactivation cycle. Considering an average methane generation from MSW approximately 2.13 x 10^6 m^3 per year, combining with the methane generation from the co-digestion of sewer and food waste the total methane generation for a year would be 1.13x 10^7 m^3. With higher heating values of methane and diesel fuel as 37.78 MJ/m3.and 36 MJ/l respectively, the total energy content of the predicted methane generation will be equivalent to 1.154 x 10^7 liters of diesel fuel. At 0.75 US$ per liter of diesel the value of methane is equivalent to US$ 8.65 M. If the actual methane generation is even 50% of the estimated capacity the equivalent saving in diesel is appreciable.

The actual methane yield may differ since the predictions were based on models. Further it assumes that the quantities and the composition remains consistent throughout and the generation of methane occurs at precise intervals.

The total volume of waste for 5 years at 700 tons per day will amount to 2.56 x 10^6 m^3. Assuming a total height of 20 m the footprint of the landfill will be approximately 1.28 x 10^5 m^2 which is 12.8 hectares or a land area of approximately 250 m x 510 m.

The CSTR reactor for the cogeneration of sewer with food waste will occupy a volume of in excess of 30,000 m^3. If a 20 m high reactor is considered the foot print of the reactor will be 1,500 m^2.

6.1 Future Studies and Recommendations

A study has to be undertaken to obtain the methane generation potential L_0 and the methane generation rate k for the MSW generated locally. Further economical sizing of the reactors needed and the economic viability of methane gas collection, storing, distribution and usage should also be studied

Appendix A

MSW Composotions in a Sample of Local Authorities within Wester Province (Source Waste Management Authority, Western Province September 2010)

Category	Municipal Council 1	Municipal Council 2	Urban Council 1	Urban Council 2	Pradeshiya Saba 1	Pradeshiya Saba 2
	Average %	Average %	Average %	Average %	Average %	Average %
Easily Bio degradable	39.62	28.23	71.19	59.89	74.11	52.93
Long term Biodegradable	35.22	55.63	7.74	18.93	13.10	19.12
News Paper	7.97	2.76	2.60	5.14	2.17	5.85
Cardboards	3.23	1.41	0.00	1.06	0.00	1.54
Cotton	2.79	1.26	1.84	3.42	1.75	0.29
plastic	1.09	1.14	2.93	0.82	3.46	0.67
Polythene	5.16	7.14	9.04	7.76	5.14	17.55
PVC	0.92	0.02	0.00	0.00	0.00	0.00
Rubber	0.04	0.43	0.00	0.00	0.00	0.00
Construction Demolitions	1.30	0.14	0.69	0.77	0.18	0.69
Glass	1.36	0.57	2.30	0.73	0.00	1.17
Nylon	0.90	0.41	1.68	1.39	0.09	0.19
E Waste	0.02	0.32	0.00	0.00	0.00	0.00
Clinical Waste	0.06	0.08	0.00	0.09	0.00	0.00
Others	0.30	0.46	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00
Average Moister content of the above waste 40% - 45%						

Appendix B

Methane generation estimation using the First Order Model

Daily MSw input Mt	700	No of years open	5
No of days per year	340	L_0	93
MSW input per year R_x	238000	k	0.04

$$Q_{T,x} = k\, L_0\, R_x e^{-k(T-x)}$$

Year	$e^{-k(T-x)}$	Methane Gas generated m^3 from Waste collected respective years					Total Methane
		Year 1	Year 2	Year 3	Year 4	Year 5	
1	0.96078	850,636					850,636
2	0.92311	817,285	850,636				1,667,921
3	0.88692	785,243	817,285	850,636			2,453,164
4	0.85214	754,451	785,243	817,285	850,636		3,207,615
5	0.81873	724,871	754,451	785,243	817,285	850,636	3,932,486
6	0.78662	696,442	724,871	754,451	785,243	817,285	3,778,292
7	0.75578	669,137	696,442	724,871	754,451	785,243	3,630,144
8	0.72614	642,895	669,137	696,442	724,871	754,451	3,487,796
9	0.69767	617,689	642,895	669,137	696,442	724,871	3,351,034
10	0.67032	593,475	617,689	642,895	669,137	696,442	3,219,638
11	0.64403	570,198	593,475	617,689	642,895	669,137	3,093,395
12	0.61878	547,843	570,198	593,475	617,689	642,895	2,972,100
13	0.59452	526,364	547,843	570,198	593,475	617,689	2,855,569
14	0.5712	505,718	526,364	547,843	570,198	593,475	2,743,598
15	0.54881	485,894	505,718	526,364	547,843	570,198	2,636,018
16	0.52729	466,841	485,894	505,718	526,364	547,843	2,532,661
17	0.50661	448,532	466,841	485,894	505,718	526,364	2,433,350
18	0.48675	430,949	448,532	466,841	485,894	505,718	2,337,935
19	0.46766	414,047	430,949	448,532	466,841	485,894	2,246,265
20	0.44932	397,810	414,047	430,949	448,532	466,841	2,158,180

Appendix C

Total Wastewater loads for options 1 and 2 (Source - (Sri Lanka Consultancy Engineering Sciences Inc, 1981))

Options	Year	Flow (m^3/day)	BOD (kg/day)	COD (kg/day)	SS (kg/day)	NH_3 (kg/day)
Option 1	2003	23884	7651	14387	3110	65
	2025	40368	12153	22357	6573	251
Option 2	2003	26919	8535	15911	3991	122
	2025	44743	13465	24536	7815	332

Appendix D

Characteristics of food waste, (Source: (Dilnayana, 2011)

Parameters	Composition	kg COD/kg
Carbohydrates	68.93 %	1.067
Proteins	21.1 %	1.381
Lipids(Fat)	5.1 %	2.878

Appendix E

Input Flow data of sewer and food waste and Reactor configuration

Input Scenarios	01	02	03	04	05	06
Sewer(m^3)	23,884	23,884	23,884	23,884	23,884	23,884
Food Waste(ton)	0	1	5	10	25	50
Food Waste(m^3)	0	1.85	9.26	18.52	46.3	92.6
Total Flow ($m^{3/}$day)	23,884	23,885.85	23893.26	23902.52	23930.3	23976.6
Reactor Volume(m^3)	477680	477717	477865.2	478050.4	478606	479532
Headspace Volume(m^3)	47768	47771.7	47786.52	47805.04	47860.6	47953.2

References

Asian Productivity Organisation. 2007. Solid Waste Managemnt - Issues and Challenges in Asia Tokyo: Asian Productivity Organisation.

Dilnayana, K. W. 2011. Optimisation of an Anaerobic co-digestion process. M Sc Thesis,University of Moratuwa, Sri Lanka, Department of Chemical and Process Engineering.

Fernandez, Font, X. and Sanchez, A. 2005. Anaerobic co-digestion of a simulated organic fraction ofmunicipal solid waste and fats of animal an vegitable origin. *Biochemical Engineering Journal*, 22-28.

IPCC. 1966. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventori Reference Manual. *Volume 3.* IPCC.

Kubaska, M., Sedlacek, S., Bodik, I. and Kissova, B. 2010. Food Waste as Biodegradable Substrates for Biogas Production. Slovakia: 37th International Conference of Slovak Society of Chemical Engineering.

Lanka Hydraulic Institute Ltd. 2009. Assesing Colombo Munipality wastewater system. Report for National Water Supply and Drainage Board and Colombo Municipal Council, Colombo.

Neves , l., Ribeiro, R., Oliveira, R. and Alves, M. 2004. Enhancement of Methane production from Barley waste. *B*iomass and Bioenergy *30*: 599 - 603.

Premachandra, H. 2006. Municipal Organic Waste Management, *Sri Lanka*. Retrieved June 2011, from Central environmental Authority, Sri Lanka: www.env.go.jp/recycle/3r/en/asi/page639991.html

Reinhart, D. 2010. Lanfill Gas to Energy: Incentives and Benefits. University of Florida, Department of Civil, Environmental and Construction Engineering. Gainsville: State University System of Florida.

Sri Lanka Consultancy Engineering Sciences Inc. 1981. Sri Lanka Sewerage Project, Final Report. National Water Supply and Drainage Board, Sri Lanka, Colombo.

Sudasinghe, M., Galagedera, L. and Gunewardena, E. 2011. Performance evaluation of selected sewerage treatment plants in Sri Lanka. *Tropical Agricultural Research 22 (2)*: 154-164.

The Encyclopedia of Alternate Energy. (n.d.). Anerobic Digestion. Retrieved February 2012, from The Encyclopedia of Alternate Energy and Sustainable Living: http://www.daviddarling.info/encyclopedia/A/AE_anaerobic_digestion.html

Verma, S. 2002. Anaerobic Digestion of organics in Municipal Solid Waste. Retrieved December 2011, from Anearobic digestion of Municipal Waste: www.seas.columbia.edu/earth/vermathesis.pdf

Zhang, M., Fan, Y., Xing, Y., Pan, C., Zhang , G. and Lay, J. 2007. *E*nhanced biohydrogen production rom cornstalk wate with acidification pretretment by mixed anaerobic culture*s*. Biomass and Bioenergy.

Optimization of Energy Usage by Developing of Web Based Energy Monitoring System for Ambatale Water Treatment Plant

W.H.M.R.D. Wijekoon*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Ambatale water treatment plant is the largest water treatment complex in Sri Lanka. The maximum production capacity of the treatment plant is 550,000 m3/day. The treated water of this plant is transmitted to six service reservoirs which are located in different places in Colombo district from main transmission lines. Cost analysis of Water Treatment and transmission process shows that the major cost component is the electrical energy. Average monthly energy consumption is 5.4 GW hrs and the maximum demand is 9000 kVA. The electrical system of Ambatale water treatment plant has 19 power transformers which are in continuous operation. The individual energy measurements of these 19 sections are very important to study the characteristics of energy usage of each section. The Ambathale water treatment plant has no SCADA system for controlling and monitoring of the process. In addition to that there is no any method to monitor energy usage continuously of the treatment and transmission. The ever increasing energy demand in Sri Lanka cannot be matched with the increase in generation. Therefore optimizing and minimizing of energy is the solution for this issue. In this context, we hope to study overall energy consumption as well as individual incoming feeder consumption by using modern technology at Ambatale water treatment plant. This paper describes low cost web based energy monitoring system implemented at Ambatale water Treatment Plant to achieve these goals.

Keywords: SCADA system, energy monitoring system (EMS), water treatment plant (WTP)

1. Introduction

Amabtale Water Treatment plant is the largest water treatment plant in Sri Lanka and it provides safe drinking water to Colombo and suburb. Currently daily average daily production is 509,000 m^3. Average daily energy usage in year 2013 and 2014 are 154,512 kWh, 162,180 kWh respectively (after commissioning of Gothatuwa pumps). Average monthly maximum electricity demand is 8500 kVA. Ambatale Water Treatment plant has a dedicated 33kV/11 kV primary substation which is belonged to Ceylon Electricity Board (CEB). All energy metering is done from 33kV side of CEB Substation.

The CEB Substation has ten 11kV feeders which transmit power to whole water treatment plant through secondary transformers which belong to Water Board. The treated water is pumped to six various reservoirs namely Dehiwala, Maligakanda, Elihouse, Gothatuwa, Jubilee and Kolonnawa areas. After reaching near the pumping station, this 11kV power is again stepped down to relevant voltage levels and fed to the motor control centers. This treatment plant has no SCADA system for the control and monitoring of process.

There are different pumping capacities and different combinations (2 duty or 3 duty) used in the treatment plant for pumping water to above mention six locations. Earlier, there was no continuous monitoring system to measure individual energy usage in each section. NWSDB officer used to record manually the daily energy reading in particular time which was only one reading for the each station. Daily energy consumption pattern and time base energy consumption could not be analyzed by the above system. In addition to that there was a separate power factor correction panel connected to the above Motor Control Centers (MCC). Before 2011, CEB electricity consumer tariff structure was flat and after the year 2011 CEB has revised their tariff structure at several occasions as presented in Table 01. According to the 2013 tariff structure, peak energy consumption rate was significantly high as compare with 2011 peak rate. Due to above high energy rate, NWSDB has tried to reduce peak energy consumption and studied the energy consumption pattern. From 2011 M&E section of Ambatale tried to solve this problem and tend to establish the Energy Monitoring System. This type of energy monitoring software is available at the market but software price is very high. The most of the energy meters available in the market are used open communication system. Therefore we tried with this open communication to establish own system to Ambatale Water Treatment Plant.

* *Correspondence:*
ISSN 2478-0669 Print

Table 1: CEB I3 Tariff Category in year 2011 and year 2013

TOD (Time Band)	Year 2011/Rs.	Year 2013/Rs.
Day (05 30 -18 30)	10.25	10.50
Peak (18 30 -22 30)	13.40	24.00
Off Peak (22 30-05 30	7.40	6.00
1 kVA	750	1000.00

2. Methodology

As shown in Figure 1, the signals from the energy meters at different locations are received through RS485 and converted to RS232. Then this input is taken to the energy monitoring software which is installed in the web server. Then it can be accessed by the designated officers through Ethernet in the WTP and by using internet from anywhere. The energy monitoring software is calling data from energy meters in designated time. The received data shows in the relevant Web Page and same data is stored in a data base.

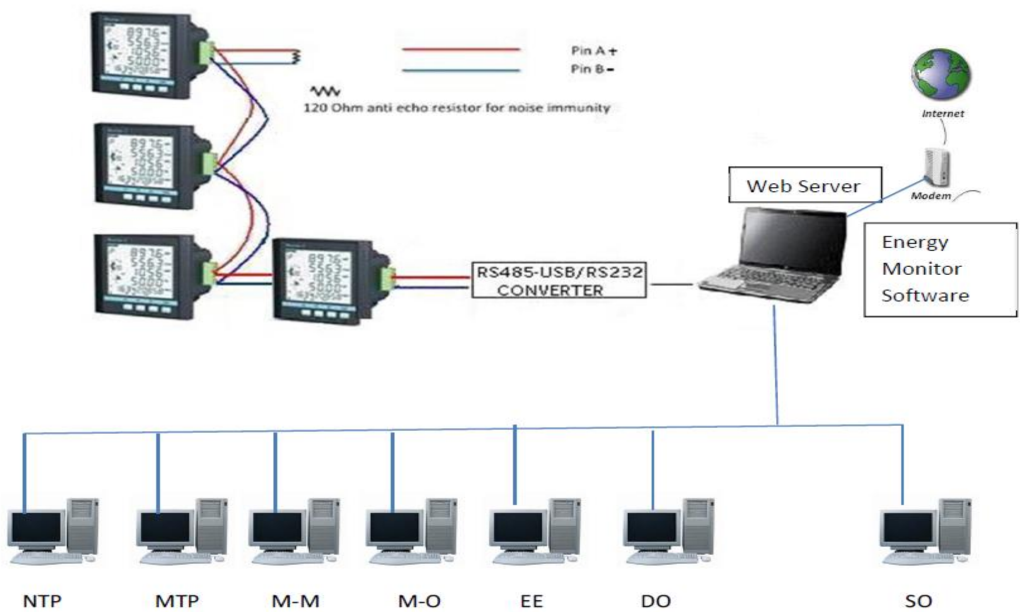


Figure 1: Typical designed EMS

Figure 2 shows the main screen which shows the total energy summary and individual feeder Summaries details. Further it shows the details of other transformers and the incomers (apparent power, active power, voltage, current, power factor). It gives the history of the monitoring parameters such as apparent power, power etc. More details of each and every incomer can be got by choosing the required incomer from the icons in the bottom of the main screen.
Figurer 03 shows a screen selected as mentioned above which the Jubilee is pump feeder. It gives the details of transformer loadings, voltages, currents in each phase, power factor, total active power, total apparent power, total power factor and total loading percentage.

Advantages

This energy monitoring system can be used to monitor

- Real time Energy Usage in WTP
- Real Time Demand
- Real Time System Parameters / Feeder Parameters (Vol, Curr, Power, PF etc..)
- Feeder Details
- Transformer Loading Capacities
- Power factor monitoring in each feeder and electrical system.
- Historical trend by data logger
- Day, Peak off , peak Energy consumption
- Identification of unusual energy usage due to human errors or machine errors. Figurer 08 shows an example for an unusual usage due to human error.

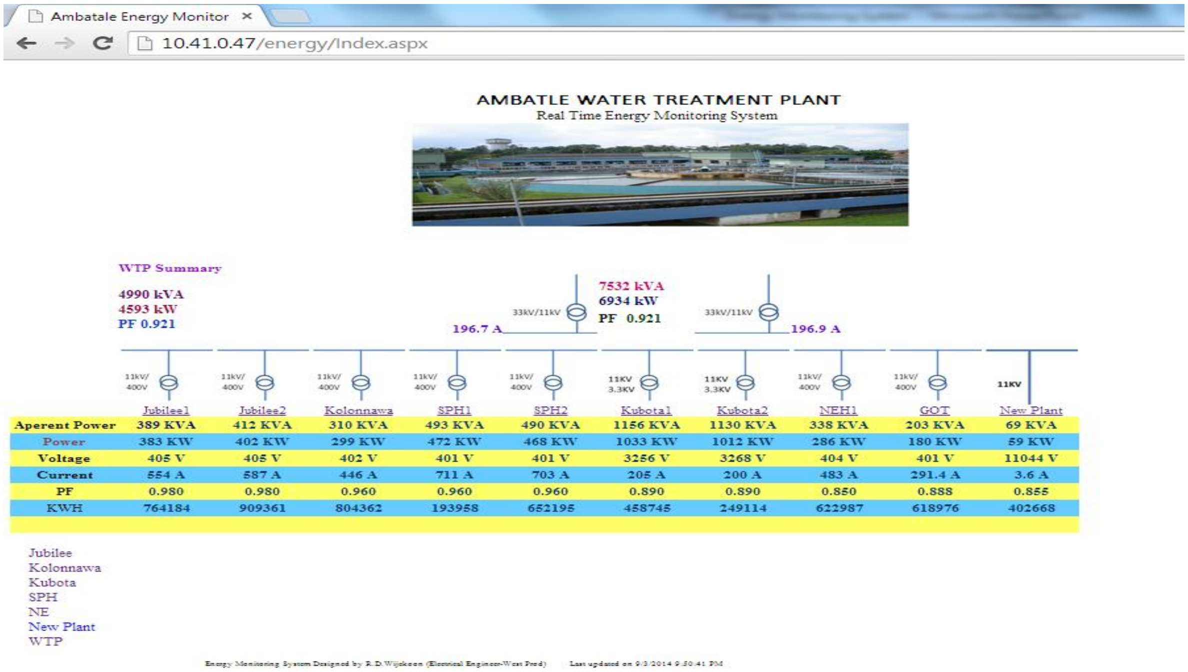


Figure 2: Home page (Total energy summary and individual feeder summaries)

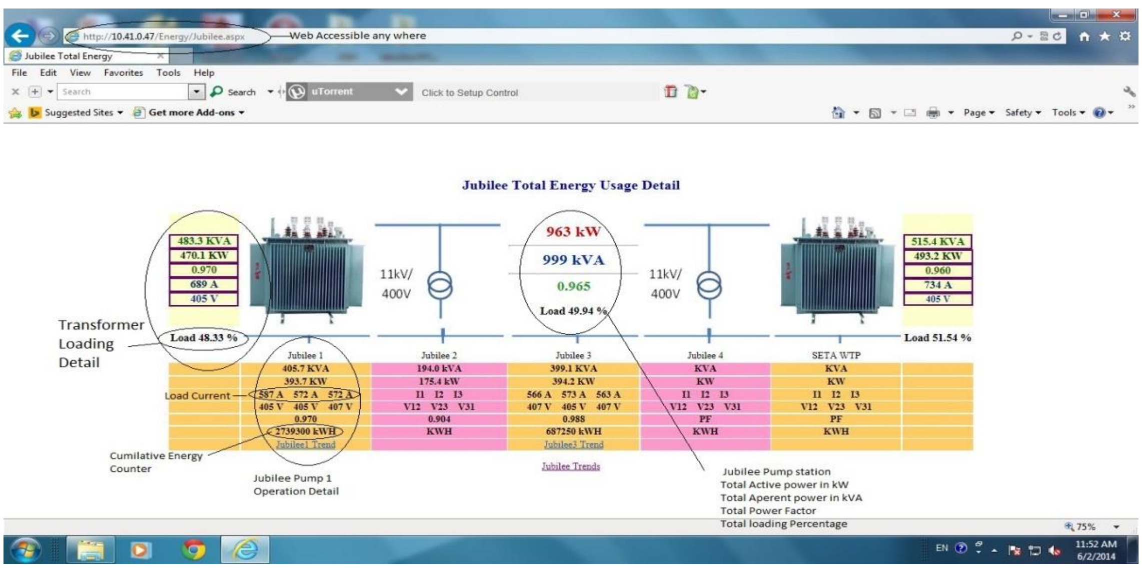


Figure 3: Details of jubilee feeder

3. Outcome

Key outcomes of the implementation of web based energy monitoring system include the following:

- Peak Energy management
  The reservoirs are fed by minimum number of pumps at CEB peak time and maximum number of pumps at off peak. Also backwashing of filters are scheduled at off peak. Figure 04 shows the change of energy usage. Figure 05 shows the changing of back washing schedules.
- Reduce Energy Cost
  The total energy cost is reduced when it is pumped more in off peak and less in peak.
- Reduce Reservoir over flowing
  Since the levels of the reservoirs are monitored, over flowing will be minimized.
- Increase Operational efficiency

The operational efficiency is normally measured by unit production cost. Since the unit energy cost is reduced, the total unit cost is also reduced.

- Max Demand Controls (Pumps on as Groups and Power factor monitoring)
  When the total plant has to be restarted (eg; sudden power failure) pumps are restarted as groups with 15 minute intervals to minimize the maximum power (kVA) demand.
  When capacitor bank defect it can be identified where the area and can be attended immediately.
- Analysis of data for Continual Improvements.
- The data that is logged in the system can be used to analyze the trends.

3.1 How it achieved

All the staff members who are involved in the system were trained and had awareness programs to give the importance of implementation of this Energy Monitoring System.

Especially duty officers and shift officers were educated on this program. The system is daily monitored by the management to ensure it is going on the correct track. This subject is included in the agenda of the regional staff meetings so that all the staff officers have a good idea about the program.

Figure 4: Previous and current energy consumption pattern

3.2 Back wash schedule to off peak

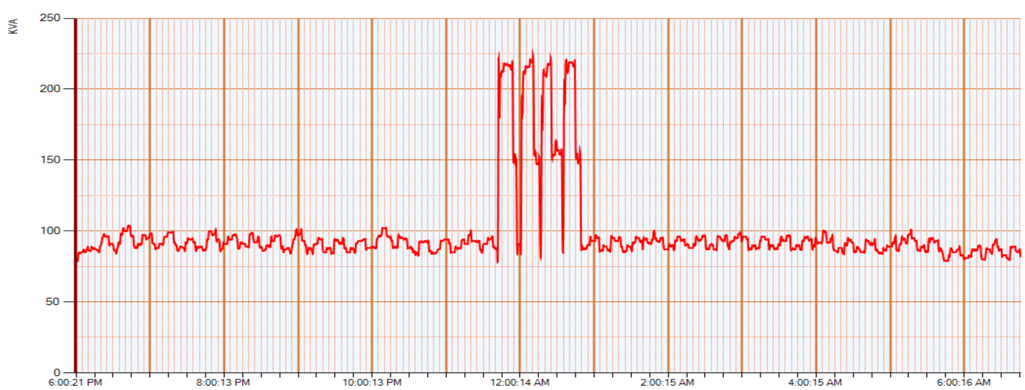


Figure 5: New plant back wash analysis

3.3 Good energy usage pattern

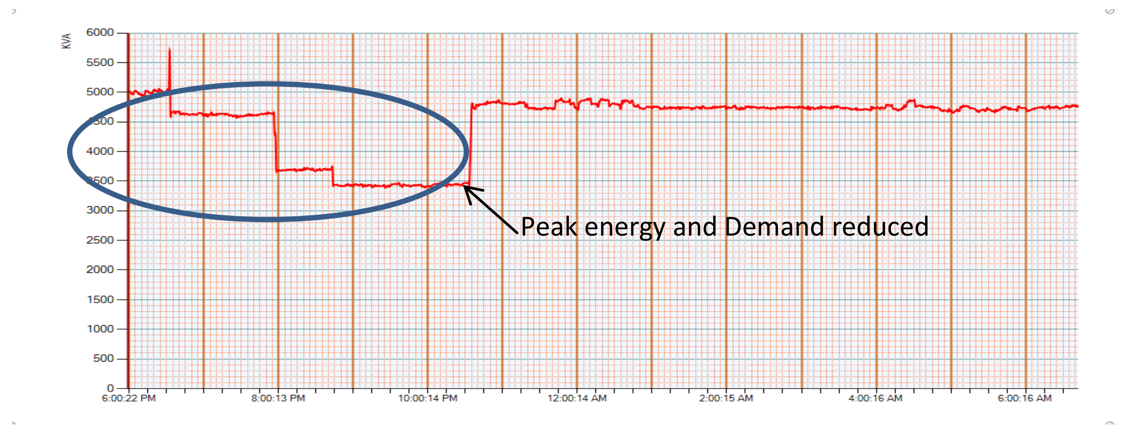


Figure 6: Electricity peak WTP energy and demand management

Figurer 6 shows the good energy usage pattern in the plant. It shows reduction of the Peak Demand, which is very important to CEB to bridge the gap in the peak hours.

3.4 Energy Pattern Identification
Best Pattern for Jubilee Station

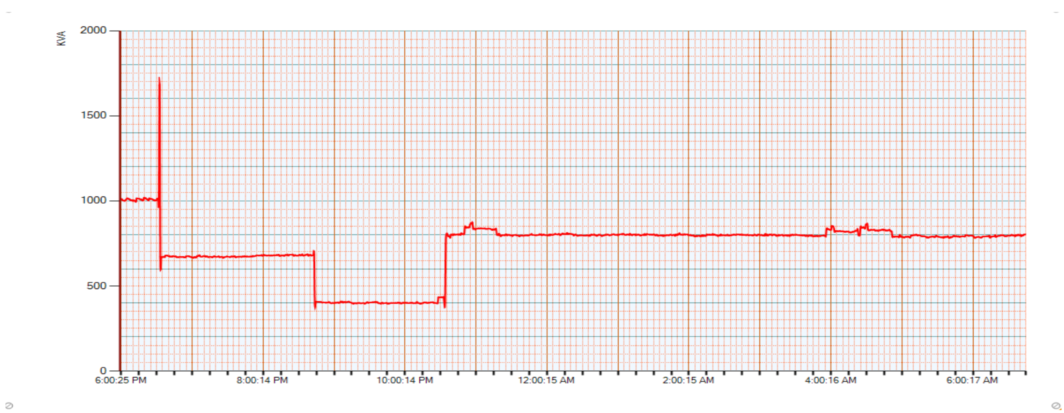


Figure 7: Energy consumption pattern with water demand at Jubilee Station

3.5 Identification of unusual energy usage

Figure 8 shows unusual energy pattern which occurred location as well as time period. As an example, New Water Treatment Plant from 2300 hrs to 0015 hrs (1 hr and 15 min) back wash was done in unusual manner. Hence that process additional energy wasted.

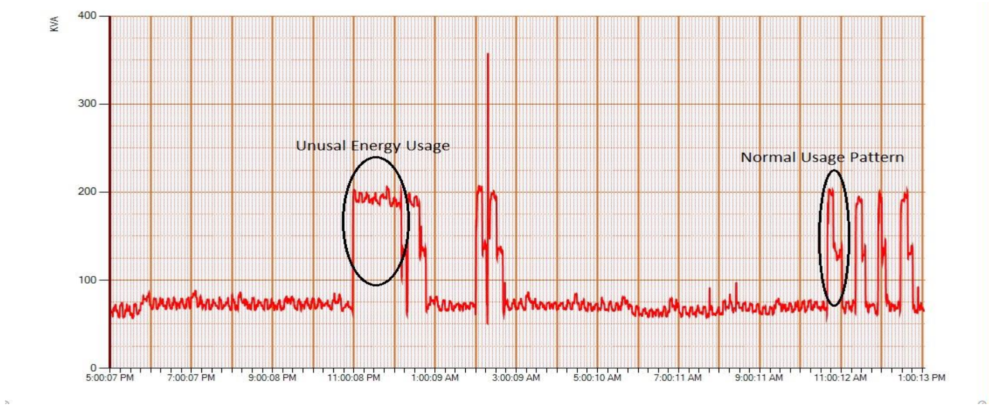


Figure 8: New plant unusual energy identification (Back wash was not performed well)

3.6 Energy loss measurement

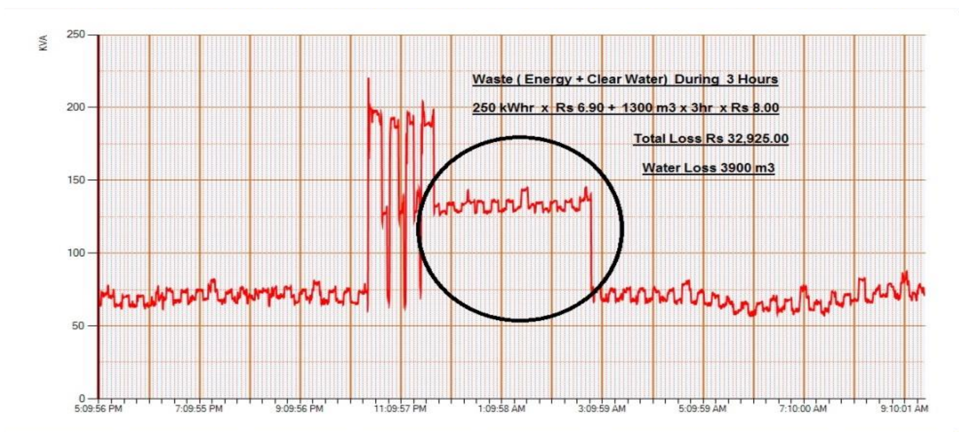


Figure 9: Energy loss calculated in new plant

3. Results

It was started to analyze the system from May 2013 after tariff was increased by the CEB From Sept 2013 to June 2014, energy saving amount at Ambathale is given below.

- Average Energy cost per kWh (After Tariff Increase) Rs. 13.18
- Average kVA Usage Up to Aug 2013 7912 kVA
- Average kWh usage Up to Aug 2013 4,796,174 kWh
- Av: Monthly cost (without energy management) Rs. 80,610,972.95
- Cost of Aug 2013 (Benchmark) Rs. 71,460,531.70
- Total Saving Up to June 2014 Rs. 21,238,373.81

The graphical view of the same is given in Figurer 10.

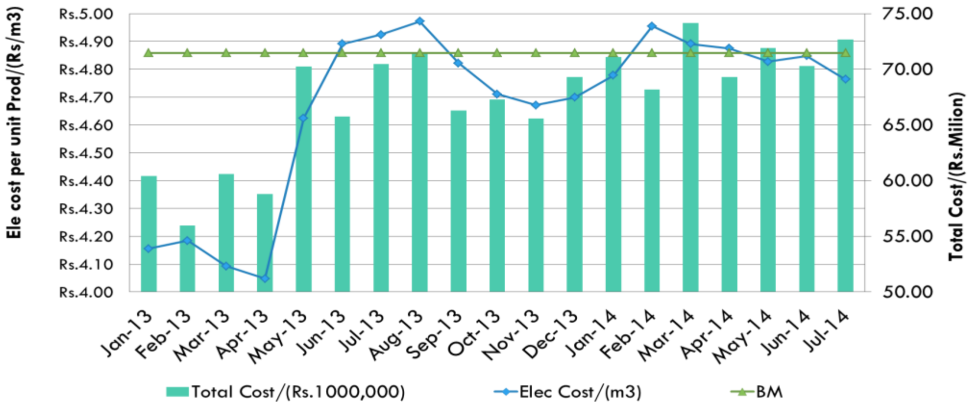


Figure 10: Electrcal cost per unit production

4. Conclusion

The energy management by using the self-developed software at Ambatale Water Treatment Plant gives a huge potential of energy and cost saving which is a great advantage from both NWSDB and CEB point of view.

References

SLSEA, E-Library - National Energy balance –Electricity data 2008 -2013, Sri Lanka Sustainable Energy Authority (SLSEA), [Online] Available, http://www.energy.gov.lk/sub_pgs/elibrary.html

Transformation of Lighting towards Solid State Lighting in Sri Lanka

H.K. Illeperuma*, I.P.S. Ilangakoon

Regional Centre for Lighting, Ceylon Electricity Board

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

The lighting load of the country contributes considerably to the night peak demand of the electricity system. In 2010, the contribution of the lighting load to the night peak demand was 35%. Major contributors to this lighting load were incandescent lamps and CFLs. Incandescent lamp is the most energy inefficient lamp. Energy efficient CFLs were introduced in 1995 and CFL penetration to the system is currently around 45%. Still incandescent lamps dominate the lamp population and contribution to the night peak. During last 2-3 years LEDs have flown in to the market and its share by now is approximately 10%. LEDs are having a higher efficacy around 90 – 100 lm/W. Mealtime, linear fluorescent technology also has developed to an energy efficient light with smaller tube and electronic ballasts. Therefore, moving towards high efficient technologies can bring in considerable savings in terms of energy and additional capacity savings for future load growth. This itself saves a lot for the utility and to the nation, and environmental saving for the planet. Under this study several scenarios were worked out, including replacement of incandescent lamps with CFLs, replacement them with LEDs and replacement of all with LEDs. The results show that there is capacity savings in the night peak ranging from 239.7 MW to 413 MW based on the current lighting load. LED technology proves higher efficacies and the technology is still developing and is expected to reach 180 lm/W levels by 2020. This is three times the efficacy of CFLs. It is a clean technology and has many other advantages as well. Flexibility in switching and dimming further enhance the energy conservation. Different colors and color changing flexibility promotes dynamic lighting and could be used for beautification and exterior lighting of buildings and monuments. Its applicability is vast in both indoor and outdoor lighting. Different light distributions can be easily achieved with different optics. LED lamp is an assembly of few components like the LED chip, heat sink, optics and the driver. Proper co-ordination and good quality of these components is vital for the best performance of the LED lamps. Hence, manufacturing of LED lamps within the country could be promoted and it will add more value with in the country enhancing the economy. One major concern with LED is the quality of all components in the assembly. Failure of any component will results in the failure of the lamp. Lumen depreciation and color shift are another concern with LED lamps. Therefore, quality assurance and product testing is a key aspect in using LEDs. Testing on lumen maintenance or life and the color shift takes long time. Therefore, RCL along with SLSEA, SLSI and University of Moratuwa is in the process of developing a short term test method to assess the life and the color shift with the assistance from LRC, NY, USA. With proper quality assurance and product testing mechanisms in place, LEDs have far more advantages and energy savings than other lighting technologies. The technology still continues to develop and local manufacturing and mass production or procurement can bring down the price of LED lamp to an affordable level. Therefore, transformation towards LED lighting is a prudent move that can benefit all stakeholders including the environment.

Keywords: LED, quality assuarance

1. Introduction

The daily electricity demand pattern highlights a spiking peak demand in the night. Grid electricity is accessible to the majority of Sri Lankan citizens and currently 98% of the household have been provided with grid electricity. The night peak demand that occurs during 1830 hrs to 2330 hrs and it is considered as mainly due to lighting load of the country. Prior to 1995, majority of the light bulbs used in households were incandescent lamps which are highly energy in efficient. In order to curb this peak demand, Ceylon Electricity Board (CEB) has introduced CFLs to its customers and people were educated to use them as it will help to reduce their electricity bill and mutually benefit the utility on

* *Correspondence: kamalccc2002@yahoo.com*
ISSN 2478-0669 Print

lowering the demand for electricity. During last few years, Light Emitting Diode (LED) lights have galloped in to market and people grabbed them for the news that they are more energy efficient and are capable of further reducing their electricity bill. LEDs were in the market for last three years and peoples experience on them is quite vivid. At the beginning their prices were quite high compared to Compact Fluorescent Lamp (CFLs) and gradually prices have come down, but still higher than CFLs. Major concerns are the life of LEDs and color changes with time. This paper will investigate different lighting technologies evolved so far and compare their performances, unique features, advantages and issues with LED lighting, standards relating to LED s and finally, how LED can be used to light up SL cleanly and efficiently.

2. Problem statement

The daily electricity demand has a peak in the night, dominated by the lighting load. The predominant lighting technologies include highly energy in-efficient technologies; some of them are not environmentally friendly. Use of energy efficient and clean technologies will enable to avoid additional generation capacities by controlling the demand. Reduction in capital investment for electricity generation can be utilized for social welfare or further reduction of electricity prices.

3. Objectives

- To identify the contribution of lighting to the electricity demand and to estimate the potential savings through energy efficient technologies,
- To find out the applicability of LED technology as energy efficient and clean technology while considering its costs and quality.

4. Predominant lighting technologies in SL and their evolution

Electric lights were first introduced in SL in 1890. Since then, incandescent lamps dominate as a lighting source. The incandescent lamp is the most energy in efficient technology that is being used today. Then, discharge lamps like Linear Fluorescent, Sodium vapor ha flown in to the market and during last two decades, CFLs are in use. CFLs were introduced to by CEB as a DSM drive in 1995 and were distributed through a credit scheme and was popularized among customers. When CFLs were introduced to the market, different quality products were flooded to the market and resulted in the market spoilage. Then Sri Lanka Sustainable Energy Authority (SLSEA) developed performance standards and labeling standards in 2002 for CFLs and labeling was first introduced on voluntary basis in 2003. The CFL labeling was made mandatory in 2009. Testing of CFL performance is carried out at Photometry laboratories of Regional Center for Lighting (RCL) and at the NERD center. Meantime, the linear fluorescent lamp technology also has improved its performance in energy efficiency with T5 tube and the electronic ballasts. During last 3-5 years, with the invention of white LED, LED lights came to the market with higher energy efficiency than CFLs. Different types of LED lamps are available in the market with wide variation of performance and quality. They are used widely in in-door and out-door applications.

5. Contribution of lighting load in the daily electricity demand

In 1998, the DSM ranch of the CEB has introduced a CFL program to reduce the lighting load which has been dominated by incandescent lamps.

5.1 Mini load research - 2009

After introducing CFLs and energy efficiency awareness programs, the SLSEA has conducted another load research with a selected sample to represent the entire household population in2009. As per the research the constituents of the electricity demand were identified as per the diagram below.

The daily demand pattern shows two significant peaks, one appears to be occurred around 5:30 - 6:30 in the morning and the other around 7:00 - 8.00 at night (For easy reference these two peak loads are referred to as Morning peak and Evening peak. Evening peak is attributed by the lighting load which accounts 43% of the total load. As the sample is a small representation and focused on the household sector, the contribution of lighting to the entire peak load cannot be taken as similar to this figure of 43%. But, light bulbs penetration can be considered as fairly uniform throughout the country. Considering the percentage mix and the contribution from each type of lamps, contribution of lighting to the entire peak load can be estimated.

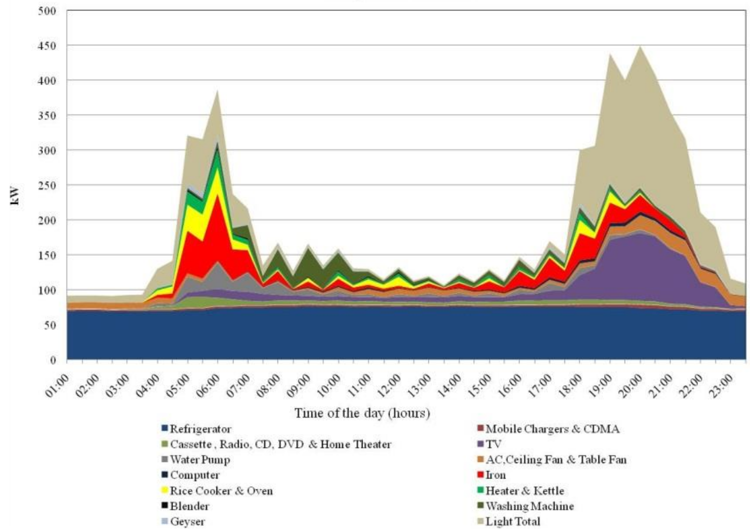


Figure 1: Daily load pattern (Source: SLSEA (2009))

Based on the above load curve of the load research, the contribution from the lighting load is significant during both morning and evening peaks. As per the load research results, use of different light technologies and their contribution to the total load curve described in the following table.

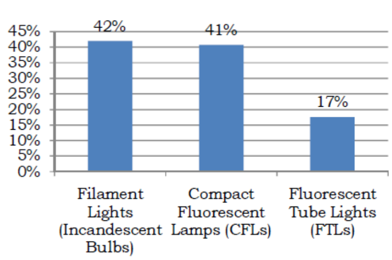
Table 1: Usage of different types of lamps and their contribution to the total lighting load (Source:SLSEA (2009))

Lamp type	% of lamps from total lamp population	(%) from morning lighting load	(%) from evening lighting load	(%) from total average lighting load
CFL	47	30	31	27
Incandescent	49	66	64	68
LFL	3.3	3	4	4
Other	0.7	1	0.3	1

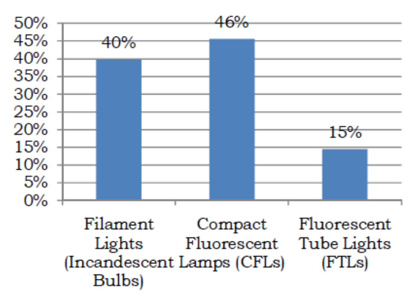
5.2 Baseline survey on lighting - 2011

Further to the above mentioned load research, a baseline survey on lighting technologies in the household sector was carried out by SLSEA in 2011 with the ADB assistance. This survey was based on a selected representative sample population of households in the country.

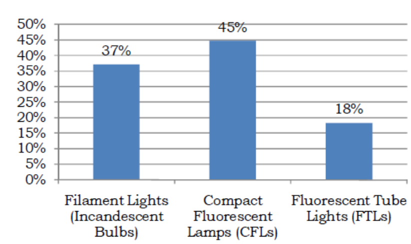
As per the survey, CFL penetration has been identified as follows.



Lamps used in below 90 category



Lamps used in 90 - 180 category



Lamps used in above 180 category

Figure 2: CFL penetration by user category
(source: ADB(2012))

5.3 Lamp imports

Majority of lamps are imported to Sri Lanka. As per the baseline survey report, the graph below is the lamp imports during 2001 to 2010.

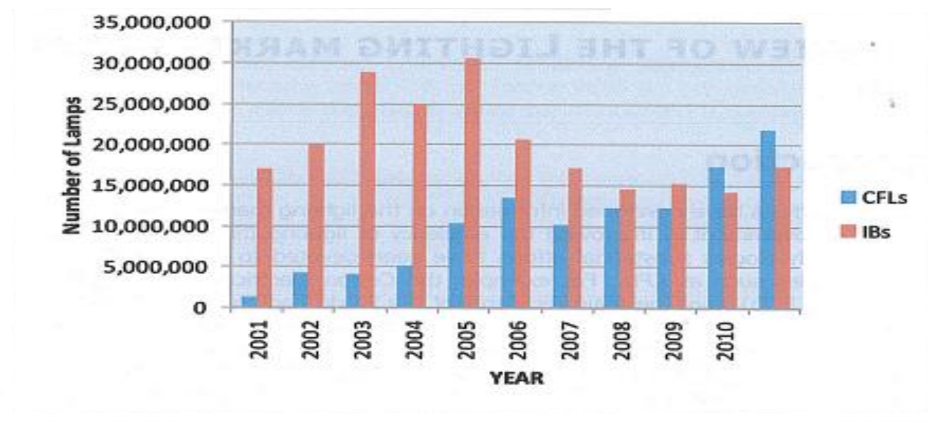


Figure 2: Lamp imports from 2001 to 2010 (source: ADB (2012))

The charts in figure 2 and the chart in figure 3 verifies that the incandescent and CFL share the lamp population almost equally.

Table 2: Demand data

Year	Demand (GWh)	Avg. Growth (%)	Total energy Losses+ (%)	Generation (GWh)	Avg. Growth (%)	Load Factor ** (%)	Peak (MW)	Avg. Growth (%)
2000	5425*	10.2	21.4	6687	10.1	54.2	1404	8.8
2001	5341*	-1.5	19.7	6520	-2.5	51.5	1445	2.9
2002	5638*	5.6	19.2	6810	4.4	54.7	1422	-1.6
2003	6209	10.1	18.4	7612	11.8	57.3	1516	6.6
2004	6782*	9.2	17.1	8043	5.7	58.7	1563	3.1
2005	7255	7.0	17.3	8769	9.0	57.3	1748	11.8
2006	7832	8.0	16.6	9389	7.1	56.6	1893	8.3
2007	8276	5.7	15.7	9814	4.5	60.8	1842	-2.7
2008	8417	1.7	15.0	9901	0.9	58.6	1922	4.3
2009	8441	0.3	14.6	9882	-0.2	60.4	1868	-2.8
2010	9268	9.8	13.5	10714	8.4	62.6	1955	4.7
2011	10026*	8.2	13.1	11528	7.6	60.8	2163	10.6
2012	10475*	4.5	11.2	11801	2.4	62.8	2146	-0.8
2013	10624	1.4	11.2	11962	1.4	63.1	2164	0.8
2014	11063	4.1	10.9	12418	3.8	65.9	2152	-0.6
Last5 year		4.5%			3.8%			2.4%
Last10 year		4.8%			3.9%			2.3%
Last15 year		5.2%			4.5%			3.1%

*Includes Self-Generation

**Load Factor excludes self-generation and NCRE peak

5.4 Analysis

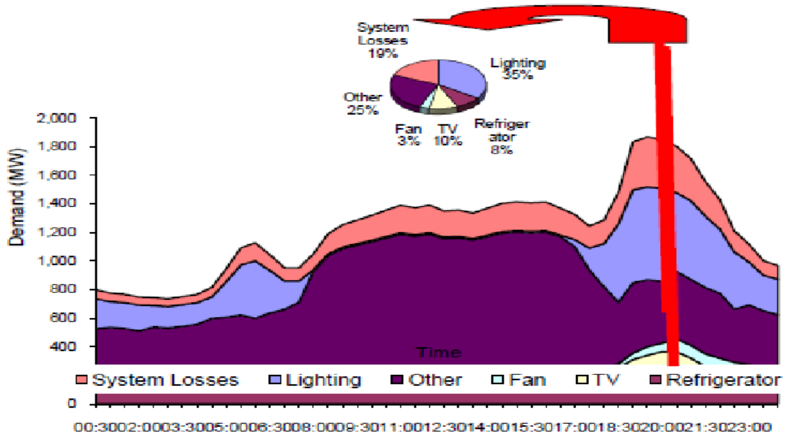


Figure 3: Daily Demand Variation (Source: SEA (2011)

After the introduction of CFLs, by the studies in 2009 & 2011, it was identified that approximately 50% of the lamps are CFL and the rest is Incandescent and other lamps. For the night peak, contributions from incandescent are approximately twice that of CFLs. In 2011, the JICA project on Energy Efficiency Improvements carried out by SLSEA has developed the load demand curve for 2010 shown the figure shows that the peak demand was 1955 MW and the contribution from lighting load is 35%.

By mini load research in 2009 and Baseline Survey in 2011, it has been established that the CFL penetration is approximately 50% and their contribution for the peak load demand is half of that of others.

When, 2010 load curve is analyzed with a above factors;

Actual lighting load in 2010 - 1955 MW X 0.35 = 684.25 MW.

Therefore, it is established that, by 2010, lighting load contributes to 35% of the night peak load and the lighting load is 684.25 MW.

In 2011 baseline survey on lighting, it has been verified that approximately 50% light lamps are CFLs and based on lamp imports this fact has been verified. Therefore, it can be established that even in 2011, CFLs are 50% from lamp population and lighting contribution is 35% to the night peak and the CFL penetration is saturated.

From the table above, it can be seen that the night peak demand and the energy demand from 2011 up to 2014 stagnates and has no considerable growth. During this period LEDs have reached the market, but LED lamp data are not available for consideration. Therefore, it can be considered that, even there is a slight demand growth for lighting, higher efficacies of LEDs would have absorbed and is a not clearly visible with the overall night peak demand growth.

Based on the factors discussed above, it can be considered that even in 2014, the contribution from lighting is 35% of the night peak demand. CFL and others mix slightly changed with the arrival of LEDs. As LED market data are not available, several scenarios will be considered.

5.5 Contributions from LED

Though, LED penetration is uncertain, based on the sample testing data on CFLs and LEDs at RCL, the following table gives as estimation about the comparison of their contributions. From these figures, it can be estimated that 7W LED gives an equivalent effect of an 11W CFL. On this basis LEDs contribution factor can be calculated compared to incandescent lamp as 0.32. So keeping incandescent lamp as reference, considering, 2014 peak load (2152 MW)and 35% lighting load, contributed by 45% Incandescent bulbs, 45% CFLs, 10% LEDs, If no. of lamps are X, Incandescent bulb wattage is W, then the peak light load contributions,

$0.45X*W + 0.45X*W*0.5 + 0.1X*W*0.32 = 2152*0.35$

$X*W = 1065.3$,

Contribution by 45% Incandescent - 479.4 MW
Contribution from 45% CFLs - 239.7 MW
Contribution from 10 % LED - 34.1 MW
Total lighting load -753.2 MW

Category	Brand	Lamp type	Rated Power (W)	Measured Values				
				Power	Lumen output (lumens)	CCT (K)	CRI	Power factor
LED 4-5 W	Philips	LED	4	3.76	358	6311	84.15	0.52
	Osram	LED	4.7	5.68	405	6855	83.46	0.58
	Orange	LED	5	4.88	300	2708	56.54	0.45
LED 7-7.5 W	Philips	LED	7	6.14	610	6581	83.16	0.57
	Osram	LED	7.5	8.65	708	6434	83.27	0.59
	Berger	LED	7	8.43	655	7061	85.88	0.41
	LG	LED	7.5	7.37	554	3121	84.15	0.97
CFL 10-12 W	Osram	CFL	12	11.96	652	6575	79.17	0.59
	Osram	CFL	13	13.46	753	6595	80.47	0.59
	Philips	CFL	11	10.45	601	6156	80.9	0.61
	Orange	CFL	11	11.73	743	6310	81.83	0.61

Figure 4: Comparison of CFL and LED performance data (Source: RCL (2015))

Scenario 1

If, all incandescent are replaced with CFLs

Incandescent loadCFL Load LED load Total Load Reduction

--- 479.4 MW 34.1 MW 513.5 MW 239.7 MW

Scenario 2

If all Incandescent lamps are replaced with LEDs

Incandescent loadCFL Load LED load Total Load Reduction

--- 239.7 MW 187.5 MW 427.2 MW 326 MW

Scenario 3

If all lamps are LEDs

Incandescent loadCFL Load LED load Total Load Reduction

---- ------ 340 Mw 340 MW413.2 MW

From above results it can be seen that, transformation towards LED lighting would bring in lot of savings on night peak demand. This will not only avoid future capacity extensions, but save on energy and hence the fuel cost.

6. Solid state lighting technology and its applications in lighting

LEDs as a solid state lighting technology has significant advantages over conventional incandescence and gas discharge lighting technologies used for many centuries. Longer life, environmental friendliness, energy efficiency and instant lighting are salient advantages. Though LEDs are efficient compared to other lighting technologies, significant amount of heat is dissipated at p-n junctions which should be extracted from the junction in the form conduction while amount of heat radiated form the junction is negligible. Otherwise, the junction temperature raises quickly reducing light output and lifetime with final catastrophic failure. In practical applications of LED systems, efficacy is typically in the range from 50 lm/W to 100 lm/W.

Based on the phosphors coating used, correlated color temperature of LEDs can be varied and warm while and daylight LEDs are typically available. Over the years color rendition performance has been improved. LEDs having CCT better than 80 are fairly available in the market now. LED chips itself claims to have useful life time around 50,000 hours. They always do not undergo through catastrophic breakdown, instead the light output decays gradually over the time.

When LEDs are built into systems together with other components, lifetime of the systems become significantly less than LED chip's life. Associated electronic components tend to fail early and lifetime of the LED chips varies with the operating junction temperature which depends on the design and the environment of operation. LEDs in the forms of light bulbs and linear LED tubes are popular in general illumination purpose of households and offices. Retrofitting lamps for exiting linear fittings and other kinds of luminaires are being evolved.

Street lighting is a filed having extreme interest on energy efficiency and maintenance less operation. Longer lifetime and energy efficiency of LED systems has made huge market for LED street lamps. High power LED chip on board (COB) and 1W LED chips are widely used for making street lamps.

7. Advantages of LED over other technologies

7.1 Lifetime

When properly engineered with good thermal management and driven at correct current with a high quality power supply, LED systems can last significantly longer time than incandescent and fluorescent lamps. End of life of a LED system is either the catastrophic failure or the light depreciation more than the usable amount. Depreciation of light more than 30% (L70 Life) is considered as end of useful life for LED products used for illumination.

7.2 Efficiency

Luminous efficacies of production LED systems are typically in the range from 40lm/W to 120lm/W. Variation of energy efficiency is wider. There are systems having efficiency surpassing other technologies and systems having efficiency lower than existing technologies in real life.

7.3 Environmentally friendly

LEDs do not contain mercury which causes problems to nature when disposing. Fluorescent lamps contain mercury are dangerous to dispose. The energy-efficient nature of LEDs also makes them environmentally friendly by reducing the fuel burning at the power generation plants.

7.4 Color

LEDs have a wide range of colors and it possible make more colors by mixing RGB LEDs. Traditional light sources do not permit color changes easily.

7.5 Dimming

By using forward current control and pulse width modulation, LEDs can be dimmed properly and easily. PWM method gives a greater dimming range and a linear response in dimming. Dimming has no associated effect to the lifetime of the LEDs like other traditional lighting sources.

7.6 Switching

Sources like fluorescent are highly sensitive to the on – off switching cycles ultimately resulting in a shorter lifetime. LED systems are less sensitive to switching effects and the lifetime is not affected. Lifetime of the driver circuit is affected in a small fraction.

8. Complexity of white LEDs and concerns

8.1 Thermal management

Constrain of optimization of any LED system is the p-n junction temperature of LEDs. Design engineers has to decide the size of the heat sink, properties of the thermal interface materials and LED forward current in order to keep the junction temperature in a safe margin.

8.2 Orientation of burning and luminaire usage

It is strictly required to burn the LED systems in the orientation they are designed to be used. Performance of the heat sink varies with the orientation and it directly affects to lifetime and light output.
When used inside a luminaire, natural convective cooling of the heat sink is blocked. Temperatures of the heat sink as well as the p-n junction tend to rise above the safe margin reducing light output and lifetime.

8.3 Light depreciation and color change

Inherently, light output of the LEDs decay gradually. Useful lifetime has been declared as the point of remaining light of 70% (L70) or 50% (L50) from initial light output. The color (CCT) of the light emitted changes with time due to the degradation of the phosphors layer above the emitting surface of LEDs. Color rendition index also get reduced as a reason of this.

8.4 Lifetime of the driver circuit

Driver circuit is more vulnerable to failures than the LEDs. Electrolytes of the electrolytic capacitors inside the drivers evaporate eventually and result in driver failures. Therefore it is required to use high quality components in manufacturing driver circuits.

8.5 Power quality issues

Power factor and the content of harmonics generated are the most important parameters interested. Penetration of low power factor LED lamps results in an added loss in utility's network. Most of the LED systems in Sri Lankan market has poor power factors even low as 0.5 - 0.2.
Total harmonic distortion of current is typically more than 100% because of the switch mode power supplies used.

8.6 Energy efficiency

Not all LED systems are more energy efficient than the existing technologies like CFL and linear fluorescent. Misperception among the public that the LEDs are the most efficient leads to result in spending money for no advantage of efficiency or light quality.

8.7 Led standards and quality assurance

LED as a light source has higher energy efficiency, but it associates with several components such as the driver, heat sink, optics and its luminaire. All these components have an effect on the performance of the LED light and failure of driver circuit will result in failure of the LED light. Therefore, quality assurance of all these components is vital for the quality assurance of the LED lights. Therefore, there are many standards on these components.

In local laboratories, a suitable test method for LED testing is being developed matching to conditions of Sri Lanka in order to assess the performance in terms of lumen maintenance and color maintenance.

9. Conclusion

- The lighting load of the daily electricity demand is still dominated by incandescent lamps. The CFL penetration is approximately 45% and LED has approximately 10%. The contribution of the lighting load to the daily electricity peak demand is approximately 35%. In 2014, the night peak demand is 1955 MW and the lighting load contribution is 753.2 MW. CFLs are having efficacies around 55 – 65 lm/W and LEDs are having efficacies around 90 – 100 lm/W. Therefore, replacing the highly inefficient incandescent laps with CFLs and LEDs, the peak demand could be reduced considerably. Following scenarios will exhibit capacity saving potential on peak lighting load.

Scenario 1
If, all incandescent lamps are replaced with CFLs

Incandescent load	CFL Load	LED load	Total Load	Reduction
---	479.4 MW	34.1 MW	513.5 MW	239.7 MW

Scenario 2
If all Incandescent lamps are replaced with LEDs

Incandescent load	CFL Load	LED load	Total Load	Reduction
---	239.7 MW	187.5 MW	427.2 MW	326 MW

Scenario 3
If all lamps are LEDs

Incandescent load	CFL Load	LED load	Total Load	Reduction
----	------	340 Mw	340 MW	413.2 MW

From the above scenario analysis, it can be seen that the capacity reductions on peak load are quite considerable. The LED technology still develops further and by 2020, it is expected to reach 180 lm/W efficacy levels. This is approximately three times the efficacy of CFLs. Therefore, moving towards LED lighting is a prudent move and it brings in promising benefits of energy savings and capacity savings in the system load.

- LED is a complex unit that constitute of several components, the LED chip, heat sink, optics and the driver. Proper co-ordination and quality assurance of these components is vital for the expected performance and life of the lamp. Lumen depreciation and color shift are the two major factors to be monitored and tested. Along with the photometry and electrical testing, the lumen maintenance and color shit testing would ensure the expected performance and life of LEDs.

- LEDs are available in different colors and color changing effects can be easily achieved. Also, its switching capability, makes LED the best choice for illumination and beatification projects. LED is a clean technology and hence it can be used to light up Sri Lanka cleanly and efficiently.

References

Asian Development Bank, 2012. TA No: 7778 – SRI – Implementation of Energy Efficiency Initiatives. Development of Energy Efficient Lighting Policy for the Residential Sector.

Sri Lanka Sustainable Energy Authority, 2009. Load Research. Regional Centre for Lighting, 2015. Lamp testing data.

Sri Lanka Sustainable Energy Authority, 2011. JICA project on Energy Efficiency Improvements.

Case Study: Conservation of Energy by Provision of Ownership for Water in Underserved Settlement in Colombo City

S.G.G. Rajkumar*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Colombo City water supply was initiated in 1876, by storing raw water in impounded reservoirs away from the city. The city population continued to increase resulting in tapping other sources for raw water. Obtaining raw water from river require quite a lot of energy, subsequent pumping to storage tanks and delivery to point of usage require additional energy. Obtaining raw water has its own limitations, the source availability, regular rain pattern etc. Having an old system over 100 years is naturally prone for higher level of losses from deteriorated reticulation. The water was provided free of charge during the municipal council management. After formation of National Water Supply & Drainage Board consumption metering commenced in 1980. Payment had to be made in proportion to the consumption. There was a segment that could not be metered as their residence were temporary, they depended on common water outlets, this represented 40% of the city population. They were categorized as underserved population. Value of commodity is not known unless payment is made for them, to serve the people, different approach of management could be adopted to solve a long standing social problem. The stake holders could be from the organization or from outside. This case study will look into one of the management approach taken to reduce Non Revenue Water in Colombo City from 54% to 46% using available resources,that enabled conservation of Energy. The tools used include creation of awareness, empowerment, and ownership to dignify the underserved water users.

Keywords: create ownership, conserve energy, reduce water loss

1. Introduction

Colombo City water supply was initiated over 125 years ago, first treatment plant was at Labugama, there after Kalatuwawa was constructed. Lately larger treatment plants were constructed in Ambatale and other side of Kelani river as the Kelani right bank treatment plant. Initially the plant capacity was 59,000 m^3/day now the plant capacities have been increased to over 850,000 m^3/day to serve areas in western province. The migration of population to cities and suburbs gave rise to demand for additional water. When the water supply was under Municipal council cost of water supply was covered under assessment tax, consumption based billing commenced after the management was handed over to National Water Supply and Drainage Board (NWSDB).

In the city there exist underserved settlements (USS), there are over 1730 USS, having more than 66,000 houses, which represents over 40% of the city population. Some of the USS are in private lands. Since the proof of ownership of premises occupied was not readily available, provision of individual connections was not effected at the time of meter installation. This population continued to enjoy the existing free water outlets, there were over 6000 free water outlets in year 2000. A program named "Randiya" was initiated to provide individual connections in lieu of disconnection of free water outlets. Non Revenue water in Colombo City was 53.84% in 2009. Free water was one of the major contributory factors.

The system pressure was low indication the whole of city supply was of low pressure system compelling people to have individual sumps or collect water from below ground level.

* *Correspondence: dgmdev@waterboard.lk*
ISSN 2478-0669 Print

Figure 1: Low pressure in the System

2. Underserved settlement

In Colombo city, there are over 1730 USS. The extent of land utilized for each house would be around one and half perches (25 Sq.m). There are nearly 66,000 houses in these settlements obtaining water from nearly 4,000 common outlets [1]. There are no meters to measure the water consumption local authority / users do not pay for the valuable water. The value of water is not known to the users.

Some of the constraints faced in water supply were;

- Low pressure in distribution systems in the area
- Mainly most of the Underserved Settlement situated in low line area
- Reluctant to work with Government officers
- No spaces to have a bath tap
- No proper drainage facilities available in the Underserved Settlement
- No proper access
- No space to obtain individual connections
- No space for individual septic tank
- Low literacy level
- Protest against to disconnect common outlets

3. Socio economic study

Survey on Willingness to pay observed in one house hold at least one person goes for employment, most of the occupants are daily wage earners, with insecure jobs. There are houses where one member has gone abroad seeking employment. Most of the houses have minimum one mobile phone. There is fair proportion who has obtained electricity to their houses.

The survey also found 93% of the population want individual connections, 73% has electricity and permanent roof and walls, 80% monthly income was around Rs 10,000/= being in the city there was large discrepancy in income level resulting in mean income to be Rs18,000/=. Monthly bill payment of Rs 100/= to Rs 300/= was acceptable.

In some areas transacted value of land had been over Rs 1,300,000/= (USD 1,000) per perch.

4. Randiya program

A program called “Randiya” was initiated in 2000 to provide individual water connections to the population living in Tenement Gardens, Individual water supply was given at concessionary terms in lieu of free water outlet disconnection. It cost only Rs 4000/= plus VAT. Cost of water supply could be paid in 36 installments, to send the monthly bill proof of address was required, it could be given by the Municipal Council of by the Grama Sevaka. By 2010 it had given 20,531 connections, covering 607 USS. The momentum for request from this approach reduced.

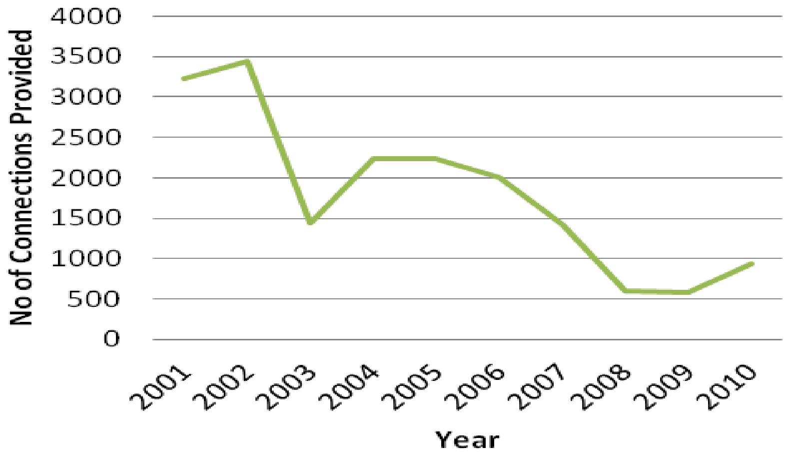


Figure 2: Performance of Randiya program

Table 1: Remaining Number of Common Outlets in all USS in 2010

Common outlets remaining		
Bath tap	Toilet tap	Stand post
1333	810	1640

5. Metering of common outlets

Metering of way side stand post and requesting way side stand post users to pay was initiated in 2011, having the knowledge that there is willingness to pay.

In some of the underserved settlements people have been living for generations, they needed to be educated about the cost of water, economics of pipe borne water, benefits of safe drinking water, convenience enjoyed etc. Even though the settlements existed for many years they didn't have a representative who could liaise with NWSDB.

Available staff in NWSDB had to be used to commence the mobilization. The team that visited the Underserved settlements consisted of multi discipline, and there were sociologist and technical persons. They visited each underserved settlements, met the user at the point of use, spoke to them about the cost of water, necessity to conserve, cost effectiveness of pipe borne water, use the valuable resources sparingly, why it has to be metered and a small charge had to be initiated, emphasis on creation of ownership was emphasized. Having understood, a volunteer was selected among the users of the stand post, to receive the monthly bills of water board.

By end of 2013 all the USS in Colombo city had water by individual connection or they belonged to the 1735 societies.

6. Expectations / Achievements

This method had brought about a win win situation where NWSDB is in a position to account for the water and the residents have the pride of ownership of water supply and enjoy following benefits.

- Upgrade living condition of the Underserved Settlement
- Improve health conditions
- Less number of users for common outlets than previously
- Improve the capability of community leadership and actively involve for the project
- Eliminate wastage of water (Social responsibility)
- Reduce Non Revenue Water (Social responsibility)
- Avoid boiling of water for drinking.

Within a short period of time 24 months, end of year 2013 all the free water outlets had been metered after forming customer societies. The non revenue water (NRW) reduced from 50% to 46% as shown in figure 3.

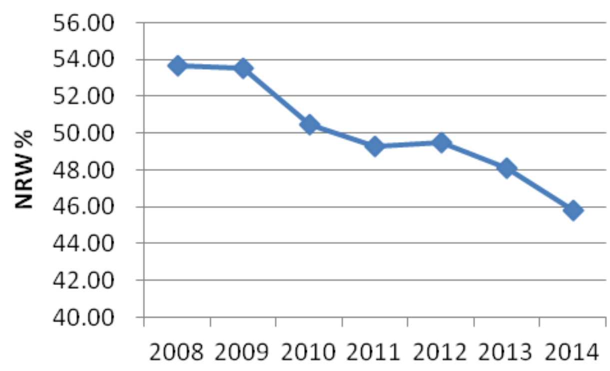


Figure 3: Reduction of NRW over the years

7. Energy saving

Reduction of NRW means there is saving from water that was lost, which is used to serve more customers, amount of water that need to be transmitted to the city from the treatment plant is reduced, reduction in treated water in the production plant, system pressure improvement to eliminate all 17 low pressure areas. Pressure measurement taken in 2014 is shown in Figure 4. Increase in system pressure allowed water to be stored in overhead storage tanks this avoided secondary pumping by individual customers. In 2008 the city received 297,000m^3/day treated water to serve 116,000 customers, in 2015 290,000 m^3/day is received to serve 139,000 customers. In spite of 20% increase in customer base, inflow had been reduced, this brings about saving energy in treatment process and transmission.

Fernando in his study found those who obtained individual connections through Randya Program moved away from the practice of boiling the water for drinking purpose.

8. Outcome of the study

All engineering activities are done for betterment of human living. An engineering problem of low pressure, wastage of valuable resources, and customer dissatisfaction has been approached by provision of water at affordable cost, the area where formal society doesn't exist they were brought together only for one purpose, in few instances when they found they couldn't co-exist, they voluntarily go for another option within the organization objective. To solve the issue in hand, professionals from other discipline were used for social mobilization and social Marketing.

In this study it shows people are reluctant to change, giving below cost only a few opt for that option, they need to be continuously educated and approached in different ways to find solution based on their comfort zone. When empowered, they take the ownership and continue to maintain for sustainability.

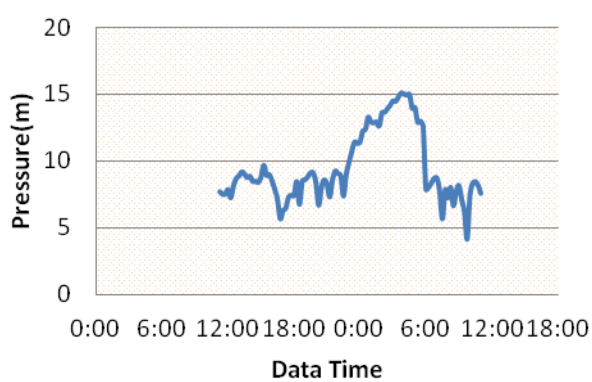


Figure 4: System pressure improvement

When people got water supply to their home there was confidence of quality of water which avoided boiling of water for drinking purpose. Reduction of losses reduced the amount of treated water being pumped to the city. System pressure improvement avoided secondary pumping.

Benefits obtained are;

- System pressure improved enabling everyone to receive water from their garden tap 24/7
- The value of water was understood and self control was implemented resulting in conservation of water
- Maintenance of the water outlet became the responsibility of the users, reducing operational cost
- Wastage was minimized
- Amount of water supplied to these USS are measured
- People living in the USS felt being recognized in the society
- Water that was provided free was converted to revenue
- New water connections were provided without bring in additional water
- Those who obtained water under Randiya Program, access to free water got eliminated reducing the number of users in the society
- Country benefited from reduction in usage of Energy
- NWSDB customers benefited from avoidance of secondary pumping

References

NWSDB, Tenement Garden Directory. 2008, National Water Supply & Drainage Board (NWSDB). CEPA,Survey on Willingness and Ability to Pay for Pro-Poor Household Water Connections, Centre for Poverty Analysis (CEPA). Page 11 – 27, 2009.

Fernando, W.B.G., Socio Economic Benefits of Individual Water Connections for Underserved Settlements in Colombo City. 2013.

CEPA, Analysis of Pro-Poor Service Models for Urban Areas in Sri Lanka, Centre for Poverty Analysis (cepa), 2010.

Thermal Regeneration and Its Applications towards Energy Sustainability in Industrial Pollution Control

A.S.K. Warahena[1*], J.A.A.D. Jayasuriya[1], Y.K. Chuah[2]

[1]*National Engineering Research and Development Centre of Sri Lanka, Ekala, Ja-Ela, Sri Lanka*
[3]*Department of Energy and Air-conditioning and Refrigeration Engineering, National Taipei University of Technology, Taipei 10608, Taiwan*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Same as "the journey is a foot" and "the ocean is a drop", "the energy is a Watt". Every unit of energy utilization as well as transformation should be done in the best effective manner, which would not be naturally happening. As a solution approach, "A national plan with effective multifaceted approach with sustainability in mind" is a critical need of the day for the uninterrupted growth and the sustainability of the nations, and even to face the global competitiveness. The above context is very much significant for the nations' use of thermal energy. This paper identifies the need of sustainability in the thermal energy usage in pollution control, as a growing national importance. The paper discusses the importance of thermal regeneration technique, in heat recovery in "solid waste incineration" and "in thermal oxidation of VOC laden air emissions". Also, the paper introduces a sensitivity parameter X to judge the sensitivity of heat interaction in incineration / oxidation of pollutants.

Key words: regeneration, pollution control, VOC, energy, sustainability

1. Introduction

The extent of thermal energy applications in industrial, commercial, power generation, services, and residential sectors become ever increasing. In propelling the economies, nations and governments are facing an ever increasing challenge of meeting this energy and resource supply irrespective of the national and global situations. Keeping in mind "the energy is a Watt", thermal energy recovery and recycling has an ever increasing importance.

With the addition of a new dimension of keeping the environment clean, thermal energy usage in pollution control become another increasing application. The cumulative thermal energy interaction in pollution control would be counted in megawatts. As an example, in solid waste incineration in hospitals in Sri Lanka, biomedical wastes are burnt at over 900^0C. Raising the temperature of solid wastes and the supply air to such high levels from the ambient temperatures needs an enormous and high quality energy interaction, and in almost all the cases need an external energy supply by means of LPG burning, other than the energy generated by the combustion of the solid waste itself. Similar applications could be seen in solid waste incinerations in some other industries and municipalities.

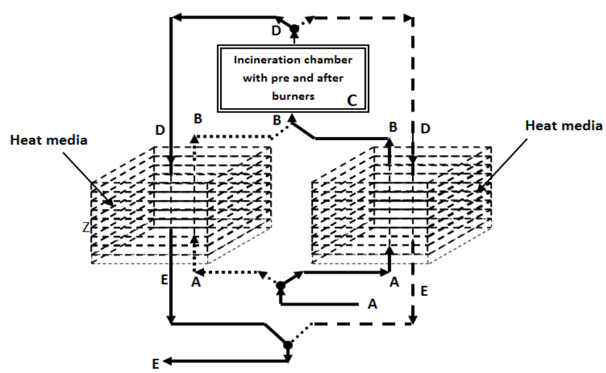
In air pollution due to industrial gas emissions, the man made processes in industry, manufacturing, power-generation, transportation, etc. are accountable for the polluted air emissions causing health and environmental concerns (Brian et al., 2003). Air emissions laden with Volatile organic compounds (VOC) are such health hazardous wastes requiring serious attention. Modern industries such as semiconductors, TFT-LCD, refineries, chemical processing, surface treatment, printing, etc. and even recovery and recycling of some electronic and chemical wastes, are becoming major concerns of VOC emissions nowadays. In many VOC industrial pollution control applications, VOC laden air is thermally-treated by exposing to high temperatures of about 730-850℃ (Warahena, 2009). Such high temperature requirements for VOC thermal oxidation deserve serious attention for heat recovery, because of its high temperature high energy interactions. Technological advancements are being continually sought, to mitigate VOC emission concerns, as well as to improve energy and environment sustainability in VOC abatement processes.

* *Correspondence: aruna.warahena@nerdc.lk*
ISSN 2478-0669 Print

1.2 Thermal regeneration connected with incineration

Heat recovery and recycling is generally being done by using heat exchangers with tube bundles with different configurations. However, the efficiency of the heat exchanger has a practical limitation of around 65%, especially because of the cost factor and the payback period of any more increasing of its size for further efficiency enhancements [3]. However thermal regeneration process has the economic feasibility to reach greater efficiencies in energy recovery and recycling (Warahena and Chuah, 2009).

Heat media which are generally formed as stationary and packed ceramic beds, in such thermal regeneration mechanisms, undergo alternate phases of heat-regeneration (recover) and heat-degeneration (release) due to the periodic reversal of the flow through heat media. When one heat media canister is in heat degeneration mode, the other is in heat regeneration mode. Figure 1 shows a schematic of a heat (thermal) regenerator connected with an incinerator. The thermal regenerator consists of two towers alternately undergoing regenerative and degenerative modes. The periodic reversing of the flow is enabled by control mechanism. Figure 2 shows the process cycle of a thermal regenerator. The complete process cycle comprises of half-cycles of heat-degeneration and heat-regeneration, for each canister. As the effective heat content per canister (tower) is almost fully regenerated or degenerated during the half cycles, the heat exchange efficiency can reach even above 90%. The heat media formed as fixed beds in the towers are used alternatively to recover heat (regeneration) from leaving combusted gasses, and to release heat (degeneration) to preheat pollutant gas or air entering the regenerator system.



A: *Heat degeneration tower inlet pollutant gas /air*

B: *Heat degeneration tower outlet gas / air (entering incinerator/combustion chamber)*

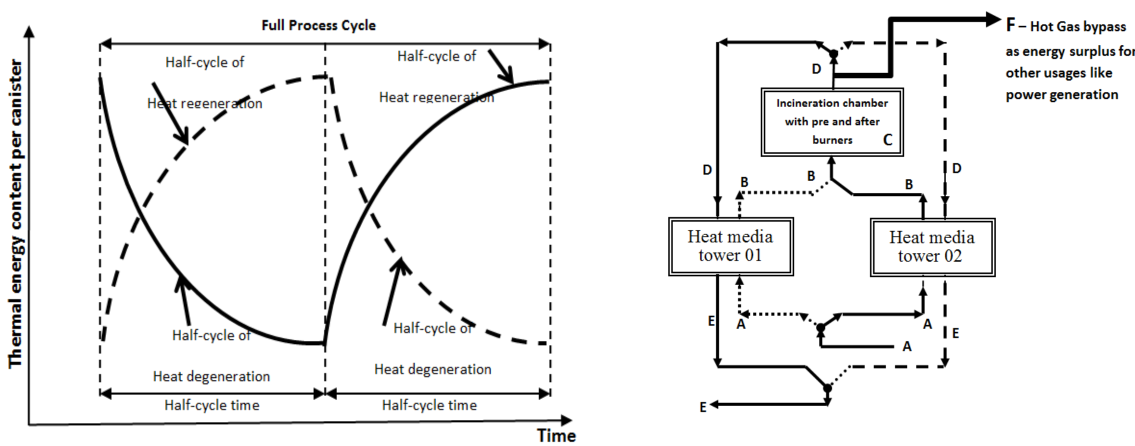
C: Incineration / combustion chamber (process)

D: *Process outlet (Heat regeneration tower inlet)*

E: *Heat regeneration tower outlet to stack*

Z: *Ceramic (heat media) bed height.*

Figure 1: Schematic of a thermal regenerator combined with an incinerator



(a) (b)

Figure 2: (a) Process cycle of a thermal regenerator and (b) Hot gas bypass – F

2. Methodology

2.1 Thermal treatment of solid waste and air emissions laden with pollutant gas and their Thermal energy interaction and heat recovery for energy sustainability;

Considering the "Energy is a Watt", the recovery of heat in thermal oxidation or incineration associated with pollution control has become a serious consideration, nowadays in industry. The formulations given below justify the importance of higher heat recovery in facing the challenges in thermal treatment of solid wastes and pollutant gas laden air. If the recovery efficiency η is defined as,

$$\eta = Q_{Recovery} / Q_T \quad (1)$$

Where;

Q_T = Total heat required to raise the solid wastes to the set Temperature of incineration.

$$Q_T = Q_{Comb} + Q_{Burner} + Q_{Recovery} \quad (2)$$

Where;

Q_{comb} = the heat of combustion of solid wastes

Q_{Burner} = the burner heat

$$Q_{Burner} = (1-\eta) \times Q_T - Q_{Comb} \quad (3)$$

At the point of marginal sustainability the burner heat input is zero, $Q_{Burner} = 0$.

$$\eta = \eta_s = \left(1 - \frac{Q_{Comb}}{Q_T}\right) \quad (4)$$

For "below-sustainable-operation" with burner heat inputs, $Q_{Burenr} \rangle 0$ and $\eta \langle \eta_s$. And for "above- sustainable-operation" with extra heat generation, $Q_{Burenr} \langle 0$, and $\eta \rangle \eta_s$. In such situations with extra heat generation, a portion of hot gas has to be extracted out prior to entering the heat regeneration tower as hot gas bypass, as is shown in Figure 3. This thermal energy from the hot gas bypass can be used for power generation, steam generation, and other thermal processes like heating, drying, etc. (Bannai, 2006).

2.2 All in one solid-waste incineration and all in one polluted-air incineration

In industrial pollutant laden air, as an example in TFT-LCD plant VOC (volatile organic compound) laden airflow emissions with different types of VOCs in different compositions can be seen in Table 1 (RTO Project, 2009).

Table 01: Constituents of VOC emissions in TFT-LCD plant

Main Chemical Compounds	M.W.	Heat of Combustion (kJ/kg)	% by Volume
PGME ($C_4H_{10}O_2$)	90	27660.424	17.71%
PGMEA ($C_6H_{12}O_3$)	131	24815.304	6.14%
Cyclohexanone ($C_6H_{10}O$)	98.14	33597.52	46.33%
1-Butyl acetate ($C_6H_{12}O_2$)	116.16	28212.712	8.07%
Benzene (C_6H_{12})	120.19	6204.872	18.61%
Acetone (C_3H_6O)	58.08	28539.064	3.00%
Average	102.93	26275.52	100.00%

In such air pollution controls, as the viable option, all the pollutants are thermally treated together as a mixture flown together with air. Solid wastes are also coming as collections in bulk and may consist of varieties of matter with a wide range of calorific values and thermal decomposing temperatures. Solid waste segregations and category based pollution control processes and temperature selections for incineration would be viable in some cases, but may not be for bio-medical like wastes.

3. Results and Discussion

3.1 The essentiality of a higher heat recovery, to lessen the sensitivity of higher energy interaction and energy bills, in all-in-one incineration

If "all in one incineration" is the reliable option of pollution abatement, the unnecessary over heating of certain categories of waste including water contents in wastes, would be a trade off in terms of energy for the prevention of health and infection hazards. Such situations warrant the need of heat recovery, as a damping effect on the cost and other impacts of higher energy usage due to the unnecessary extra-heating (overheating) situations associated with individual waste types in non-segregated all in one incineration of pollutant laden matter.

On the other hand, if the heat associated with waste pollution control is well recovered, there would not be any economic viability for the segregation of waste prior to incineration. This too underlines the importance of an enhanced heat recovery in solid waste incineration.

$$Q_{T,i} = Q_{Comb,i} + Q_{Burner,i} + Q_{\mathrm{Re\,cov}er,i}$$

Hence,

$$Q_{X,i} = Q_{T,i} - Q_{N,i} \qquad 5$$

The total cumulative heat Q_T of raising the solid waste items to the set incineration temperature, in all in one oxidation of the waste with no segregation, the sum of the heat sufficient for thermal decomposition of individual segregated solid waste items Q_N , and the resultant Cumulative extra heat Q_X can be expressed below as the summation of itemized solid waste matters.

$$Q_T = \sum_{i=0}^{n} Q_{T,i}, Q_X = \sum_{i-1}^{n} Q_{X,i}, Q_N = \sum_{i=1}^{n} Q_{N,i} \qquad 6$$

$$\sum_{i=1}^{n} Q_{X,i} = \sum_{i=1}^{n} Q_{T,i} = \sum_{i=1}^{n} Q_{N,i}$$

Hence,

$$Q_x = Q_T - Q_N \qquad 7$$

X = the quantity ratio of cumulative extra heat Q_x to total heat

Recovery $Q_{\mathrm{Re}\,ceovery}$ which is an index of the sensitivity of overheating

Against the heat recovery.

Then,

$$X = \frac{Q_X}{Q_{\mathrm{Re\,cov}ery}} \qquad 8$$

Where;

$$Q_{\mathrm{Re\,cov}ery} = \sum_{i=1}^{n} Q_{\mathrm{Re\,cov}ery,i}$$

Therefore from equation 7 and 8, and from the recovery efficiency η defined in equation 1, X can be expressed as,

$$X = \frac{1}{\eta}\left(1 - \frac{Q_N}{Q_T}\right) = A \bullet \frac{1}{\eta} \qquad 9$$

Where;

$$A = \left(1 - \frac{Q_N}{Q_T}\right)$$

In the achievement of heat recoveries through heat exchangers made of tube bundles, if the recovery efficiency η would be limited to 65%.And if this efficiency η is 85% for thermal regeneration. Let $X_{regeneration}$ and $X_{heat\ exchanger\ tubes}$ represent X in the above equation 8, for the respective usage of "thermal regeneration technique" and "tube bundles" for heat recovery. Hence,from the above equation 9,

$$\left(X_{regeneration} - X_{heatexchangertubes}\right) / X_{heatexchangertubes} = A \bullet \left(\frac{1}{0.85} - \frac{1}{0.65}\right) / \left(\frac{A}{0.65}\right) = (-41\%)$$

Accordingly, in all-in-one-incineration implementation of thermal regeneration with higher efficiency would minimize the effect of energy requirement due to extra heating by 41%, when compared with the lesser efficient heat exchanger heat recovery. Furthermore, this reduction in 41% would reflect the reduction in the energy bill as well with a certain degree of proportionality. The energy utilized in the operation of heat exchangers with tube bundles, and that of thermal regeneration process would show some differences. And similarly would be the cost of the equipment. Such economic and operations aspects are necessary in the detailed analysis, prior to the usage of particular heat recovery techniques.And according to the equation 9 , sensitivity of overheating against the heat recovery X behaves exponentially, for smaller or no heat recovery. On the other hand, for larger heat recovery efficiencies (or larger η), X or the sensitivity of overheating of segregated items in all in one incineration seems to be relatively less sensitive.

Also as shown in Figure 4 (a), the smaller the parameter A due to a closeness of Q_T and Q_N , also results in reduced sensitivity of overheating against the heat recovery. This would be possible if the thermally treatable waste matters have closer thermos-physical properties and destructive temperatures.

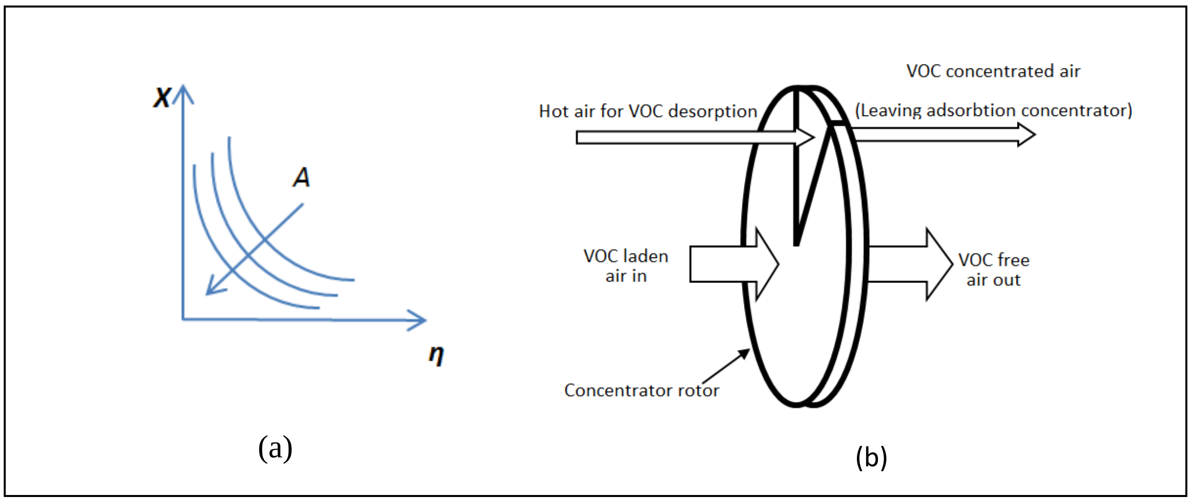


Figure 4: (a) "A" and "η" effect on X and (b) Schematic of VOC concentrator rotor

3.2 Air pollution abatement, thermal energy interaction, and heat recovery

In the handling of large process flow rates in the scale as high as 10^5 m^3 h^{-1}, and also with low VOC concentrations in the scale as low as 10^1ppm, treating VOC at higher temperatures 730 - 850℃ needs a very high energy and operational cost other than the higher cost of the equipment which has to be bigger in size. In order to reduce such economic disadvantage, higher efficiencies of thermal energy recovery is a point of interest. In contrary, achieving higher heat recovery efficiencies in thermal treatment of lean VOC laden air may need larger size of heat recovery equipment, which would be an added cost with an extended payback time of even beyond the equipment usage time period. Instead of such unsegregated all in one incineration, an innovative approach of filtering out VOC free air direct to the stack, results in a technology of using VOC adsorbtion concentration coupled with regenerative thermal oxidations in lean VOC laden gasses.

This adsorption of VOC from the main exhaust air stream with low VOC concentration is often achieved by using Zeolite impregnated honeycomb type concentrator rotors (Lin et al., 2009). The VOC adsorbed into the concentrator rotor is then released to a much smaller desorption air volume but with high temperature. Figure 4 shows the schematic of the use of adsorption concentrator. When the VOC laden air crosses through the adsorber concentrator, VOC is fully adsorbed and the resulted VOC free air leaving the concentrator is directed to the stack. In order to desorb the VOC trapped in the adsorber concentrator, heated fresh air is fed through the desorbtion zone of the concentrator, as shown in the Figure 4. In the rotor concentrator, the desorbed elements of the concentrator is gradually moving towards and into the adsorbtion zone, while the adsorbed elements of the concentrator are gradually moving towards and into the desorbtion zone. Likewise, the concentrator’s Pi-shaped elements are experiencing a smooth and alternate nature of adsorption and desorption.

$$C_{effect} = \frac{C_{voc,out}}{C_{voc,in}} \qquad 10$$

Where;

C_{effect} = Concentrator effect as the ratio of VOC concentrations of leaving and entering desorb concentrator

$C_{voc,in}$ = Concentrations of the VOC streams entering the desorb concentrator

$C_{voc,out}$ = Concentrations of the VOC streams leaving the desorb concentrator

The increased VOC concentrations as well as reduced process air volume have the potential for both the equipment size reduction and sustainable VOC combustion, which also results in lowering of equipment and operating costs. Lean VOC laden air possesses higher values of the sensitivity parameter *X*, and the use of concentrator rotor effectively reduces the value of *X*. Furthermore, the reduction of the value of X and the reduction of the equipment size would be simultaneous, and working towards the minimization of *X* would provide the directions for technology innovation in the thermal treatment of pollutants.

Furthermore, as beyond the limits of sustainability, for higher VOC concentrations, the heat of combustion could exceed the amount of heat recovery. In such instances, the extra heat or surplus energy can be utilized in the other applications such as running of boilers or in the other thermal processes, as well as in power generations. In such instances, higher heat recovery by using thermal regeneration would be important. Also as shown in figure 5, hot air for VOC desorption can be taken as fresh air absorbing a portion of heat from the thermally treated got gas leaving the thermal oxidizer.

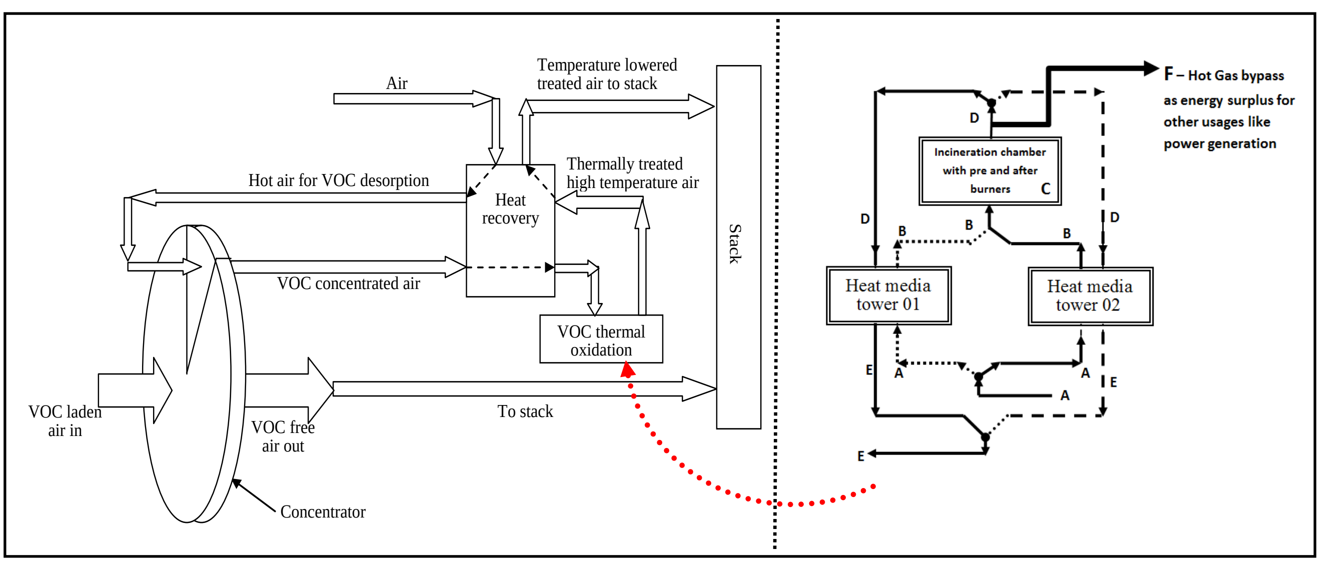


Figure 5: Higher heat recovery by using thermal regeneration

4. Conclusion

Cumulative interaction of thermal energy in thermal oxidation pollutants would be counted in megawatts. Thermal regeneration technology is important for the sustainability in all-in-one or non-segregated thermal oxidation/incineration in VOC laden air and solid waste treatments. Working towards the minimization of the sensitivity parameter X would provide the effective heat interaction in the thermal treatment of pollutants. Hot gas bypass, and its usage in other thermal applications like steam and power generations are the opportunities seen in the thermal treatment of pollutants with higher efficient heat recoveries. The usage of VOC concentrator rotor like technologies as a strategy for the controlling of equipment and operational costs would be important in sustainable pollution control in large volume of air flows laden with lean VOC concentrations.

References

Ozil, F., Tschamber, V., Haas, F.and Trouvé, G. 2009. Efficiency of catalytic processes for the reduction of CO and VOC emissions from wood combustion in domestic fireplaces.

Bannai,M., Houkabe, A., Furukawa, M., Kashiwagi, T., Akisawa, A., Yoshida, T.and Yamada, H. 2006. Development of efficiency-enhanced cogeneration system utilizing high-temperature exhaust-gas from a regenerative thermal oxidizer for waste volatile-organic-compound gases.

Brian,J. and Cannon, D. 2003. Dual-Chamber RTO Oxidizers Provide Cost-Effective VOC Compliance for Metal Finishers and Coaters, Metal Finishing. Vol.101 (1): 53-56.

Desiccant Technology Corporation. 2009. RTO Project proposal for a TFT-LCD fab, Taiwan.

Lin, Y.H. and Chang,F.T. 2009. Optimizing operating parameters of a honeycomb zeolite rotor concentrator for processing TFT-LCD volatile organic compounds with competitive adsorption characteristics.

Passanta, N.R., Richardsona, S.R., Swannell, R.P.J., Gibsona, N., Woodfielda, M.J., Lugtb, J.P., Wolsinkb J.H. and Hesselink, P.G.M. 1993. Emissions of volatile organic compounds (VOCs) from the food and drink industries of the European community.

Warahena, A.S.K. and Chuah, Y.K. 2009. Energy recovery efficiency and cost analysis of VOC thermal oxidation pollution control technology, Environmental Science & Technology.

Warahena, A.S.K. and Chuah, Y.K. 2007. Analytical model for transient and stabilized conditions of RTO operation, IEEE conference proceedings of ICIAfS (included in IEEE Xplore)

Site Selection and Basic Design Configuration for Pumped Storage Power Plants and Pumped Storage Power Plant Complexes

M.T.A.P. Wickramarathna*

Ceylon Electricity Board, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Sri Lanka is currently looking forward for the coal based power plants for its power requirement. Currently one coal power plant is in operation along the west coast of the island with an installed capacity of 3 X 300MW. As per the national energy plan there will be more than 10 new coal power plants to be introduced to the power system in future.

In Sri Lanka the electricity demand rapidly varies with the time. The daily load curve shows a minimum of 1000MW during off peak time whereas during peak hours it rises to 2150 MW. These kind of rapid variations in load results in coal power plants are being operated with low efficiency. Such situations created opportunities for and emphasizes the importance of having storage power plants in the power system of Sri Lanka. Pumped storage power plant (PSPPs) is one of such storage power plant that could be deployed in Sri Lanka. Country's natural geography is suitable to facilitate nearly 5000MW of PSPPs and some attractive sites are already been identified. Most importantly some of them can be designed as the Pumped Storage Power Plant Complexes. A common large upper pond or lower pond can be utilized by two or more lower ponds or upper ponds form a PSPP complex. The economic viability of having PSPPs in Sri Lanka can be improved with this kind of PSPP complexes and this paper is to discuss the basic design principles of proposed PSPP complexes in Sri Lanka.

Key words: electricity *demand, coal based power, pumped storage power plant complexes*

1. Introduction

Why do people need electricity? Because electricity runs most of their essentials, give comfort etc. Not only that the country's economy totally depends on electricity supply. Sri Lanka has reached the national electrification ratio of 99.5% by now. The maximum demand is around 2164MW while the installed capacity is 3362MW (Statistical Digest 2013, CEB). Sri Lanka has to run expensive thermal power in the peak demand time. At present Sri Lanka has 900MW coal power plants but they cannot run efficiently at full load during off peak time and some parts of the day peak. In year 2013, peak demand is around 2150MW while off peak is around 1000MW. This off peak demand is maintained by the utility by giving subsidized tariff for Industries, Hotels and General Purpose customers at off peak time. As an example the off-peak tariff is Rs. 5.90 while peak tariff is Rs. 23.50 for Industrial-3 customers. That means peak tariff is four times than off peak tariff which does not reflect the actual cost of the unit electricity. By reducing the rapids of the load curve using PSPP, Sri Lanka may be able to produce cheap electricity while giving actual cost reflective low tariff for their customers.

The attractive sites have been identified for the PSPP in Sri Lanka. They are along Kiriketi Oya in Haputale; Halgran Oya in Hanguranketha; Maha Oya, Kuda Oya, Mal Oya and Gurugal Oya in Gampola and Dambagastalawa Oya in Nuwara Eliya. Most importantly some of them can be designed as the Pumped Storage Power Plant Complexes. A common large upper pond or lower pond can be utilized by two or more lower ponds or upper ponds form a PSPP complex.

2. Methodology

2.1 Establishment of criteria to locate a project site

Table 1 shows the criteria used for determining the sites of PSPPs in a reconnaissance study and their expected status. For example, the selected site should be suitable for the construction of a power plant more than 250 MW in capacity and should run for six hours during the period of higher demand each day.

* *Correspondence: twickramarathna@yahoo.com*

ISSN 2478-0669 Print

Table 1: Criteria for pumped storage power project finding in Sri Lanka

	Issue	Item	Criteria status
Technical	Generation Plan	-Peak duration time	-6 hrs
	Limit of manufacturing of power facility	-Installed Capacity	-More than 250 MW
		-Design Head	-More than 500m of maximum head
		-Max. utilizing water depth of pond	-Less than 75m
	Location / Layout	-Catchment area	-More than 5km^2 (total of upper, lower dams diverted)
		-Dam crest length	-Less than 500m
		-Dam height	-Less than 180m
		-Length of water way	-Less than 10 Km
		-L/H ratio	-Less than 10
		-Overburden of underground power cavern	-Less than 1020m
	Geological conditions	-Active fault	-Avoid the zone of active faults and those Quaternary Era
		-Base rock conditions especially for underground power cavern	-Avoid the area of Quaternary Era and weak and unconsolidated strata
Environmental	Natural	-Protected Area (e. g. Nature Reserves)	-Beyond the confines of protected Areas (Natural Parks and reserves)
		-Endangered species	-Avoid the critical habitats of important fauna and flora
	Social	-Mining right	-Avoid the area of mining concession
		-Historical and Cultural heritage	-Avoid being submerged
		-House to be submerged	-Necessary to consider

2.2 Selecting sites for PSPPs

The suitable sites were searched using the 1:50,000 scale topographical maps. Basically natural location for the reservoir and dam with enough reservoir volume with minimum environmental and social (avoid forests, natural parks, Historical & Cultural heritage, cities with high population density as far as possible) effects and the locations which has a L/H ratio less than 10 were considered. The detailed Analysis was done for the selected sites, using 1:10,000 scale topographical maps. The basic design and the calculation were done for each PSPP using the 1:10,000 scale topographical maps. The following table shows the basic details of the selected sites for PSPP.

The locations and design parameters for the four PSPPs each with 500MW capacity, namely Kiriketi I, Keriketi II, Keriketi II and Halgran PSPPs were discussed in the Hydro 2011 conference. This paper discusse the details of locations and design parameters of the remaining PSPPs.

2.3 Maha pumped storage power plant complex

The project is to be situated on the Maha Oya, in the Gampola area, No. 61, 1:50,000 map. There are two options for the Upper Pond. The two Upper Ponds are in Kandy district, Central Province and Lower Pond is in Kegalla district, Sabaragamuwa Province of the Sri Lanka. Travelling a distance is 90 kilo- meters from Colombo on the Colombo-Kandy road. The principal features of the Project; are given in Table 3.

Table 2: Summery of candidate PSPP

No.	Name of the Pumped Storage Complex	Name of the Pumped Storage Plant	Project Feature				1:50,000 Map No.
			Capacity (MW)	Length L (m)	Rough Height H (m)	Ratio L/H	
1	Maha PSPP	Uduwella PSPP	500	4,110	410	10.0	61
2		Alugolla PSPP	500	3,890	510	7.6	61
3	KMG PSPP	Mul PSPP	250	4,510	400	11.3	61
4		Gurugal PSPP	500	5,320	650	8.2	61
5		Puna-Kotmale PSPP	500	6,570	700	9.4	61
6		Dambagastalawa PSPP	300	2,840	470	6.0	68
7		Agra PSPP	300	3,640	330	11.0	68

Figure 1: MAHA pumped storage power plant complex in 1:50,000 map

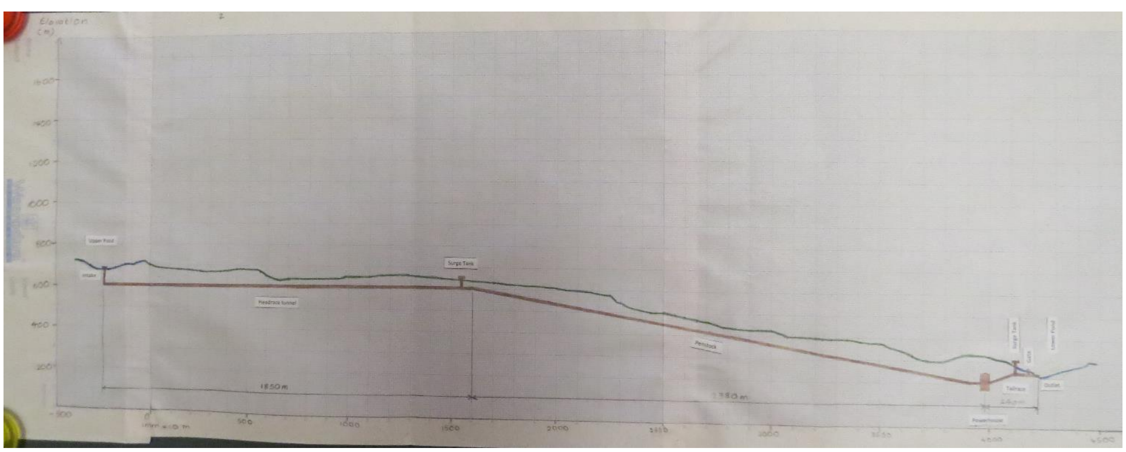


Figure 2 : Waterway profile of Uduwella upper pond to Arama lower pond

Table 3: Summery of basic design configuration of Maha PSPP complex

	Maha pspp complex	Uduwella pspp	Alugolla pspp
Project	Installed Capacity P (MW)	500	500
Specification	Designed Discharge Q (m^3/s)	152	121
	Effective Head H_e (m)	387.6	485.2
	Peak Duration Hours	6	6
Upper Reservoir	Dam Type	Rock Fill	Concrete Gravity
	Dam Height (m)	32	41
	Crest Length (m)	340	260
	Reservoir Volume at FSL (Mil m3)	3.38	2.6
	H.W.L (m)	714	814
	L.W.L (m)	694.45	785
	Usable Water Depth (m)	19.55	29
Lower Reservoir	Dam Type	Concrete Gravity	
	Dam Height (m)	57	
	Crest Length (m)	350	
	Reservoir Volume at FSL (Mil m3)	5.94	
	H.W.L (m)	300	
	L.W.L (m)	267.2	
	Usable Water Depth (m)	32.8	
	Headrace (m)	1850	2350
Water way	Penstock (m)	2400	1320
	Tail Race (m)	200	430
Power House	Type	Underground	Underground
L/H		10.64	7.86
Construction Period (yrs)		6	6
Average Rainfall (mm)		1450	1450

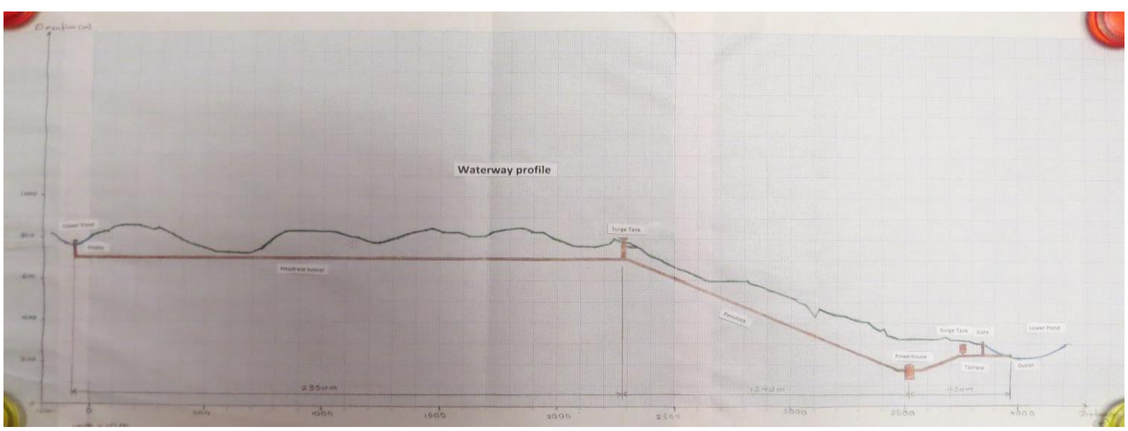


Figure 3: Waterway profile of Alugolla upper pond to Arama lower pond

3. Results and Discussion

3.1 Calculation of catchment area

When the dam site is selected, the watershed is checked using the topographic map. Catchment Area of "Arama" Lower Pond: 17.725 km^2 ,Catchment Area of "Uduwella" Upper Pond: 4.8754 km^2,Catchment Area of "Alugolla" Upper Pond: 2.725 km^2.

3.2 Preparation of storage capacity curve

The reservoir area at each elevation is measured with a planimeter on a topographic map, and the water storage capacity curves shown in Figure 6, Figure 7 and Figure 8 are prepared.

3.2.1 Temporary fixing of maximum plant discharge

The maximum plant discharge is obtained by the following equation;

Uduwella upper pond: $$Q_{max} = \frac{P}{9.8 \times H \times \eta} = \frac{500{,}000kW}{8.5 \times 410} = 143.5m^3/s \quad (1)$$

Alugolla upper pond : $$Q_{max} = \frac{P}{9.8 \times H \times \eta} = \frac{500{,}000kW}{9.5 \times 510} = 115.3m^3/s \quad (2)$$

Where;

Q_{max}	=	Maximum plant discharge (m^3/s)
P	=	Maximum output (kW)
H	=	Head (Difference in riverbed elevation between upper and lower dams[1650m-880m])
η	=	Combined efficiency at maximum output, the value $9.8 \times \eta = 8.5$ should be used in the study.

3.2.2 Determination of storage capacity of pond

The peak duration hour is set at 6 hours to obtain the active storage capacity.

$$V_e = Q_{max} \times T \times 3600 \quad (3)$$

Where;

Ve = Effective storage capacity (m^3)

T = Peak duration hours (hr)

Uduwella upper pond	=	3,099,600 CM
Alugolla upper pond	=	2,491,349 CM
Arma lower pond	=	5,590,949 CM

3.2.3 Estimation of sediment volume and determination of sedimentation level

3.2.3.1 Estimation of Sediment Volume

The sedimentation level is determined by estimating sedimentation for 100 years. The sediment volume is estimated as follows provided that qs is assumed to be $200m^3/km^2/year$.

$$V_s = qs \times Ca \times 100 \quad (4)$$

Where;

Vs	=	Sediment volume for 100 years (m^3)
qs	=	Specific sediment yield ($m^3/km^2/year$)
Ca(d)	=	Catchment area at dam site (km^2)

Uduwella Upper Pond	=	$200m^3/km^2/year \times 0.4.87454\ km^2 \times 100years$	=	$97{,}508\ m^3$
Alugola Upper Pond	=	$200\ m^3/km^2/year \times 2.725\ km^2 \times 100years$	=	$54{,}500\ m^3$
Arama Lower Pond	=	$200\ m^3/km^2/year \times 17.725\ km^2 \times 100years$	=	$354{,}500\ m^3$

3.2.3.2 Setting of Sedimentation level

The sedimentation level is obtained as follows based on the reservoir area and storage capacity curve as shown below.

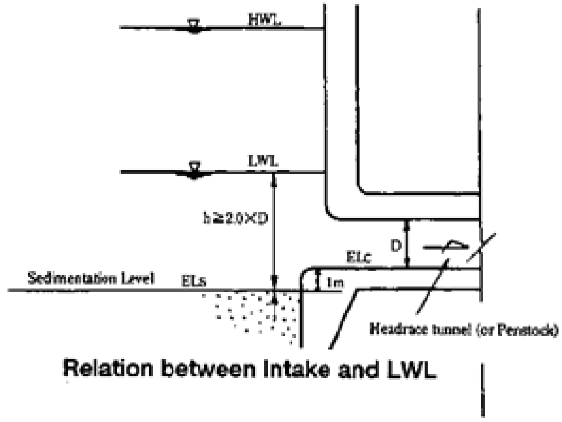


Figure 4: Setting of sedimentation level

Uduwella Upper Pond: EL 683.25m, Alugola Upper Pond: EL 775.00m, Arama Lower Pond: EL 256.00m.

3.3 Determination of water level (upper and lower ponds)

3.3.1 Low water level

The low water level (LWL) is set at a position of about twice the inner diameter (D) of the headrace tunnel above the sedimentation level as shown in Figure 5, to prevent intrusion of air into the tunnel.

$$Q = \pi \times D^2 \times 6m/s \quad (5)$$

Where;

Q = Plant Discharge (m^3/s)

D = Diameter of Headrace Tunnel (m)

The tunnel inner diameter is here obtained as follows by setting the flow velocity at 6 m/s.
Uduwella PSPP is 5.6m and Alugolla PSPP is 5m.

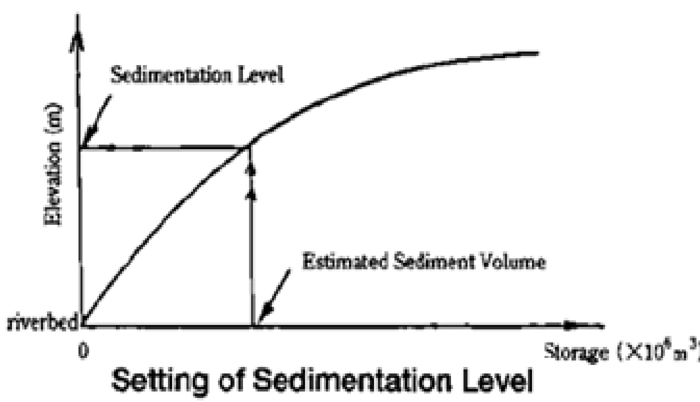


Figure 5: Relation between intake and LWL

Thus the low water level (LWL) is calculated as below.

Uduwella Upper Pond	=	*EL 683.25m + 2x5.6*	=	*EL. 694.45 m*
Alugolla Upper Pond	=	*EL 775.00m + 2x5.0*	=	*EL. 785.0 m*
Arama Lower Pond	=	*EL 256.00m + 2x5.6*	=	*EL. 267.2 m*

3.3.2 High Water Level

The high water level (HWL) is determined by using the storage capacity curves shown in Figure 6, Figure 7, adding the low water level (LWL) to the available drawdown (ha) corresponding to the effective storage capacities are obtained by equation.

$$Ve = Q_{max} \times T \times 3600 \qquad 6$$

Thus the high water level (HWL) is calculated as below.

Uduwella Upper Pond	=	*LWL 694.45 m + ha 19.55m*	=	*HWL 714m*
Alugolla Upper Pond	=	*LWL 785.0 m + ha 29*	=	*HWL 814m*
Arama Lower Pond	=	*LWL 267.2 m + ha 32.8m*	=	*HWL 300m*

Where;
ha =Available drawdown (m)

3.4 Determination of normal intake water level and tailwater level

The normal intake water level and tailwater level which correspond to mean water levels of both reservoirs are determined by the following equation.

$$HWL\ (U) - ha(U)/3 \qquad 7$$

Uduwella Upper Pond	=	*MWL(U)*	=	*714 m – 19.55 m/3*	=	*707.5 m*
Alugolla Upper Pond	=	*MWL(U)*	=	*814 m – 29 m/3*	=	*804.3 m*
Arama Lower Pond	=	*TWL(L)*	=	*300 m – 32.8 m/3*	=	*289.1 m*

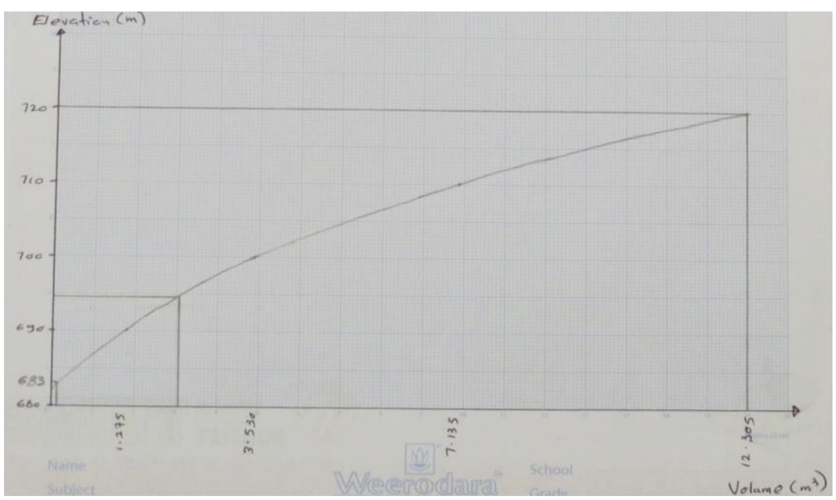


Figure 6: Uduwella upper pond - capacity curve

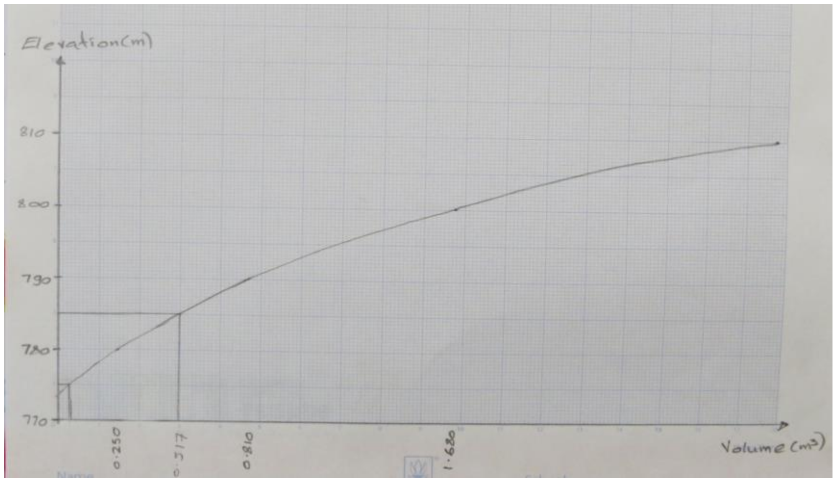


Figure 7: Alugolla upper pond- capacity curve

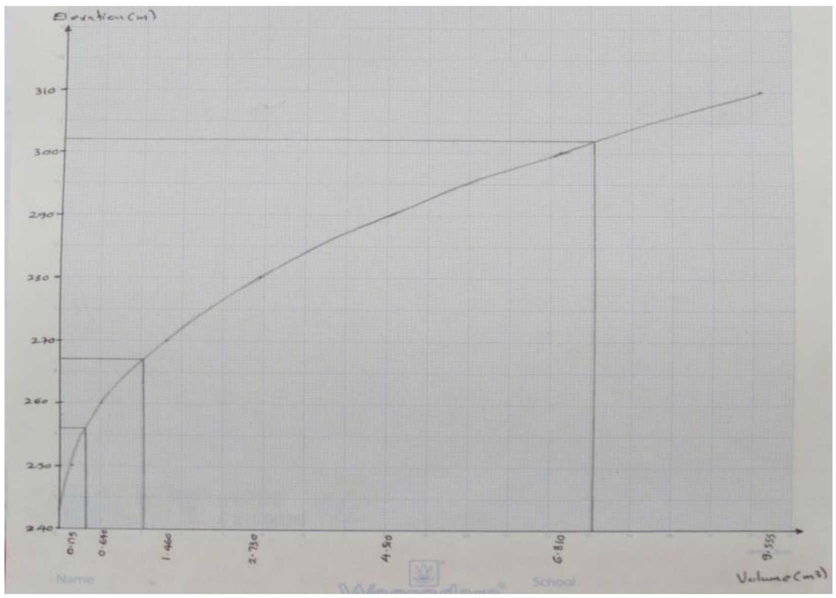


Figure 8: Arama lower pond - capacity curve

Where;

HWL, LWL, ha	=	High water level, low water level and available drawdown (m) of upper pond (U) and lower pond (L), (m)
MWL	=	Normal intake water level (m);
TWL	=	Normal tailwater level (m)
ha	=	Available drawdown (m)

3.4 Preparation of waterway profile

3*.5.1 Setting the elevation of turbine center*

The turbine center is set at the elevation corresponding to the draft head below the low water level of the lower pond as described in the following formula.

- For Uduwella PSPP

Elevation of Turbine Center = LWL (Lower Pond) – Draft Head (m) 8

= LWL 267.2m - 56m = EL 211.2m

- For Alugolla PSPP

Elevation of Turbine Center = LWL (Lower Pond) – Draft Head (m) 9

= LWL 267.2m - 64m = EL 203.2m

- For Uduwella PSPP (Head Loss ignored)

Maximum Pumping Head (m) = *HWL (Upper Pond) – LWL (Lower Pond) + Head Loss* 10

= 714m – 267.2m = 446.8m

- For Alugolla PSPP - (Head Loss ignored)

Maximum Pumping Head (m) = *HWL (Upper Pond) – LWL (Lower Pond) + Head Loss* 11
= 814m – 267.2m = 546.8m

Draft Head is obtained from the relation between the maximum pumping head and draft head as shown in Figure 9:

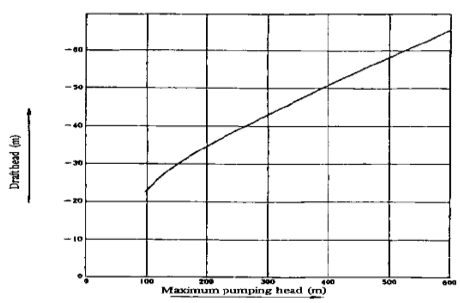


Figure 9: Relation between the maximum pumping head and draft head

Dam specification and turbine centerDam specifications (HWL and LWL) and the elevation of turbine centre of the power plant are determined as below.

Uduwella Upper Pond	=	*HWL: 714m; LWL: 694.45 m*	=	*Available drawdown: 19.55 m*
Alugolla Upper Pond	=	*HWL: 814 m; LWL: 785 m*	=	*Available drawdown: 29 m*
Arama Lower Pond	=	*HWL: 300 m; LWL: 267.2 m*	=	*Available drawdown: 32.8 m*
Turbine Center for Uduwella PSPP	=	*EL: 211.2 m*		
Turbine Center for Alugolla PSPP	=	*EL: 203.2 m*		

3.5.2 Calculation of head loss and effective head for uduwella pspp

The effective head is calculated on the basis of the following equation.

$$H_g = MWL - TWL - \frac{ha}{3} - TWL = 707.5m - 289.1m = 418.4m \quad 12$$

$$H_l = a \times L_1 + b \times L_2 + c \times L_3 + \Delta h = 1/300 \times 1850 + 1/100 \times 2400 + 1/300 \times 200 + 3.5 = 30.8$$
13

$$H_e = H_g - H_l = 418.4 - 30.8 = 387.6$$
14

Where;

MWL	=	Normal intake water level (m)	=	707.5 m
TWL	=	Tailwater level (m)	=	289.1 m
H_g	=	Gross head (m)	=	418.4 m
H_l	=	Head loss (m)	=	30.8 m
H_e	=	Effective head (m)	=	387.6 m
L_1	=	Length of headrace (m)	=	1850 m
L_2	=	Length of penstock (m)	=	2400 m
L_3	=	Length of tailrace (m)	=	200 m
Δh	=	Other head losses (m)	=	3.5 m
a	=	Coefficients to obtain losses, Pressure headrace tunnel	=	1/300
b	=	Coefficients to obtain losses, Penstock	=	1/100
c	=	Coefficients to obtain losses. Pressure tailrace tunnel	=	1/300

3.6 Calculation of head loss and effective head for alugolla PSPP

The effective head is calculated on the basis of the following equation.

$$H_g = MWL - TWL = HWL - \frac{h_a}{3} - TWL = 804.3m - 289.1m = 515.2m \quad 15$$

$$H_l = a \times L_1 + b \times L_2 + c \times L_3 + \Delta h = 1/300 \times 2350 + 1/100 \times 1320 + 1/300 \times 430 + 3.5 = 30m \quad 16$$

$$H_e = H_g - H_l = 515.2 - 30 = 485.2 \quad 17$$

Where;

MWL	=	Normal intake water level (m)	=	804.3 m
TWL	=	Tailwater level (m)	=	289.1 m
H_q	=	Gross head (m)	=	515.2 m
H_l	=	Head loss (m)	=	30 m
H_e	=	Effective head (m)	=	485.2 m
L_1	=	Length of headrace (m)	=	2350 m
L_2	=	Length of penstock (m)	=	1320 m
L_3	=	Length of tailrace (m)	=	430 m
Λh	=	Other head losses (m)	=	3.5 m 3.6

3.7 Re-calculation of maximum plant discharge-uduwela PSPP

The normal effective head (Hes) 387.6 m is determined and the maximum plant discharge is then determined from the following equation.

$$Q_{max} = \frac{P}{9.8 \times H \times \eta} = 500{,}000kW / (8.5 \times 387.6m) = 152m^3 / s \quad 17$$

3.8 Re-calculation of maximum plant discharge-alugolla PSPP

The normal effective head (Hes) 485.2 m is determined and the maximum plant discharge is then determined from the following equation.

$$Q_{max} = \frac{P}{9.8 \times H \times \eta} = 500{,}000kW / (8.5 \times 485.2m) = 121m^3 / s \quad 18$$

3.9 Calculation of annual energy generation-Uduwella PSPP

The annual energy generation is obtained by the following equation.

$$E = P \times T = 500{,}000kW \times 2190 hours = 1095GWh \quad 19$$

Where;

E = Annual energy generation (kWh)

T = Annual generating hours (hrs)

3.10 Calculation of reservoir volume-Uduwella PSPP

$$V_e = Q_{max} \times T \times 3600 = 152\frac{m^3}{s} \times 6hrs \times 3600 = 3{,}282{,}200CM \quad 20$$

3.11 Calculation of reservoir volume-Alugolla PSPP

$$V_e = Q_{max} \times T \times 3600 = 121\frac{m^3}{s} \times 6hrs \times 3600 = 2{,}613{,}600CM \quad 21$$

3.12 KMG pumped storage power plant complex

The project is to be situated on three streams namely Kuda Oya, Mul Oya and Gurugal Oya, in the Gampola area, No. 61, 1:50,000 map. The upper ponds are in Mul Oya and Gurugal Oya. All the three ponds are in the Nuwara Eliya district, Central Province of the Sri Lanka. The principal features of the Project are given in Table 4.

3. 13 Puna-Kotmale pumped storage power plant

The project is to be situated on the Puna Oya and Kotmale Oya which are connected to Kotmale Oya reservoir in the Nuwara Eliya district, Central Region of the Sri Lanka. The principal features of the Project are given in Table 5.

3.14 Dambagastalawa pumped storage power plant

The project is to be situated on the Dambagastalawa Oya, near Ambewela, Pattipola feilds in the Nuwara Eliya district, Central Region of the Sri Lanka. The principal features of the Project are given in Table 6.

Table 4: Summery of basic design configuration of KMG PSPP Complex

	KMG PSPP complex	KM PSPP	KG PSPP
Project	Installed Capacity P (MW)	250	500
Specification	Designed Discharge Q (m^3/s)	80.2	98.25
	Effective Head H_e (m)	366.7	598.7
	Peak Duration Hours	6	6
Upper Reservoir	Dam Type	Concrete Gravity	Rock Fill
	Dam Height (m)	53	64
	Crest Length (m)	220	420
	Reservoir Volume at FSL (Mil m^3)	1.732	2.122
	H.W.L (m)	1114	1348
	L.W.L (m)	1086	1305.8
	Usable Water Depth (m)	28	42.2
Lower Reservoir	Dam Type	Rock Fill	
	Dam Height (m)	24	
	Crest Length (m)	260	
	Reservoir Volume at FSL (Mil m3)	3.854	
	H.W.L (m)	708	
	L.W.L (m)	694.3	
	Usable Water Depth (m)	13.7	
	Headrace (m)	1120	3280
Water way	Penstock (m)	2320	1220
	Tail Race (m)	1260	1560
Power House	Type	Underground	Underground
L/H		11.6	9.0

Table 5: Summary of basic design configuration of Puna-Kotmale PSPP

Puna-Kotmale PSPP		
Project Specification	Installed Capacity P (MW)	500
	Designed Discharge Q (m^3/s)	88
	Effective Head H_e (m)	666.5
	Peak Duration Hours	6
Upper Reservoir	Dam Type	Concrete Gravity
	Dam Height (m)	49
	Crest Length (m)	270
	Reservoir Volume at FSL (Mil m3)	1.9
	H.W.L (m)	1503
	L.W.L (m)	1471.4
	Usable Water Depth (m)	31.6
Lower Reservoir	Dam Type	Concrete Gravity
	Dam Height (m)	57
	Crest Length (m)	220
	Reservoir Volume at FSL (Mil m3)	1.9
	H.W.L (m)	790
	L.W.L (m)	775.4
	Usable Water Depth (m)	14.6
Water way	Headrace (m)	4110
	Penstock (m)	2230
	Tail Race (m)	430
Power House	Type	Underground
L/H		9.4

Table 6: Summary of basic design configuration of Dambagastalawa PSPP

Dambagastalawa PSPP		
Project Specification	Installed Capacity P (MW)	300
	Designed Discharge Q (m^3/s)	79
	Effective Head H_e (m)	445.8
	Peak Duration Hours	6
Upper Reservoir	Dam Type	Rock Fill
	Dam Height (m)	26
	Crest Length (m)	440
	Reservoir Volume at FSL (Mil m3)	1.7
	H.W.L (m)	1831
	L.W.L (m)	1813
	Usable Water Depth (m)	18
Lower Reservoir	Dam Type	Rock Fill
	Dam Height (m)	28
	Crest Length (m)	280
	Reservoir Volume at FSL (Mil m3)	1.7
	H.W.L (m)	1363
	L.W.L (m)	1351.5
	Usable Water Depth (m)	11.5
Water way	Headrace (m)	1760
	Penstock (m)	850
	Tail Race (m)	690
Power House	Type	Underground
L/H		6.0

3.15 Agra pumped storage power plant

The project is to be situated on the Agra Oya, near Pattipola field in the Nuwara Eliya district, Central Region of the Sri Lanka. The principal features of the Project are given in Table 7.

Table 7: Summary of basic design configuration of Agra PSPP

AGRA PSPP		
Project Specification	Installed Capacity P (MW)	300
	Designed Discharge Q (m^3/s)	86.9
	Effective Head H_e (m)	406
	Peak Duration Hours	6
Upper Reservoir	Dam Type	Rock Fill
	Dam Height (m)	22
	Crest Length (m)	440
	Reservoir Volume at FSL (Mil m3)	1.9
	H.W.L (m)	1827
	L.W.L (m)	1813.2
	Usable Water Depth (m)	13.8
Lower Reservoir	Dam Type	Rock Fill
	Dam Height (m)	36
	Crest Length (m)	250
	Reservoir Volume at FSL (Mil m3)	1.9
	H.W.L (m)	1401
	L.W.L (m)	1389.2
	Usable Water Depth (m)	11.8
Water way	Headrace (m)	120
	Penstock (m)	630
	Tail Race (m)	2730
Power House	Type	Underground
L/H		11.0

4. Conclusion

The summary of the basic design configuration of the four main sites are given in Table 8.

Table 8: The Summary of the basic design configuration of the four main sites

		MAHA PSPPC		KMG PSPPC				
	Design Configurations	Uduwella PSPP	Alugolla PSPP	KM PSPP	KG PSPP	PUNA-KOTMALE PSPP	DAMBA GASTA LAWA PSPP	AGRA PSPP
Project Specification	Installed Capacity P (MW)	500	500	250	500	500	300	300
	Design Discharge Q (m3/s)	152	121	80.2	98.25	88	79	86.9
	Effective head He (m)	387.6	485.2	366.7	598.7	666.5	445.8	406
	Peak Duration Hours	6	6	6	6	6	6	6
Upper Reservoir	Dam Type	Rock fill	Conc. Gravity	Conc. Gravity	Rock fill	Conc. Gravity	Rock fill	Rock fill
	Dam Height	32	41	53	64	49	26	22
	Crest Length	340	260	220	420	270	440	440
	Reservoir Volume at FSL (million m3)	3.38	2.6	1.732	2.122	1.9	1.7	1.9
	HW (m)	714	814	1114	1348	1503	1831	1827
	LWL (m)	694.45	785	1086	1305.8	1471.4	1813	1813.2
	Usable Water Depth (m)	19.55	29	28	42.2	31.6	18	13.8
Lower Reservoi	Dam Type	Concrete Gravity		Rock fill		Conc. Gravity	Rock fill	Rock fill

r	Dam Height (m)	57		24		57	28	36
	Crest Length (m)	350		260		220	280	250
	Reservoir Volume at FSL (million m3)	5.94		3.854		1.9	1.7	1.9
	HWL (m)	300		708		790	1363	1401
	LWL (m)	267.2		694.3		775.4	1351.5	1389.2
	Usable Water Depth (m)	32.8		13.7		14.6	11.5	11.8
Water way	Headrace (m)	1850	2350	1120	3280	4110	1760	120
	Penstock (m)	2400	1320	2320	1220	2230	850	630
	Tail Race (m)	200	430	1260	1560	430	690	2730
L/H		10.64	7.86	11.6	9	9.4	6	11
Power House Type		Undergr	Undergr	Undergr	Undergr	Undergr	Undergr	Undergr

References

Guide Manual for Development Aid Programs and Studies of Hydro Electric Power Projects, New Energy Foundation, Tokyo, Japan 1996

Economical Evaluation of Pumped Storage Power Plant Complexes and Comparison with Other Candidate Pumped Storage Power Plants Proposed for Sri Lanka

M.T.A.P. Wickramarathna*

Ceylon Electricity Board, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

The daily electricity demand in Sri Lanka varies significantly with the time. The daily maximum demand occurs between 06,30pm to 09,30pm and the lowest demand occurs between 00.30am to 04.30am. The maximum demand is more than twice the lowest demand. According to the Ceylon Electricity Board (CEB) Long Term Generation Plan 2013~2032, 16 number coal power plants with 4700MW will be added to the Sri Lanka power system in future. For economic operation of coal power plants in a power system which has significantly varying load throughout the day, significantly emphasis the requirement of energy storage mechanism such as Pumped Storage Power Plant (PSPP). The studies reveal that Sri Lanka has several attractive natural sites for Pumped Storage Power Plants, among which two sites can develop as Pumped Storage Power Plant Complexes (PSPPC). This paper present the economic evaluation of possible sites and the findings show that developing 1000MW Maha Pumped Storage Power Plant Complex would be the most economical candidate site when considering the capacity requirement with the time.

Keywords: pumped storage power plant complex, construction cost, B/C, EIRR

1. Calculation method

The calculations were done by the measured values based on layouts done on 1:10,000scale topographical maps and formulae based on the quantities of existing facilities. These formulae used were developed in Japan for the purpose of the hydropower potential study. These formulas are prepared for each facility such as intake weir, intake, and headrace etc. The quantities of works are calculated for main work items such as excavation, concrete, embankment, reinforcement bars, gates, screens, and steel conduits.

Following symbols and units are used in the calculation. V_e :Excavation volume (m^3), V_c :Concrete volume (m^3), V_f :Dam embankment volume (for fill dam) (m^3), W_r :Weight of reinforcement bars (ton), W_g :Weight of gate (ton), W_p :Weight of steel conduit (ton), W_s:Weight of screen (ton). Quantities of work items other than main work items are not calculated. However, their costs are calculated as “others” in a lump-sum at a certain ratio against the total cost of main work items. Quantities of works of headrace tunnels and penstock are calculated based on their inner diameters.

2. Conditions for construction cost estimate

Construction cost calculations are described in Table 5 for Maha PSPPC. In the preparatory works, cost of access roads, camp and facilities is calculated based on the quantity of civil works, and the percentage cost are calculated making reference to actual costs of similar projects. For access road 5% for pumped storage type of the total cost of civil works is estimated. While camp and facility cost is 3% and Environment mitigation cost is 3% for pumped storage type of the total cost of the civil works. The costs of civil works and hydraulic equipment are calculated by multiplying the quantity of main items of works by unit cost which is described in Table 3 and Table 4 for Maha PSPPC. The work quantity is obtained from tables, diagrams and numerical formula. In this evaluation, the main work items of structures of civil works are excavation, concrete, embankment, and reinforcement bars and those of hydraulic equipment are gate, screen, and steel pipe. The costs of other items of work, other than the main items, are calculated as “Others” in a lump-sum at a

* *Correspondence: twickramarathna@yahoo.com*
ISSN 2478-0669 Print

certain ratio against the total cost of the main work items. Unit costs are obtained by making reference to the latest data of similar works in Sri Lanka Upper Kotmale Hydro Project.

The construction costs of turbines, generators, control devices and main transformers, etc. are appropriated in a lump-sum in "Electro-mechanical equipment". There is a relationship that is almost as a straight line on logarithmic paper between electro-mechanical equipment cost according to each turbine type and $P/\sqrt{He}$ (P: maximum output in kW, He: effective head in meters), as shown in the example in Figure 1 and escalated as required.

In this paper, the construction cost of transmission lines is not considered. The following are included in the costs of "administration", "engineering service", "contingencies", which are calculated by multiplying the direct construction cost by an appropriate ratio. The administration cost includes personnel expense and expenses to maintain the construction office. The engineering service cost includes expenses related to technical services such as design work and construction supervision conducted by consultants. In this evaluation, 15% of the direct construction cost is appropriated as the cost of administration and engineering service. The contingency includes physical contingency which is the increase of quantities of work, and 10% of the direct construction cost is appropriated for the contingencies. Interest during construction is calculated based on the following conditions.

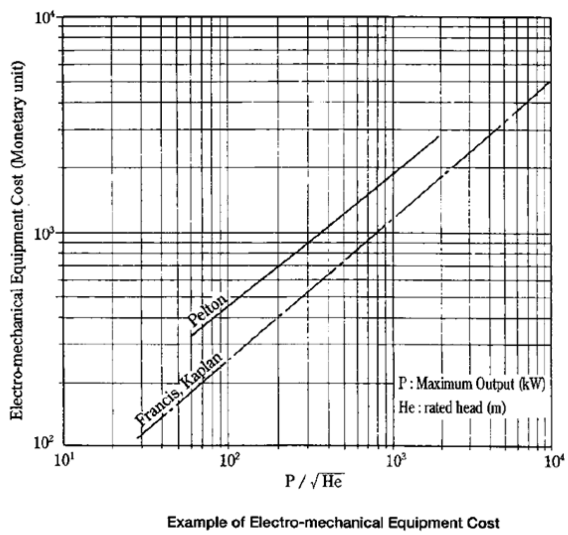


Figure 1: Example of electro-mechanical equipment cost

Interest rate (i) is calculated taking into account the ratio of local currency and foreign currency. For example, if the local and foreign currency portions are 25% and 75% respectively the calculation is as follow.

$$i = i_1 \times 0.25 + i_2 \times 0.75 = 6\ \% \qquad 1$$

i_1 : Interest rate for local currency = 20 %
i_2 : Interest rate for foreign currency =1.4 %

Interest during construction
= (cost of preparatory works + cost of environmental mitigation + cost of civil works + cost of hydraulic equipment + cost of electro mechanical equipment + cost of administration and engineering service + contingency) × 0.4 × i × T

2

Where;
T : Construction period (years) = 5 years
The value of 0.4 is a cash flow coefficient which is an empirical value of existing projects.

3. Quantities of work for Maha pumped storage power plant complex

3.1 Uduwella pumped storage power plant

3.1.1Uduwella PSPP – Upper dam

a. Structural design

Rock fill type dam is adopted because of the following reasons.

- Environment friendly type to harmonize with the estate (integration with nature, gentle inclination with nature rock)
- Catchment area is narrow
- Possible to utilize the excavated material
- Difficult to transport concrete

Dam specifications are determined as below.

Crest Elevation:719 m; Crest Length: 340 m; Dam Height (H_d): 32 m

Data such as Creager's curve should be used to calculate the design flood discharge if available. In case such data are not available, it is estimated by using annual rainfall, and the following simplified formula should be used as reference.

$$Q_f = q \times A$$
$$q = a \times A^{\left(A^{-0.05}-1\right)} \qquad 3$$

Q_f : Design flood discharge (m^3/s); q : Specific discharge ($m^3/s/km^2$); a : Region coefficient = 100; A : Catchment area (km^2) : 4.8754 km^2

$$Q_f = 432\, m^3/s \qquad 4$$

b. Quantity of work

i) Rock fill dam

Excavation and filling volume of dam are obtained by the following equations.

$$V_e = 10.0 \times H_d \times L \qquad 5$$

$$V_e = \frac{1}{6} \times (m+n) \times H_d^2 \times (L + 2 \times B) + W/2 \times H_d \times (L+B) \qquad 6$$

H_d : Dam height (m) : 32 m; L : Dam crest length (m) : 340 m; B : River bed width (m) : 60 m; W : Crest width : 10m; m : Upstream slope of dam (m=2.0 in this Manual); n : Downstream slope of dam (n=1.8 in this Manual)

V_e = = 108,800 m^3; V_c = = 362,325 m^3

Cost of other items of works such as grouting not included in the main items described above is estimated at 20% of the cost of the main items.

ii) Spillway

In the case of a fill type dam, the quantity of work of the spillway is calculated by the design flood discharge. The excavation volume, concrete volume, weight of reinforcement bars, and weight of gates are calculated according to the following equations.

$$V_e = 84 \times \sqrt{Q_f} \times H_d$$
$$V_e = 13 \times \sqrt{Q_f} \times H_d \qquad 8$$

$$W_r = 0.02 \times V_c \qquad 9$$

$$W_g = 0.22 \times Q_f \qquad 10$$

Q_f : Design flood discharge (m3/s) : 432 m^3/s

H_d : Dam height (m) : 32m

V_e = 55,878 m^3; V_c = 8,648 m^3; W_r = 173 ton;
W_g = 95 ton
Cost of other items of works which is not included in the main items described above is estimated at 20% of the cost of the main items.

3.1.2 Allugolla PSPP - Upper dam

a. Structural design

Concrete gravity type dam is adopted because of the following reasons.
Possible to obtain the sound rock for the dam foundation, River span is narrow, Easy to overflow during the flood period, Easy to transport concrete.
Dam specifications are determined as below.
Crest Elevation:819 m; Crest Length: 260 m; Dam Height (H_d):41 m

$$Q_f = 259.467\, m^3 / s \qquad 11$$

b. Quantity of work

Excavation volume and volume of dam is obtained by the following equations.

$$V_e = 10.0 \times H_d \times L \qquad 12$$

In the case : $H_d^2 \times L > 100 \times 10^3$

$$V_c = 0.34 \times (H_d^2 \times L) \quad (B/L = 0.5)$$

$$V_c = 0.30 \times (H_d^2 \times L) \quad (B/L = 0.4)$$

$$V_c = 0.27 \times (H_d^2 \times L) \quad (B/L = 0.3)$$

$$V_c = 0.21 \times (H_d^2 \times L) \quad (B/L = 0.2)$$

$$V_c = 0.16 \times (H_d^2 \times L) \quad (B/L = 0.1)$$

$$W_g = 0.13 \times Q_f \qquad 13$$

B : River bed width (m) : 35 m; L : Crest length (m) : 260 m; Q_f : Design flood discharge : 259.5 m^3/s; H_d : Dam height (m): 41m

$V_e \approx$ *106, 600.00* m^3
$V_c \approx$ *69,929.60* m^3
$W_g \approx$ *33.7 ton*

Cost of other items of civil works such as grouting and coffering not included in the main items above, is estimated at 20% of the main items.

3.1.3 Lower dam – Arama lower dam

a. Structural design

Concrete gravity type dam is adopted.
Dam specifications are determined as below.
Crest Elevation:305 m; Crest Length: 350 m; Dam Height (H_d): 57 m

$$Q_f = 1206\, m^3 / s \qquad 14$$

B : River bed width (m) : 45 m; L : Crest length (m) : 350 m; Q_f : Design flood discharge : 1206 m^3/s; H_d : Dam height (m)

$V_e \approx 199,500\ m^3$
$V_c \approx 181,944\ m^3$
$W_g \approx 156.8\ ton$

Cost of other items of civil works such as grouting and coffering not included in the main items above, is estimated at 20% of the main items.

3.1.4 Uduwella PSPP - Intake

a. Structural design

A pressure type is adopted. The inner diameter of waterway is obtained from Figure 2. by using the maximum plant discharge.

Inner Diameter : 6.9 m

Maximum plant discharge: 152 m^3/s

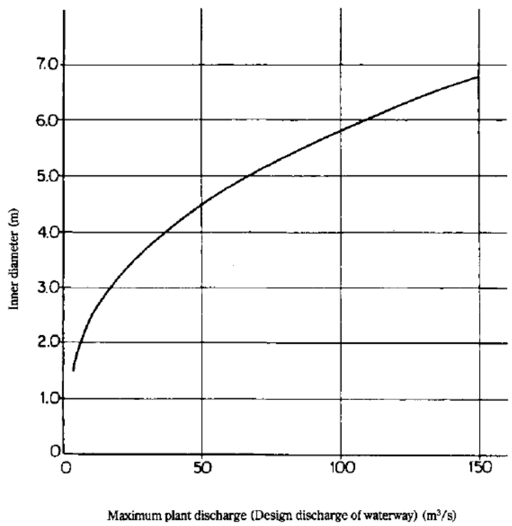


Figure 2: Inner diameter of waterway

a. Quantity of work

The excavation volume, concrete volume, weights of reinforcement bars, gate and screen are calculated by the following equations.

$$V_e = 130 \times \left[\{(h_a + D) \times Q\}^{1/2} \times n^{1/3} \right]^{1.27} \quad 15$$

$$V_e = 56.5 \times \left[\{(h_a + D) \times Q\}^{1/2} \times n^{1/3} \right]^{1.23} \quad 16$$

$$W_r = 0.04 \times V_c \quad 17$$

$$W_g = 0.9 \times \left\{ (h_a \times D)^{1/9} \right\} \times Q \quad 18$$

$$W_g = 0.5 \times \left\{ (h_a \times D)^{1/9} \right\} \times Q \quad 19$$

Where;

h_a = Available drawdown (m) : 19.55 m
Q = Number of waterway channels : 1
n = Inner diameter of waterway : 6.9 m
D = Maximum plant discharge (m^3/s) : 152 m^3/s

V_e = 25,273 m^3; V_c = 9,304 m^3; W_r = 372 ton;
W_g = 236 ton; W_s = 131 ton

Cost of other items of works such as coffering and trash rack, rake, etc. not included in the main items above are estimated at 25% of the main items.

3.1.5 Uduwella PSPP - Headrace

a. Structural design

A circular fully lined pressure tunnel is adopted. Diameter of tunnel is calculated assuming that a flow velocity in the tunnel is 6.0 m/s.

$$Diameter = \left(4 \times \frac{Q_{max}}{6\pi}\right)^{0.5} = 5.7m \qquad 20$$

b. Quantity of work

The excavation volume of the pressure tunnel, concrete volume and weight of reinforcement bars are calculated by the following equations.

$$V_e = 3.2 \times (R + t_0)^2 \times L \times n \qquad 21$$

$$V_e = \left\{3.2 \times (R + t_0)^2 - \pi R^2\right\} \times L \times n \qquad 22$$

$$W_r = 0.04 \times V_c \qquad 23$$

R: Tunnel radius (m) = 2.85m; t_0: Lining concrete thickness (m) = 55cm ; L: Total length of waterway channels (m) = 1850m;

N: Number of waterway channels =1

V_e = 68,435

V_c = 21,250

W_r = 850

Cost of other items of works such as grouting, adit, ect. Not included in the main items stated above is estimated at 15% of the cost of the main items.

3.1.6 Uduwella PSPP – Headrace surge tank

a. Structural design

Surge tank shall be provided to protect the headrace tunnel against the pressure of water hammer.

b. Quantity of work

The excavation volume, concrete volume, and weight of reinforcement bars are calculated in accordance with the following equations.

$$V_e = 38 \times q \times (h_a + L)^{1/4} \times n \qquad 24$$

$$V_c = 11 \times q \times (h_a + L)^{1/4} \times n \qquad 25$$

$$W_r = 0.05 \times V_c \qquad 26$$

q : Design discharge (m3/s) = 152 m^3/s; L : Total length of waterway (m) = 1850 m; $_a$: Available drawdown of regulating pond or reservoir (m) = 19.55 m; n : Number of waterway channels = 1

V_e = 37,980 m^3

V_c = 10,994 m^3

W_r = 550 ton

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

3.1.7 Uduwella PSPP - Penstock

a. Structural design

A circular fully steel lined pressure tunnel is adopted. The inner diameter of penstock is calculated assuming that a flow velocity in the penstock is 10 m/sec.

Diameter : $(4\times Q_{max}/10\pi)^{0.5} = 4.4\ m$

b. Quantity of work

For embedded type of penstock, excavation volume and concrete volume are obtained by the following equation, assuming constant thickness of backfill concrete of 60 cm.

$$V_e = \frac{\pi}{4}\left(D_m + 2t\right)^2 \times L \quad 27$$

$$V_c = \frac{\pi}{4}\left(D_m + 2t\right)^2 - D_m^2 \times L \quad 28$$

D_m : Average inner diameter of steel pipe (m) = 4.4 m; t : Thickness of backfill concrete (m) = 0.6 m; L : Total length of penstock (m) :2400 m

$V_e = 59{,}082\ m^3$

$V_c = 22{,}608\ m^3$

Cost of other items of works such as grouting, audit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

The weight of the steel conduit is obtained by the following equations for embedded type in tunnel.

$$W_p = 7.85 \times \pi \times D_m \times t_m \times 1.1 \times L \quad 29$$

$$t_m = 0.0270H \times D_m + 2 \quad 30$$

Where;

W_p = Weight of steel conduit (ton)

t_m = Average thickness of steel conduit (mm)

W_p = 48 mm

H = 13,743 ton

3.1.8 Uduwella PSPP – Underground powerhouse

a. Structural design

Underground type is adopted for Powerhouse.

b. Quantity of work

The excavation volume, concrete volume, and weight of reinforcement bars are obtained by the following equations.

$$V_e = 27 \times A + 1.3 \times A \times d \quad 31$$

$$V_c = 15 \times A \quad 32$$

$$W_r = 0.6 \times A \quad 33$$

Provided that;

A = 1,798 m^2

Q = Maximum plant discharge (m3/s) = 152m^3/s; He : Effective head (m) = 387.6 m

A = Area of powerhouse (m2) = 1,798 m^2

d = Height of powerhouse (m) = 40m

V_e = 142,027 m^3

V_c = 1,079 ton
W_r = 26,967 m^3

The cost of powerhouse building and transformer chamber is included in 50% of "Others".

3.1.9 Uduwella PSPP – Tailrace tunnel

a. Structural design

A circular fully lined pressure tunnel is adopted.

Diameter of tunnel is calculated assuming that a flow velocity in the tunnel is 6.0 m/sec.

Diameter : $(4\times Q_{max}/6.0\pi)^{0.5} = (4\times 152/6.0\pi)^{0.5} = 5.7\ m$

b. Quantity of work

The excavation volume of the pressure tunnel, concrete volume, and weight of reinforcement bars are calculated by the following equations.

$$V_e = 3.2\times(R+t_0)^2\times L\times n \quad (34)$$

$$V_e = 3.2\times(R+t_0)^2 - \pi R^2\times L\times n \quad (35)$$

$$W_r = 0.04\times V_c \quad (36)$$

R : Tunnel radius (m) = 2.85 m; t0 : Lining concrete thickness (m) = 55cm; L : Total length of waterway channels (m) = 200 m; n : Number of waterway channels = 1

$V_e \fallingdotseq 7,398\ m^3$
$V_c \fallingdotseq 2,297\ m^3$
$W_r \fallingdotseq 92\ ton$

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

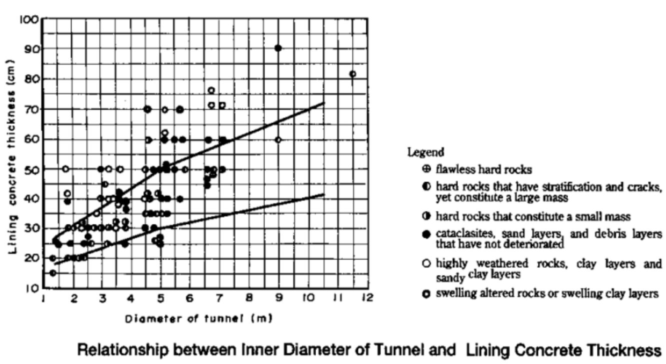


Figure 3: Relationship between inner diameter of tunnel and lining concrete thickness

b. Quantity of work

The excavation volume, concrete volume, and weight of reinforcement bars are calculated in accordance with the following equations.

$$V_e = 38\times q\times(h_a+L)^{1/4}\times n \quad (37)$$

$$V_c = 11\times q\times(h_a+L)^{1/4}\times n \quad (38)$$

$$W_r = 0.05\times V_c \quad (39)$$

q : Design discharge (m3/s) = 152 m^3/s; L : Total length of waterway (m) = 200 m; h_a : Available drawdown of regulating pond or reservoir (m) = 33 m; n : Number of waterway channels = 1

$V_e = 22{,}566\ m^3$
$V_c = 6{,}532\ m^3$
$W_r = 327\ ton$

Cost of other works such as steel lining not included in the main items above is estimated at20% of the main items.

3.1.10 Uduwella PSPP – Tailrace outlet

a. Structural design

A pressure type is adopted same as the intake.

b. Quantity of work

During pumping operation the tailrace outlet becomes an intake, therefore, calculation method of quantity of work for intake is adopted.

$Ve = 130\times(((33+5.7)\times152)^{1/2}\times1^{\ 1/3})^{1.27} = 32{,}182$ m3
$Vc = 56.5\times(((33+5.7)\times152)^{1/2}\times1^{\ 1/3})^{1.23} = 11{,}758$ m3
$Wr = 0.04\times11{,}758 = 470$ ton
$Wg = 0.9\times(33\times5.7)^{1/9}\times152 = 245$ ton
$Ws = 0.5\times(33\times5.7)^{1/9}\times152 = 136$ ton

Cost of other items of works such as coffering and trashrack, rake, etc. not included in the main items obtained above is estimated at 25% of the cost of the main items.

3.1.11 Uduwella PSPP – Access tunnel to powerhouse

a. Quantity of work

Excavation volume, concrete volume, and weight of reinforcement bars of the access tunnel are obtained by the following equations. The maximum gradient of the access tunnel is l :10.

$V_e = 45 \times L\ (m^3)$ 40
$V_c = 10 \times L\ (m^3)$ 41
$W_r = 0.03 \times V_c\ (ton)$ 42

T : thickness of overburden at Powerhouse = 70 m; L : Length of access tunnel (m) = 30m

$V_e = 1{,}350\ m^3$
$V_c = 300\ m^3$
$W_r = 9\ ton$

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

3.1.12 Uduwella PSPP – Miscellaneous works

Cost of miscellaneous works such as the disposal area and landscaping work is estimated at 10% of the total civil work cost.

3.1.13 Alugolla PSPP - Intake

Inner Diameter : 6.4 m

a. Quantity of work

$V_e = 26{,}310\ m^3$
$V_c = 9{,}674\ m^3$
$W_r = 387\ ton$
$W_g = 194\ ton$
$W_s = 108\ ton$

Cost of other items of works such as coffering and trash rack, rake, etc. not included in the main items above are estimated at 25% of the main items.

3.1.14 Alugolla PSPP - Headrace
a. Structural design

Diameter = 5.0m

b. Quantity of work

$V_e = 67,680$
$V_c = 21,561$
$W_r = 862$

Cost of other items of works such as grouting, adit, ect. Not included in the main items stated above is estimated at 15% of the cost of the main items.

3.1.15 Alugolla PSPP – Headrace surge tank
a. Structural design

$V_e = 32,112\ m^3$
$V_c = 9,295\ m^3$
$W_r = 465$ *ton*

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

3.1.16 Alugolla PSPP – Penstock
a. Structural design

Diameter : = 3.9 m

b. Quantity of work

$V_e = 29,951\ m^3$
$V_c = 11,191\ m^3$
$W_p = 7,398$ *ton*
$t_m = 53$ *mm*

3.1.17 Alugolla PSPP – Underground powerhouse
a. Structural design
Underground type is adopted for Powerhouse.

b. Quantity of work
Q : Maximum plant discharge (m3/s) = 121 m^3/s
$V_e = 136,570\ m^3$
$V_c = 25,931\ m^3$
$W_r = 1,037$ ton
The cost of powerhouse building and transformer chamber is included in 50% of "Others".

3.1.18 Alugolla PSPP – Tailrace tunnel
a. Structural design

Diameter : $(4\times Q_{max}/6.0\pi)^{0.5} = 5.1\ m$

b. Quantity of work

$V_e \fallingdotseq 12,800\ m^3$
$V_c \fallingdotseq 4,020 m^3$
$W_r \fallingdotseq 161$ *ton*

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

3.1.19 Alugolla PSPP – Tailrace surge tank

a. Structural design

$V_e = 21{,}329\ m^3$
$V_c = 6{,}174\ m^3$
$W_r = 309\ ton$

Cost of other works such as steel lining not included in the main items above is estimated at 20% of the main items.

3.1.20 Alugolla PSPP – Tailrace outlet

a. Structural design

A pressure type is adopted same as the intake.

b. Quantity of work

$Ve = 27{,}568\ m^3$
$Vc = 10{,}121\ m^3$
$Wr = 405\ ton$
$Wg = 192\ ton$
$Ws = 107\ ton$

Cost of other items of works such as coffering and trashrack, rake, etc. not included in the main items obtained above is estimated at 25% of the cost of the main items.

3.1.21 Alugolla PSPP – Access tunnel to powerhouse

a. Quantity of work

$V_e = 2{,}250\ m^3$
$V_c = 500\ m^3$
$W_r = 15\ ton$

Cost of other items of works such as grouting, adit, etc. not included in the main items stated above is estimated at 15% of the cost of the main items.

3.1.22 Alugolla PSPP – Miscellaneous works

Cost of miscellaneous works such as the disposal area and landscaping work is estimated at 10% of the total civil work cost.

4. Economic analysis

4.1 Benefit-Cost method (B/C Method)

The economics of the project is analyzed on the basis of maximum output, energy generation and the construction cost obtained.

4.2 Methodology of analysis

An economic analysis of the hydro power project is made by a method to compare its benefit (B) and cost (C). The benefit of a hydro power project is the cost of an alternative thermal power that supplies electric power equivalent to the hydro power project, and the cost is derived from the construction cost of the hydro power project. In the case of benefit cost ratio (B/C) is 1.0 or over, hydro power is economically better than the alternative thermal power while in the case B/C<1 (or B-C<0), hydro power is economically less attractive than the alternative thermal power. It is also possible to judge that a certain hydro power project is economically attractive if the B/C value is outstanding among a number of hydro power projects that are compared. Yet another method is to use the latter method and calculate the Economic Internal Rate of Return (EIRR) applying a discount rate which will give equal present values for both B and C.

4.3 Selection of alternative thermal power

The alternative thermal power plants are gas turbine, coal fired, oil fired, liquefied gas fired, combined cycle, and diesel power plants.

4.3.1 Standard thermal power

One method is to select the power source most commonly used in the electric power system. This is defined as the "standard thermal power". This method is suitable to compare the economic viability of a number of hydro power sites according to same criteria, and this method is used for hydro power potential survey, master plan studies, etc. For example, in the case of an electric power system consisting mainly of coal fired thermal power plants or new coal fired plants are scheduled to be constructed, coal fired plants are selected as the standard thermal power.

4.3.2 Alternative thermal power equivalent to hydropower

The other method is to select an alternative thermal power which is equivalent to the planned hydro power project to evaluate its position as the source of supply in the electric power system. For instance, a gas turbine plant is often selected as the alternate thermal power for the reservoir type, pondage type and pumped storage type power plants that are designed to supply power for peak demands.

4.4 Benefit and cost of conventional hydropower projects

4.4.1 Benefit

Annual benefit (B) of a hydro power project is obtained in accordance with the following formula, based on the fixed cost (mainly the equipment cost) and variable cost (mainly the fuel cost) of the alternative thermal power selected.

$$B = B_1 + B_2 \quad (43)$$

$$B_1 = Ph \times b_1 \quad (44)$$

$$B_2 = E \times b_2 \quad (45)$$

Where;

B	=	Annual benefit of hydro power plant (monetary unit)
B_1	=	kW benefit (monetary unit/kW)
B_2	=	kWh benefit (monetary unit/kWh)
Ph	=	Effective output (kW), maximum output is used in the case of pumped storage type
E	=	Annual energy generation (kWh) at 2190 hours operation in a year (6 hours per day)
b_1	=	kW value (also called capacity value), which is the fixed cost per kW for alternative thermal power (monetary unit/kW)
b_2	=	kWh value (also called energy value), which is mainly the fuel cost and is the variable cost per kWh for alternative thermal power (monetary unit/kWh)

Loss rate and Outage rate is omitted.

4.4.2 Calculation of kW value (b_1) and kWh value (b_2)

The kW value and kWh value are calculated from the following equations for the selected power source.

$$b_1 = Ct \times \beta \times \alpha \quad (46)$$

b_2= Heat rate (kcal/kWh) × fuel price (monetary unit/kcal) ×860 (kcal/kWh)/thermal efficiency × Fuel price (monetary unit/kcal)

Ct: Unit construction cost of thermal power (monetary unit/kW)

α = Annual cost factor of thermal power

β = kW adjustment factor; correction factor due to the difference in reliability (station use, forced outage, scheduled outage) between hydro power and thermal power.

The annual factor and thermal efficiency for gas turbine plant is shown below.

Table 1: The annual factor and thermal efficiency for gas turbine plant

	Gas Turbine
Annual cost factor	Approx. 18%
Thermal Efficiency	Approx. 30%
Service life	20 years

The following equation is used to calculate more detailed annual factor.

Annual cost factor (α) = Capacity Recovery Factor (CRF) + Operation & Maintenance cost (OM: fuel cost excluded)

$$\alpha = CRF + OM = \frac{i(1+i)^n}{(1+i)^n - 1} + 0.03 \qquad 47$$

Where;

i = Interest rate

n = Service life (years) (hydro power=50years)

Economic Analysis results for Maha pumped storage power plant complex are shown in Table 6.

4.4.3 Improving the economic condition of PSPP sites

All PSPPs are pure pumped storage type. That means inflow to the upper pond is very small. The increase of the inflow to the upper pond increases the economic condition of PSPP, because it reduces the pumping cost.

5. Conclusion

According to the economic evaluation results Kiriketi Pumped Storage Power Plant III is the best site. Kiriketi Pumped Storage Power Plant II and Halgran Pumped Storage Power Plant have near same B/C ratio. So both sites have the equal opportunity to develop the power plant. The economical condition of Kiriketi PSPPs can be increase by diverting Belihuloya to their upper pond via Run Of the River type conventional hydropower plant.

References

Guide manual for Development Aid Programs and Studies of Hydro Electric Power Projects, New Energy Foundation, Tokya, Japan 1996.

“Study on Pumped Storage Power Plans and Optimization for Peaking Power Generation in Sri Lanka” – Volume II – Part II– Site Selection and Basic Design Configuration by Ms. M.T.A.P.Wickramarathna, October 2013.

Planning of Pumped Storage Power Plants in Sri Lanka, M.T.A.P. Wickramarathna, *SLEMA Journal*, Volume 14(2), September 2011.

Forecasting Load Curve Shape for Predicting the Possible Capacity of Pumped Storage Power Plant by MTAP Wickramarathna, EMTG Jayathilake, SLEMA Journal, Volume 14-No.2, September 2011.

Table 2: Economic evaluation summery

	Construction Cost (Civil) (USD)	Construction Cost (Hydro-mechanical Equipment Cost) (USD)	Construction Cost (Electro-mechanical Equipment Cost) (USD)	Total Cost (USD)	Capacity (MW)	Design Discharge Q (m^3/s)	Effective Head (m)	L/H	Project cost per kW (USD/kW)	EIRR (%)	Benefit /Cost
Maha-Alugolla PSPP	205,189,962	62,140,374	151,768,750	664,702,542	500	121	485.2	7.84	1,329	39.90%	2.65
Maha PSPPC	556,830,901	172,045,045	273,702,618	1,600,091,621	Udu. / Alu. 500 / 500	Udu. / Alu. 152 / 121	Udu. / Alu. 387.6 / 485.2	Udu. / Alu. 10.64 / 7.84	1,600	34%	2.4
Puna-Kotmale PSPP	279,501,762	102,958,931	158,254,594	859,822,180	500	88	666.5	9.4	1,720	34%	2.4
Maha-Uduwella PSPP	358,266,582	111,385,988	121,933,868	948,648,602	500	152	387.6	10.64	1,897	29.10%	2.14
KM PSPP	215,730,430	57,751,710	76,532,960	561,841,272	250	80.2	366.7	11.6	2,247	24.81%	1.91
Dambagastala	334,948,441	32,165,864	93,396,154	746,936,019	300	79	445.8	6	2,490	23%	1.8
Agra PSPP	382,574,211	26,241,954	90,801,816	813,267,607	300	86.9	406	11	2,711	21%	1.7
KMG PSPPC	1,117,397,665	116,179,268	230,896,048	2,383,233,673	KM / KG 250 / 500	KM / KG 80.2 / 98.25	KM / KG 366.7 / 598.7	KM / KG 11.6 / 9.0	3,178	18%	1.5
KG PSPP	904,786,946	58,418,642	154,363,088	1,826,567,624	500	98.25	598.7	9	3,653	15.35%	1.35

Table 3: Calculation of construction cost (civil cost)-Maha PSPP complex

Item	Unit	Unit Price	Quantity	Cost	Remark
(1) Upper dam					
1. Care of river	L.S.	–	1	28,269,870	1. = 2. × 0.20
2. Concrete dam					2. = ① + ② + ③
①Excavation	m^3	22	215,400	4,727,942	①
②Concrete	m^3	262	432,255	113,063,183	②
③Others	L.S.	–	1	23,558,225	③ = (① + ②) × 0.2
Sub Total				169,619,220	
(2) Lower dam					
1. Care of river	L.S.	–	1	12,472,633	1. = 2. × 0.2
2. Concrete dam					2. = ① + ② + ③
①Excavation	m^3	22	199,500	4,378,944	①
②Concrete	m^3	262	181,944	47,590,360	②
③Others	L.S.	–	1	10,393,861	③ = (① + ②) × 0.2
Sub Total				74,835,797	
(3) Intake					
①Excavation	m^3	22	51,583	1,132,234	①
②Concrete	m^3	273	18,978	5,172,258	②
③Reinforcement bar	ton	2,625	759	1,992,534	③
④Others	L.S.	–	1	2,074,256	④ = (① + ② + ③) × 0.25
Sub Total				10,371,282	
(4) Headrace					
①Excavation	m^3	134	136,115	18,175,012	①
②Concrete	m^3	267	42,813	11,433,315	②
③Reinforcement bar	ton	2,625	1,713	4,495,016	③
④Others	L.S.	–	1	5,115,501	④ = (① + ② + ③) × 0.15
Sub Total				39,218,844	
(5) Surge tank (Headrace)					
①Excavation	m^3	172	70,093	12,051,612	①
②Concrete	m^3	216	20,290	4,379,337	②
③Reinforcement bar	ton	2,625	1,014	2,662,860	③
④Others	L.S.	–	1	3,818,762	④ = (① + ② + ③) × 0.2
Sub Total				22,912,570	
(4) Penstock					
①Excavation	m^3	199	86,034	17,153,029	①
②Concrete	m^3	190	33,799	6,429,569	②
③Others	L.S.	–	1	3,537,390	③ = (① + ②) × 0.15
Sub Total				27,119,988	
(5) Powerhouse					
①Excavation	m^3	209	278,598	58,093,626	①
②Concrete	m^3	424	52,898	22,447,903	②
③Reinforcement bar	ton	2,625	2,116	5,553,921	③
④Others	L.S.	–	1	43,047,725	④ = (① + ② + ③) × 0.5
Sub Total				129,143,175	
(6) Tailrace					
①Excavation	m^3	134	20,199	2,697,057	①

②Concrete	m^3	267	6,318	1,687,252	②
③Reinforcement bar	ton	2,625	253	663,344	③
④Others	L.S.	—	1	757,148	④ = (① + ② + ③) × 0.15
Sub Total				5,804,802	
(7) Surge tank (Tailrace)					
①Excavation	m^3	172	43,895	7,547,290	①
②Concrete	m^3	216	12,707	2,742,548	②
③Reinforcement bar	ton	2,625	635	1,667,609	③
④Others	L.S.	—	1	2,391,489	④ = (① + ② + ③) × 0.2
Sub Total				14,348,936	
(8) Outlet					
①Excavation	m^3	22	59,749	1,311,476	①
②Concrete	m^3	273	21,879	5,962,897	②
③Reinforcement bar	ton	2,625	875	2,297,116	③
④Others	L.S.	—	1	2,392,872	④ = (① + ② + ③) × 0.25
Sub Total				11,964,361	
(9) Access tunnel to powerhouse					
①Excavation	m^3	134	3,600	480,696	①
②Concrete	m^3	267	800	213,643	②
③Reinforcement bar	ton	2,625	24	62,995	③
④Others	L.S.	—	1	113,600	④ = (① + ② + ③) × 0.15
Sub Total				870,934	
(10) Miscellaneous	L.S.	—		50,620,991	(10) = Σ{(1~9)} × 0.1
Total				556,830,901	

Table 4: Calculation of construction cost (hydro mechanical equipment cost) - Maha PSPP complex

Item	Unit	Unit Price	Quantity	Cost	Remark
1. Upper Dam and spillway					
Gate	ton	12,842	34	433,169	
2. Lower Dam and spillway					
Gate	ton	12,842	157	2,013,642	
3. Intake					
Gate	ton	10,767	430	4,634,876	
Screen	ton	5,578	239	1,334,001	
4. Penstock (steel pipe)	ton	6,097	21,141	128,892,381	
5. Tailrace outlet					
Gate	ton	10,767	437	4,707,810	
Screen	ton	5,578	243	1,354,992	
6. Others	L.S.	—	1	28,674,174	(1 + 2 + 3 + 4) × 0.2
Total				172,045,045	

Table 5: Construction cost summery-- Maha PSPP complex

Item	Cost (USD)	Note
1. Preparation and Land acquisition		
(1) Access road	27,841,545	(3 Civil work) × 0.05
(2) Compensation & Resettlement		
(3) Camp & Facilities	11,136,618	(3 Civil work) × 0.02
2. Environmental mitigation cost	16,704,927	(3 Civil work) × 0.03
3. Civil Work		556,830,901
(1) Upper Dams	169,619,220	
(2) Lower Dam	74,835,797	
(3) Intakes	10,371,282	
(4) Headrace	39,218,844	
(5) Surge tank (Headrace)	22,912,570	
(6) Penstocks	27,119,988	
(7) Powerhouses	129,143,175	
(8) Tailraces	5,804,802	
(9) Surge tanks (tailrace)	14,348,936	
(10) Outlets	11,964,361	
(11) Access tunnels to powerhouses	870,934	
(12) Miscellaneous	50,620,991	((1)~(9)) × 0.1
4. Hydraulic equipment	172,045,045	Gate, Screen, Steel Penstock, etc
5. Electro-mechanical equipment	273,702,618	Turbine and Generator, Transformer, Switchyard,etc
6. Transmission line		
Direct cost	1,058,261,654	1 + 2 + 3 + 4 + 5 + 6
7. Administration and Engineering service	158,739,248	(Direct cost) × 0.15
8. Contingency	211,652,331	(Direct cost) × 0.2
9. Interest during construction	171,438,388	(1+2+3+4+5+6+7+8) × 0.4 × 6% × 5year
Indirect Cost	541,829,967	7 + 8 + 9
Total cost	1,600,091,621	1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9
Install Capacity	1,000,000	(kW)
Project Cost per kW	1,600	(USD/kW)

Table 6: Calculation of economic evaluation indices (Base Case) - Maha PSPP complex

(Unit: US$1,000,000)

			Cost				Benefit				
Year in order		Year	Construction & Replacement	Operation & Maintenance	Pumping	Total	Construction & Replacement	Operation & Maintenance	Fuel Cost	Total	Balance
1		2015	100.26			100.26				0.00	(100.26)
2		2016	200.52			200.52				0.00	(200.52)
3		2017	300.77			300.77				0.00	(300.77)
4		2018	300.77			300.77	260.48			260.48	(40.30)
5		2019	100.26			100.26	362.40			362.40	262.14
6	1	2020		30.08	92.05	122.13		8.07	499.83	507.91	385.78
7	2	2021		30.08	92.05	122.13		8.07	499.83	507.91	385.78
8	3	2022		30.08	92.05	122.13		8.07	499.83	507.91	385.78
9	4	2023		30.08	92.05	122.13		8.07	499.83	507.91	385.78
10	5	2024		30.08	92.05	122.13		8.07	499.83	507.91	385.78
11	6	2025		30.08	92.05	122.13		8.07	499.83	507.91	385.78
12	7	2026		30.08	92.05	122.13		8.07	499.83	507.91	385.78
13	8	2027		30.08	92.05	122.13		8.07	499.83	507.91	385.78
14	9	2028		30.08	92.05	122.13		8.07	499.83	507.91	385.78
15	10	2029		30.08	92.05	122.13		8.07	499.83	507.91	385.78
16	11	2030		30.08	92.05	122.13		8.07	499.83	507.91	385.78
17	12	2031		30.08	92.05	122.13		8.07	499.83	507.91	385.78
18	13	2032		30.08	92.05	122.13		8.07	499.83	507.91	385.78
19	14	2033		30.08	92.05	122.13		8.07	499.83	507.91	385.78
20	15	2034		30.08	92.05	122.13		8.07	499.83	507.91	385.78
21	16	2035		30.08	92.05	122.13		8.07	499.83	507.91	385.78
22	17	2036		30.08	92.05	122.13		8.07	499.83	507.91	385.78
23	18	2037		30.08	92.05	122.13		8.07	499.83	507.91	385.78
24	19	2038		30.08	92.05	122.13	260.48	8.07	499.83	768.38	646.25
25	20	2039		30.08	92.05	122.13	362.40	8.07	499.83	870.31	748.18
26	21	2040		30.08	92.05	122.13		8.07	499.83	507.91	385.78
27	22	2041		30.08	92.05	122.13		8.07	499.83	507.91	385.78
28	23	2042		30.08	92.05	122.13		8.07	499.83	507.91	385.78
29	24	2043		30.08	92.05	122.13		8.07	499.83	507.91	385.78
30	25	2044		30.08	92.05	122.13		8.07	499.83	507.91	385.78
31	26	2045		30.08	92.05	122.13		8.07	499.83	507.91	385.78
32	27	2046		30.08	92.05	122.13		8.07	499.83	507.91	385.78

33	28	2047		30.08	92.05	122.13		8.07	499.83	507.91	385.78
34	29	2048		30.08	92.05	122.13		8.07	499.83	507.91	385.78
35	30	2049		30.08	92.05	122.13		8.07	499.83	507.91	385.78
36	31	2050	61.78	30.08	92.05	183.91		8.07	499.83	507.91	324.00
37	32	2051	44.57	30.08	92.05	166.70		8.07	499.83	507.91	341.20
38	33	2052	179.86	30.08	92.05	301.99		8.07	499.83	507.91	205.92
39	34	2053	114.96	30.08	92.05	237.09		8.07	499.83	507.91	270.82
40	35	2054	44.57	30.08	92.05	166.70		8.07	499.83	507.91	341.20
41	36	2055		30.08	92.05	122.13		8.07	499.83	507.91	385.78
42	37	2056		30.08	92.05	122.13		8.07	499.83	507.91	385.78
43	38	2057		30.08	92.05	122.13		8.07	499.83	507.91	385.78
44	39	2058		30.08	92.05	122.13	260.48	8.07	499.83	768.38	646.25
45	40	2059		30.08	92.05	122.13	362.40	8.07	499.83	870.31	748.18
46	41	2060		30.08	92.05	122.13		8.07	499.83	507.91	385.78
47	42	2061		30.08	92.05	122.13		8.07	499.83	507.91	385.78
48	43	2062		30.08	92.05	122.13		8.07	499.83	507.91	385.78
49	44	2063		30.08	92.05	122.13		8.07	499.83	507.91	385.78
50	45	2064		30.08	92.05	122.13		8.07	499.83	507.91	385.78
51	46	2065		30.08	92.05	122.13		8.07	499.83	507.91	385.78
52	47	2066		30.08	92.05	122.13		8.07	499.83	507.91	385.78
53	48	2067		30.08	92.05	122.13		8.07	499.83	507.91	385.78
54	49	2068		30.08	92.05	122.13		8.07	499.83	507.91	385.78
55	50	2069		30.08	92.05	122.13		8.07	499.83	507.91	385.78
56	51	2070		30.08	92.05	122.13		8.07	499.83	507.91	385.78
Total			1,448.33	1,533.95	4,694.64	7,676.91	1,868.63	411.79	25,491.47	27,771.89	20,094.98
In the condition of a discount rate of 10 %:											
Present value:		Discount Rate=		10%		1,515				3,601	2,086.14
Economic Internal rate of return (EIRR):											33.98%
B/C											2.38

An Assessment of the Public Exposure Level of Electromagnetic Fields Caused by Overhead Power Transmission Lines in Sri Lanka

A.C.S. Wijayatilake*

Ceylon Electricity Board

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Many researches are being carried out in the world for identifying the harmful effects caused by electromagnetic fields generated by high voltage power lines on human activities [1]. Therefore, it is a timely requirement of evaluating the public exposure level of electromagnetic fields caused by power transmission lines in Sri Lanka at this stage because 400kV transmission voltage is planned to be introduced here by 2018. The paper presents the magnitude of electromagnetic fields caused by existing 132kV, 220kV and the proposed 400kV transmission lines. The calculation has been carried out with first principles with the assistance of the computer software package, MATLAB. The results indicate that the public exposure levels of 132kV and 220kV systems are not up to the harmful limits defined by International Commission on Non-Ionizing Radiation Protection (ICNIRP). However, the results show that the electric field intensity caused by 400kV system is very close to harmful limit. Since, the values of the generated electromagnetic fields depend on tower height and conductor phase configuration their effect on public can be further reduced by selecting an appropriate tower design for 400kV system. The necessity of the preparation of code of instructions for public to safe use of Right of Way of the 400kV transmission line is stressed here.

Keywords: electromagnetic field, transmission lines

1.Introduction

Generally electricity generated at power plants is transported up to the load with an interconnected network of overhead lines and underground cables energized with different voltages. An electric field is generated at the surroundings of an energized conductor. The higher the voltage the stronger the electric field is. Additionally, a magnetic field is created in the vicinity of a current carrying conductor. The higher the current flow, the stronger the magnetic field is. Since transmission lines carry currents at high voltages the electromagnetic fields generated by them may be high enough to effect on human activities (Kellough, 1980). Many researches are being carried out but not yet proved about the possibility of causing cancers and mental disorders due to the electromagnetic pollution of power transmission lines. However, it has been proved that the magnetic field in the vicinity of power lines may be enough to cause certain medical equipment such as pacemakers malfunction of**.** The risk is higher for crew members of live line maintenance gangs of utilities and nearby residents due to their prolonged exposure to the fields.

Certain developed countries such as Australia, Canada and New Zealand have made the evaluation of electromagnetic field effect on public compulsory when approval is granted for construction of new transmission facilities aiming to identify any harmful effects at the design stage and introduce remedial measures to minimize them (Kellough, 1980).

In Sri Lanka, electricity is transmitted by overhead lines and cables at 132 and 220kV voltages. It is planned to introduce 400kV transmission voltage by 2018. The first 400kV transmission line is planned from Trincomalee to Habarana. Therefore, it is the ideal time to evaluate the electromagnetic pollution caused by power transmission lines in order to identify the severity of the issue and find out corrective measures aiming to achieve sustainable development while preserving the environment.

* *Correspondence: acswije@yahoo.com*
ISSN 2478-0669 Print

2. Methodology

The electromagnetic field at a point in the vicinity of a current carrying conductor can be calculated with the first principles as shown below.

2.1 Calculation of magnetic field

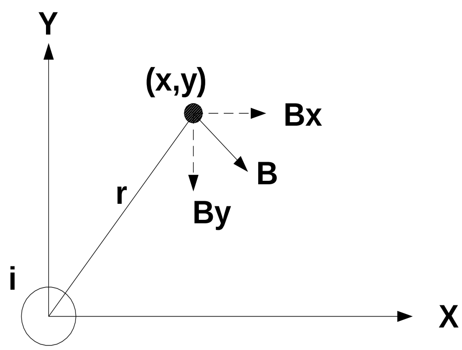


Figure 1: Magnetic field at point (x,y) due to the current carrying conductor

According to the Ampere's circuital law the integral of the magnetic field intensity around a closed contour is equal to the current enclosed by the contour, where *(H) is the magnetic field intensity* in (A/m) and i is the enclosed current (Yong, 1998).

$$i = \phi_c \times H \times dl \qquad 1$$

Magnetic field density is related with magnetic field intensity as;

$$B = \mu \times H \qquad 2$$

Where;
μ = permeability of the medium

As shown in Figure 1 the Magnetic Field Density, B, at a point (x ,y) located in the reference frame X,Y and can be expressed as;

$$Bx = \frac{\mu_0 yi}{2\pi r^2} \qquad 3$$

and;

$$By = \frac{\mu_0 xi}{2\pi r^2} \qquad 4$$

Magnetic field calculation is more accurate if the ground return path of the conductor as shown in Figure 2 is taken into account (Yong, 1998). Mathematically this is taken into account by considering an additional conductor carrying the same amount of current but in opposite direction and placed it at a point where the mirror image of the original conductor on a horizontal reflecting plane that is assumed to be at a distance y' below the ground level. The distance of y is related with the frequency f and earth resistivity ρ as shown in the following formula.

$$y' = \sqrt{\rho / 2\pi\pi_0 f} \qquad 5$$

The earth return conductor is omitted here due to the fact that the reflecting conductor is at a depth several times the height of the conductor above the ground level when practical soil resistivity values are considered.

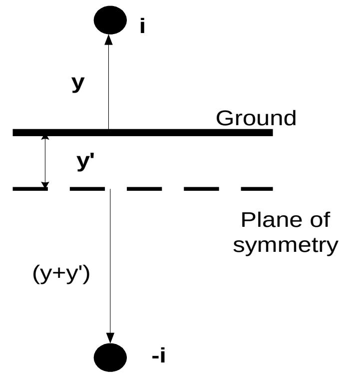


Figure 2: Position of the reflected conductor and the plane of symmetry

All power transmission circuits are three phase in construction and have one or more conductors per phase. If one phase has more than one conductor, their equivalent conductor is considered for the calculation. If there are several conductors, the same principal can be used to calculate the magnetic field density due to each conductor and the resultant can be obtained by the vector sum of all individual components (Gupta, 1997)

2.2 Calculation of electric fields

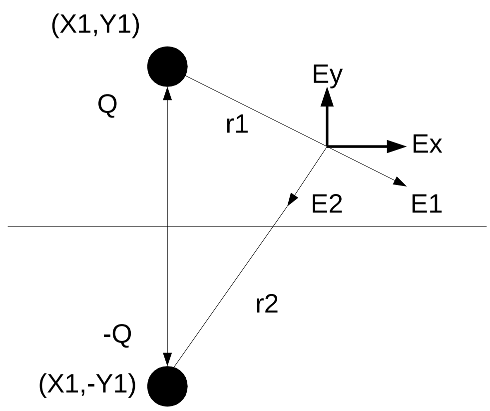


Figure 3: Electric field due to point charge Q

The potential V at any point (x,y) can be expressed as;

$$V = \frac{Q}{4\mu \in_0} \ln\left(\frac{r_2}{r_2}\right) \qquad 6$$

If the selected point is on the surface of the conductor, the potential of conductor is given by;

$$V = \frac{Q}{4\pi \in_0} \ln\left(\frac{2y+a}{a}\right)$$

Where;
a = radius of the conductor
y = vertical distance measured to the center of the conductor from the ground

Hence, the equivalent charge, Q on the conductor surface can be calculated as;

$$Q = \frac{4\pi V \in_0}{\ln\left(\frac{2y+a}{a}\right)} \qquad 8$$

As shown in Figure 3 the Electric Field Intensity (E) at the point (x,y) is caused by the charges on the conductor and its mirror image. From Coulomb's law the electric field intensity at a point (x,y) can be expressed as;

$$E_1 = \frac{Q}{4\pi \in_0} \times \frac{1}{r_1^2} \qquad 9$$

and;

$$E_2 = \frac{Q}{4\pi \in_0} \times \frac{1}{r_2^2} \qquad 10$$

They can be resolved in X and Y directions to get electric field intensity along X and Y directions i.e. E_x, E_y The results presented in this paper have been calculated with software program written in MATLAB software package and it is based on the above described principles.

3. Results and Discussion

3.1 Factors to be considered in calculating the electromagnetic field effect due to overhead electricity transmission lines

The origin of the reference frame used in defining the conductor positions of the double circuit transmission pylon is considered as the intersection point of its vertical symmetrical axis and earth surface as shown in Figure 4 in order to use geometrical symmetry for simplifying the calculation.

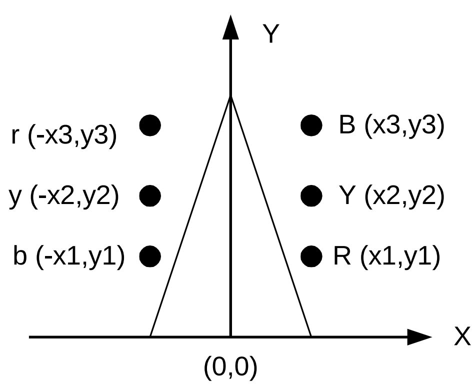


Figure 4: Location of phases in a tower line with reference to the reference frame

- Generally electricity is transmitted with three phase circuits. The phase configuration in the steel tower structure effects the electromagnetic field calculation. Therefore the location of each phase conductor in the transmission tower is considered as shown in Figure 4. This is the most generalized phase configuration for double circuit transmission circuits(Gupta, 1997).

- In power transmission circuits, bundle conductors; i.e. Several conductors for each phase, are widely used. In this analysis, a conductor having an equivalent diameter is considered for bundle conductors. The following expression is used for calculation of the equivalent conductor radius, r_{eq} for a bundle conductor having N numbers of conductors each of radius r, and separated at a distance B from each other (Gupta, 1997).

$$r_{eq} = \left(\frac{B}{2\sin\left(\frac{\pi}{N}\right)} \right) \times \left(\frac{2\sin\left(\frac{\pi}{N}\right) N r}{B} \right)^{\frac{2}{N}} \qquad 11$$

- The electric field strength increases with the operating voltages. However, there is a world tendency of operating transmission circuits near the maximum allowable operating voltage due to other reasons . Therefore, the Electric field strength calculation is conducted here for the maximum operating voltage of the circuit.

- Field strength effecting human activities is maximum when the height of conductors to the earth is less. Conductor ground clearance varies with the temperature of the conductor. Nowadays, in overhead transmission lines, conductors are designed to be operated at 75^0 C with minimum ground clearance . At the same time the current flowing through a transmission circuit depends on the load variation of the system. The load factor of the Sri Lankan system is approximately 60%. Therefore, the average conductor loading of 60% of the conductor thermal rating corresponding to the 75^0 C conductor operating temperature at night time is used in the calculations presented here. The conductor ground clearances corresponding to this loading are calculated and used in this analysis. On the other hand, the results presented here are calculated at the midpoint of the conductor span between two transmission towers when conductor ground clearances corresponding to the 60% of its night time thermal rating calculated for 75^0 C conductor operating temperature.

- The effect of the shielding conductors of overhead transmission towers on the electromagnetic field calculation is minimum and at the range of 2% . Therefore shielding conductors are not considered in this analysis.

3.2 Calculation of the electromagnetic field in the vicinity of a transmission circuit

Calculations are carried out for 132kV, 220kV, 400kV double circuit overhead transmission lines. Since the 400kV system is in design stage, appropriate dimensions were used for the 400kV tower based on the literature survey. The parameters used in the analysis are presented in Table 1.

Electric field strength and magnetic field density have been calculated and presented in Table 2. The values have been calculated on the plane on which the (X,Y) coordinate system has been drawn as illustrated in Fig.4. All directions mentioned in Table 2 are measured with reference to the coordinate system shown in Fig.4 which shows the widely adopted phase positioning of a double circuit power line, i.e. ryb and BYR, in order to minimize the differences in mutual inductances between phases. Electric field and magnetic field levels at a height of 1m above the ground level are specially presented here, since the public exposure to the electromagnetic fields on that level is higher.

Table 1: Parameters used in the analysis

Parameters	Case1:132kV Lynx double circuit line	Case2: 220kV twin Zebra double circuit line	Case3: 400kV quadruple Zebra double circuit line
Nominal system voltage/kV	132	220	400
Highest system voltage/kV	145	245	420
Average Conductor loading/A	350	1200	2400
No. of conductors in a bundle	1	2	4
Conductor separation in a bundle/mm	-	400mm	450mm
Equivalent Conductor radius of a bundle/mm	9.765	75.6	207.2
Coordinates of Phase locations as shown in Figure 4	R=(-3.9,9.8) b=(3.9,9.8) Y=(-3.7,13.99) y=(3.7,13.99) B=(-3.7,18.13) r=(3.7,18.13)	R=(-6.23,10.96) b=(6.23,10.96) Y=(-5.7,17.22) y=(5.7,17.22) B=(-5.43,23.4) r=(5.43,23.4)	R=(-7.00,12.00) b=(7.00,12.00) Y=(-9.00,20.5) y=(9.00,20.5) B=(-6.2,30.0) r=(6.2,30.0)

Electric field strength and magnetic field density have been calculated and presented in Table 2. The values have been calculated on the plane on which the (X,Y) coordinate system has been drawn as illustrated in Fiure 4 . All directions mentioned in Table 2 are measured with reference to the coordinate system shown in Figure 4 which shows the widely adopted phase positioning of a double circuit power line, i.e. ryb and BYR, in order to minimize the differences in mutual inductances between phases. Electric field and magnetic field levels at a height of 1m above the ground level are specially presented here, since the public exposure to the electromagnetic fields on that level is higher.

The guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have been used here as the results evaluation criteria. According to that the maximum allowable public exposure limit of magnetic field density is $100\mu T$ and electric field strength is $5kV/m$.

The “danger zones” where field effect is higher than allowable maximum exposure level are presented here based on the 3-D visualization of the field effect as shown in Figure 8, Figure 9 and Figure 10 for 400kV tower.

The calculated results show that the public exposure level of both the electric field strength and magnetic field density generated in the vicinity of 132kV and 220kV tower line are very much less than the values defined by (ICNIRP) .

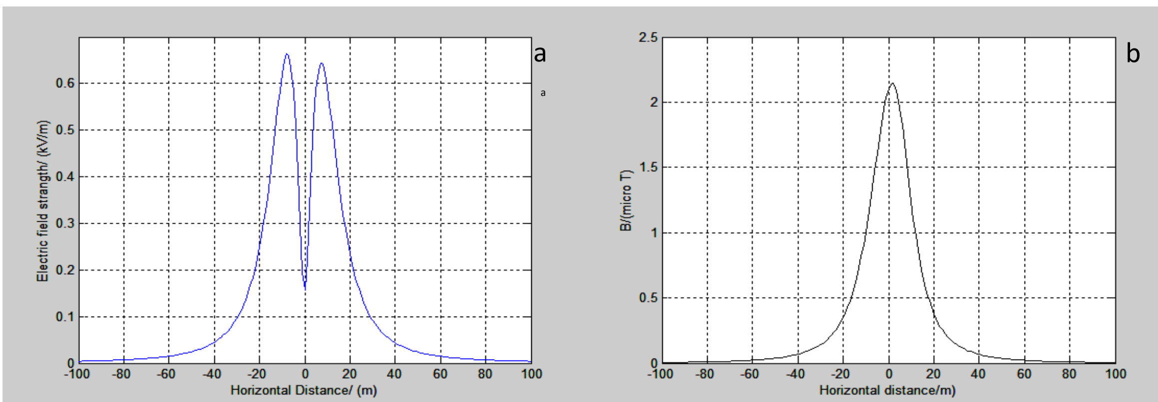


Figure 5: (a)Variation of electric field intensity and (b) magnetic field density of 132kV line at 1m above the ground level

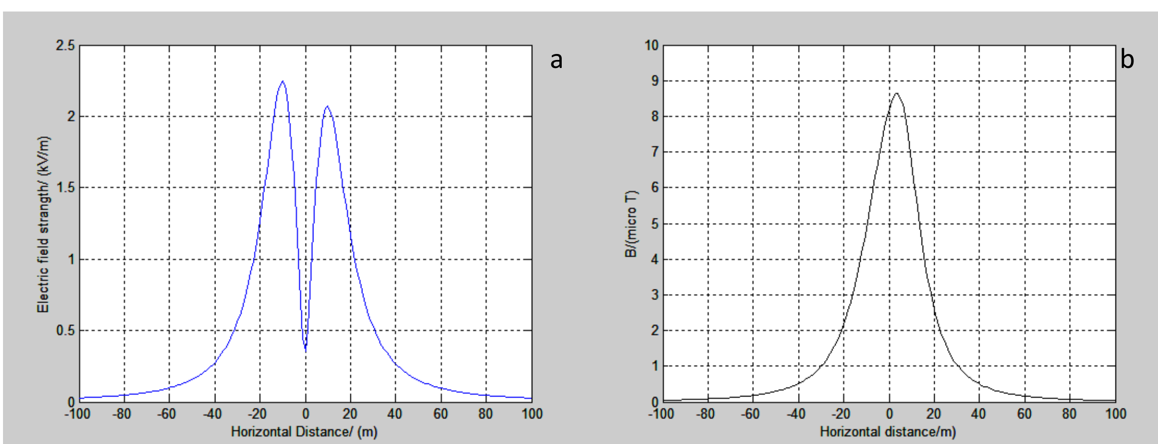


Figure 6: (a) Variation of electric field intensity and (b) magnetic field density of 220kV line at 1m above the ground level

Results further indicate that the precautions have to be taken only for 400kV transmission line designing to avoid the possible higher Electric field effects. The effect of electromagnetic fields can be minimized by increasing the tower height and positioning phase configuration appropriately.

The harmful region to public may decide the width of the Right Of Way (ROW) in 400kV line. The ROW width can be reduced by increasing the tower height. Additionally, it is necessary to educate public on the safe utilization of the ROW for their daily activities. The results show that the electric field intensity level under the line of 400kV is large enough to charge large vehicles parked under the line, metal structures such as pipe lines, fences etc.

It may also cause shock hazards to the public. More precautions have to be taken when ROW is utilized for fuel and explosive storing purposes to avoid fire and explosion threats caused by sudden discharge of electrostatic charges.

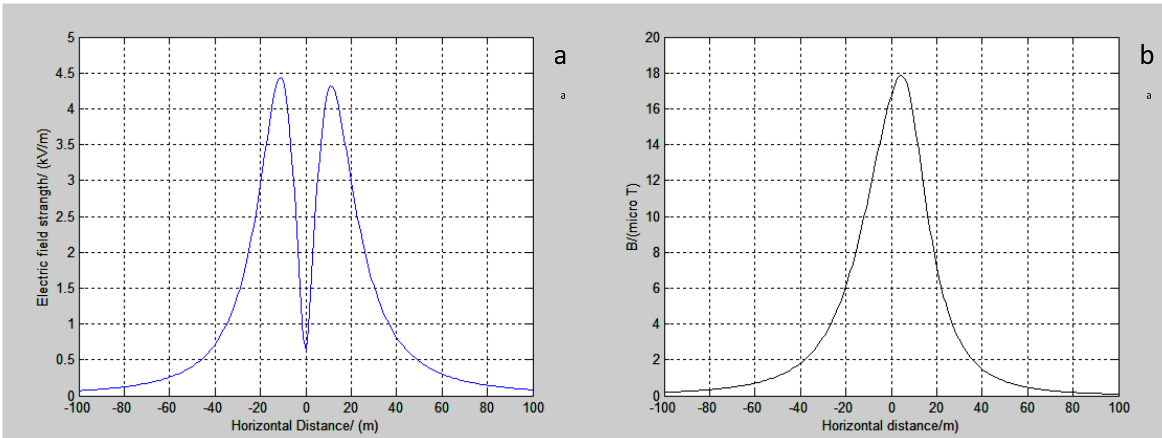


Figure 7: (a)Variation of electric field intensity and (b) magnetic field density of 400kV line at 1m above the ground level

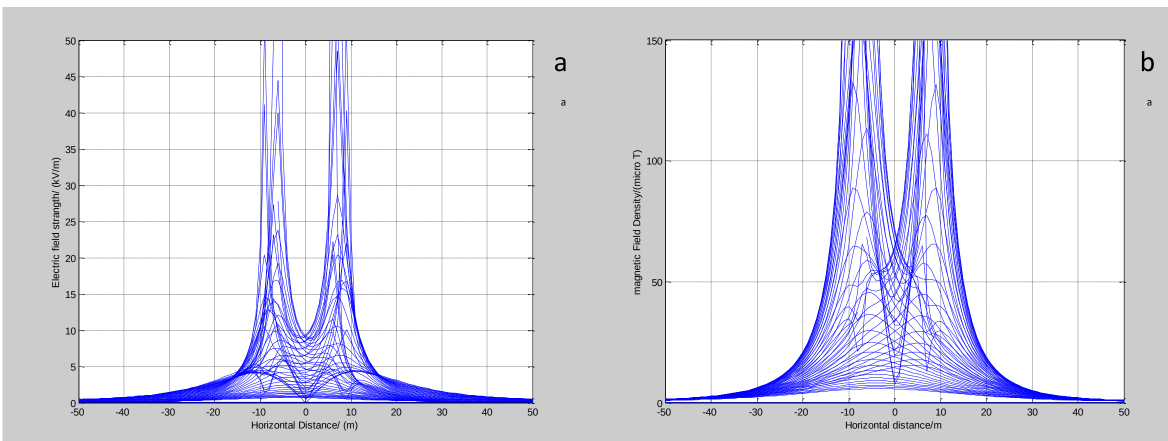


Figure 8: (a) Variation of electric field intensity along transverse direction (X) of tower for various heights (Y) above the earth surface and (b)Variation of magnetic field density along transverse direction (X) of tower for various heights (Y) of the earth surface of 400kV line

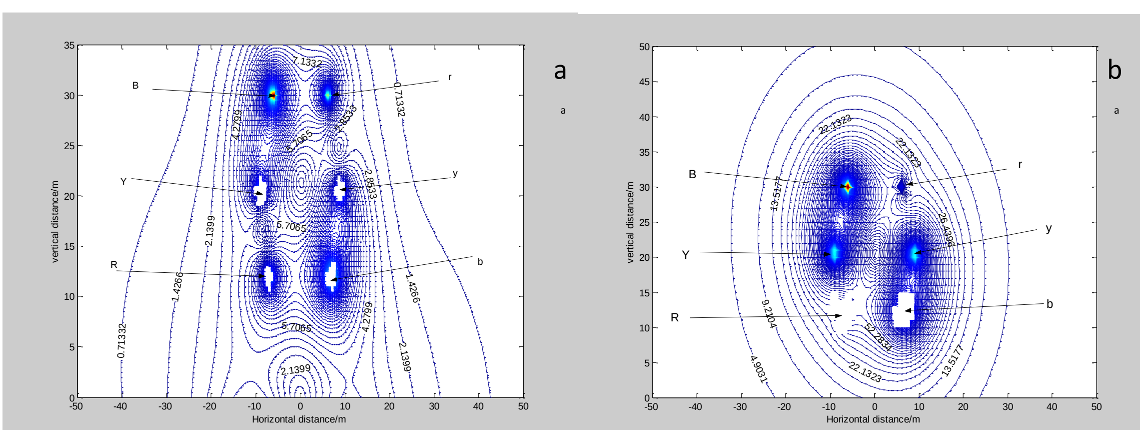


Figure 9: (b) Contours of electric field intensity on X-Y plane of the tower and contours of magnetic field density on X-Y plane of the tower (a) for 400kV line

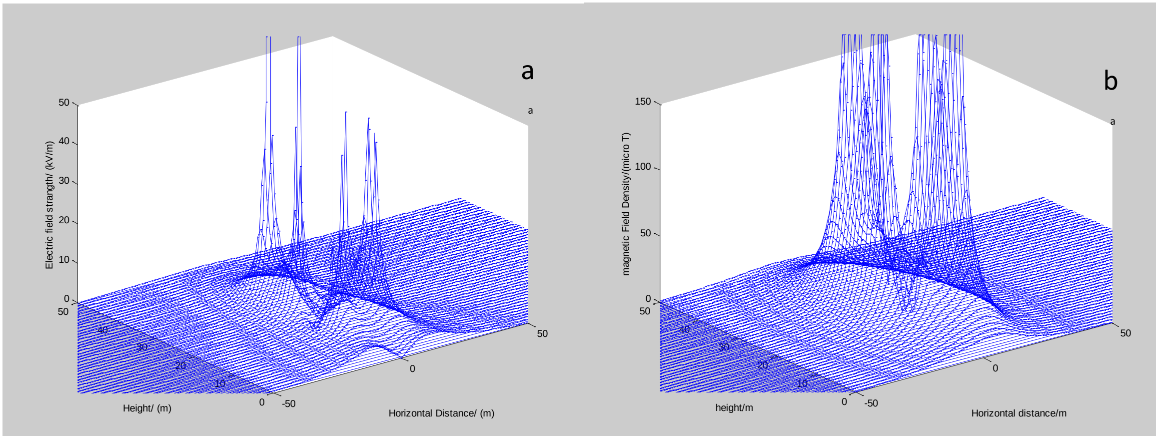


Figure 10: (a) 3D visualization of electric field intensity distribution and (b) 3D visualization of magnetic field density distribution for 400kV line

Therefore it is recommended to prepare a code of instructions for public to use the ROW safely on their activities with the introduction of 400kV transmission voltage in Sri Lanka.

Table 2: Results of the analysis

Results	Case1:132kV Lynx double circuit line	Case 2: 220kV twin Zebra double circuit line	Case 3:400kV quadruple Zebra double circuit line
Calculated values of electric field strength (E)			
Maximum E value at 1m above the ground level	E_{max}=0.68kV/m at 8m along X axis (Figure 5)	E_{max} =2.3kV/m at 10m along x axis (Figure 6)	E_{max} =4.5kV/m at 15m along x axis (Figure 7)
Demarcation of area exceeding 5kV/m value	X<5.5m and Y>8m	X<9m and Y>7m	X<13m and Y>5m (Figure 8,9 and 10)
Calculated values of magnetic field density (B)			
Maximum B value above the earth surface	B_{max}=2.8 μT at 1m along x axis (Figure 5)	B_{max} =8.6 μT at 4m along x axis (Figure 6)	B_{max} =17.8 μT at 4m along x axis(Figure 7)
Demarcation of area exceeding 100 μT value	X<4.5m and Y>10m	X<8m and Y>10m	X<12.5m and Y>9m (Figure8,9 and 10)

4. Conclusion

It is planned to measure the values in the vicinity of the power lines to compare them with the calculated results aiming to improve the calculation algorithm in order to use it for calculating field effects caused by objects of complex geometrical shape such as transformers.

References

Begamudare, R.D. 1998. High voltage AC transmission engineering.

Gupta B.R. 1997. Power system analysis and design.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). (1998).Guidelines for limiting exposure to time varying electric, magnetic and electromagnetic fields of (up to 300GHz).

Kellough, W.R. 1980. Impact assessment of electrical transmission lines: Right of Way.

Yong, H.D. 1998. College physics.

Study on Energy Loss Due to Interconnection of Embedded Generation to Distribution Network

G.N. Alahakoon[1]

Planning and Development Branch Distribution Division 3, Ceylon Electricity Board

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

This paper presents the impact on the distribution line losses due to embedded generation. Studies were performed using SynerGEE model on the selected feeders, where significant Embedded Generations (EG) are connected. Initially, a study was conducted assuming a hypothetical feeder with constant load and different level of EG capacity. It is seen that depending on the location of the load along the feeder and the EG capacity, the losses on the feeder will vary. Hence, an attempt was made to identify the optimum EG capacity that will result in minimum allowable loss on a feeder. Thereafter, studies were performed on actual feeders with load variation and EG capacity variation. It is concluded that excessive losses occur during low load condition and also during higher generation from EGs. Hence appropriate measures are to be in place to arrest excessive losses in the distribution feeders due to EGs.

Keywords: energy loss, embedded generation, synergee model

1.Introduction

Ceylon Electricity Board (CEB) initiated the development of embedded generation in mid 90s, mainly mini hydro power plants, whose installed capacity is less than 10 MW. At present there are around 140 plants with an installed capacity of 290MW scattered in the hill country of Sri Lanka. All the embedded generation is governed by the Standardized Power Purchase Agreement (SPPA) and energy is purchased through a standard tariff.

One of the main objectives of developing Embedded Generation is to promote the renewable energy contribution to the national grid as per the government policy. During the past two decades several major power plants were commissioned and to analyze the impact on the distribution system loss, a case study was carried out on selected feeders in the Rathnapura Grid Substation (GSS).

It is observed that in certain feeders of the above GSS, the power flow is negative, that is the generation from the mini hydro is greater than the local loads, which results in negative power flow. That is the power flows from the feeder towards GSS and flows along the transmission system. In order to analyze the impact of such generation on the distribution losses, feeders attached to Rathnapura GSS was selected for further analysis.

2. Theoritical analysis

Hypothetical Analysis was carried out to visualize the Distribution Line losses with respect to the location of the load along the feeder and the Mini Hydro Generation at the end of the feeder.

For this analysis, a 20 km Lynx single circuit line consisting 10 MW constant spot load and this is fed by Grid Substation and also by an Embedded Generator. Simulations were carried out using the SynerGEE model.

In order to analyze the loss variation in respect to both feeder load and amount of generation, a ratio was defined, that is the percentage of mini hydro generation with respect to the feeder load. (Feeder Load/ Embedded Generation- (L/EG).

In this analysis, location of the load along the feeder was moved from Grid Side to Embedded Generator side by keeping the ratio between Load Demand and Embedded Generation (L/EG) Constant. Thereafter, the same analysis was

[1] *Correspondence: gayanalahakoon@hotmail.com*
ISSN 2478-0669 Print

carried out for different (L/EG) ratios to calculate the distribution line loss reduction as a percentage of Embedded Generation.

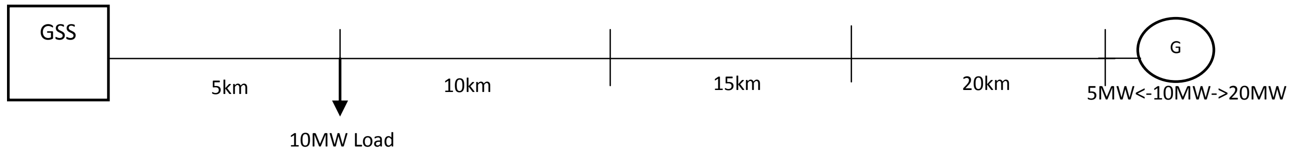


Figure 1: Typical arrangement of Load and EG

Study was performed for (L/EG) ratios for 1, 0.5 and 2.0 and the line loss variation is shown in figure 2. Figure 3 shows the line loss reduction compared to the case where there is no EG. Figure 4 shows the line loss reduction as a percentage to EG value.

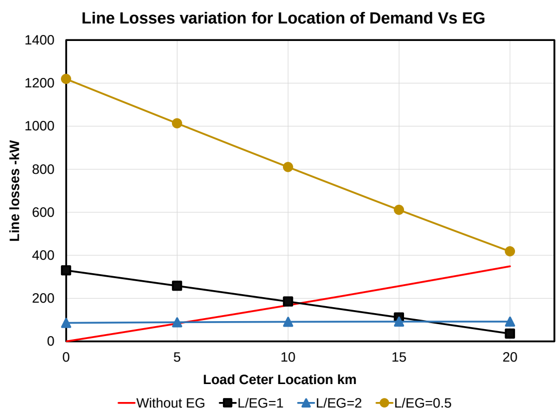


Figure 2: Line loss in kW for location of demand from the GSS

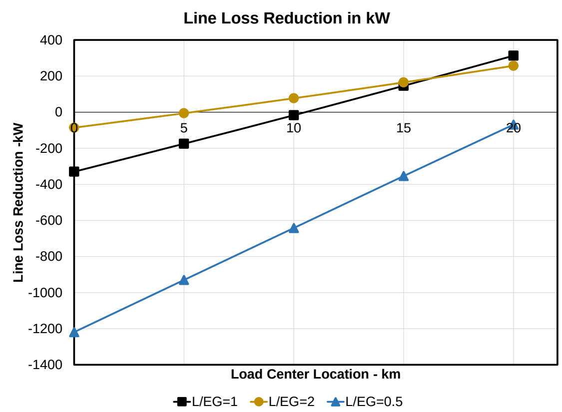


Figure 3: Line loss reduction in kW

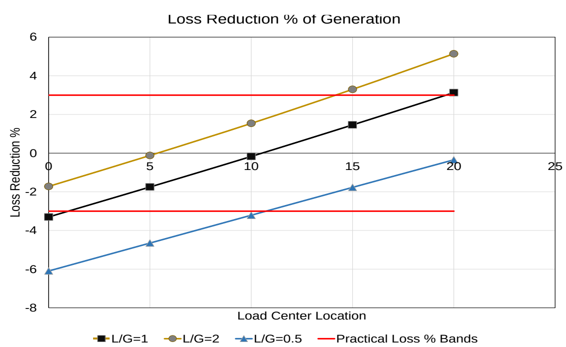


Figure 4: Loss reduction as a percentage of EG

From the above analysis following could be perceived.

- distribution losses would be minimum if the Embedded generation is closer to the load centers
- L/EG ratio ≥ 1 to minimize the cumulative line losses
- Excess EGs, that is higher than the feeder load, would result in increased distribution line losses
- Optimum EGs capacity will depend on existing locations of load centers, load demand and geographical locations of Embedded Generators.

Other issues such as voltage rise due to excessive EG are not considered in the analysis. However, the above hypothetical analysis is different from the practical scenario. In actual situation, the daily demand on a feeder varies with the time. That is, during off peak time the demand on the feeder is very low. Furthermore, actual generation from EG varies depending on the climate such as rain fall etc. In addition geographical distribution of Loads along the feeder and embedded generation necessitates that such analysis could only be carried out using computer aided models and in this case SynerGEE model is used.

3. Case study

As the demand on the feeder varies over the day, it is required to obtain the feeder wise hourly load data. Furthermore, depending on the mini hydro generation, the feeder load varies. Therefore it is required to gather information on the generation pattern of the Mini Hydros connected to that feeder. Once these information are gathered, using the SynerGEE model, losses on the selected feeder could be estimated for various load condition and also for different mini hydro generation.

3.1 Estimation of feeder load

In order to estimate the feeder load, it is assumed that the hourly load variation will be similar to that of the national daily demand curve. Based on this hypothesis, feeder load demand is separated for one hour blocks as a percentage of peak demand and is graphically is given below

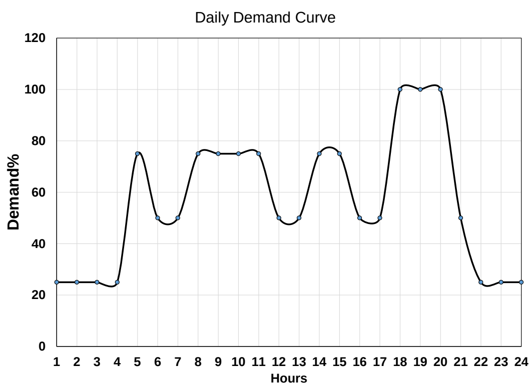


Figure 5: Typical daily demand curve

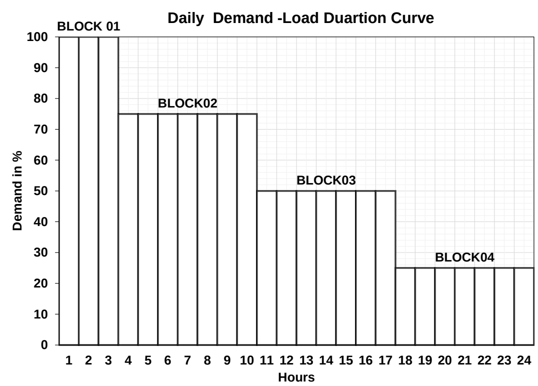


Figure 6: Load duration curve

3.2 Estimation of mini hydro generation

Since most of the EGs connected to *Rathnapura GSS* are Mini Hydro Plants (MHP), monthly plant factors (PF) of EGs are assumed by considering the actual generation for the year 2014. It is observed that in most cases maximum average PFs in MHPs are generally around 70% during heavy rainy seasons. Actual PFs of MHPs connected to Rathnapura GSS were considered for the analysis in order to calculate the line losses.

4. Methodology

Initially for each feeder, losses are calculated with the assumed daily demand curve, without considering any EG. Thereafter, averaged PFs are figured out for the given month for each feeder. Then with those constant PFs, feeder losses are re-calculated with respect to the assumed demand curve. Finally, distribution line loss reduction due to addition of EGs are observed for different PFs and optimum EG capacity could be derived which will minimize the loss on the selected feeder.

5. Case study

5.1 Rathnapura Eheliyagoda feeder (F03)

In this feeder, three commissioned MHPs with installed capacity of 12.25MW are connected and two more MHPs (2.4MW) are at proposed level. Average PF variation for the year 2014 of commissioned MHPs connected to above feeder have been taken into account to analyze the impact. Loss Analysis were carried out for PFs in the range 15%, 25%, 40%, 60% and for 70%.

Then, each average PFs were considered with daily demand curve with hourly blocks. As per the 2014 Medium Voltage (MV) plan, Rathnapura- Eheliyagoda Feeder is having a peak demand of 8,813 kVA and 12,250 kW of installed capacity of Embedded Generation. It means that, (L/EG) ratio for the above feeder under consideration is about 72%. However, as per the actual PF in year 2014, maximum PF was around 70%. Yet (L/EG) Ratio is about 102% and in heavy rainy seasons EG power flow would be towards the Grid side with higher distribution losses. As per the Hypothetical Analysis, (L/EG) ratio should be $\geq$ 100%. SynerGEE simulations were carried out for each load block and for each PF. The results for 70% PF for each block is shown below.

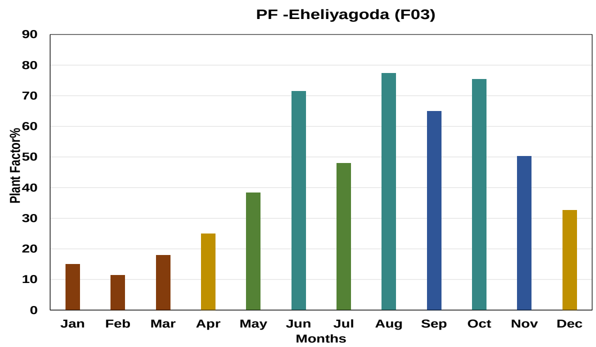


Figure 7: Plant factors of EGs during the year

15%	25%	40%	60%	70%
Jan	April	May	Sep	June
Feb	Dec	July	Nov	Aug
Mar				Oct

Figure 8: Seasonal plant factor of EG

Table 1: Results of 70% PF

			Plant Factor- 70%					
Without MHPs			With MHPs					
Load Variation of the Feeder	Load {L} Amps (A)	Loss (kW)	Grid net Load Amps (A)	Loss (kW)	Loss Reduction Due to MHPs (%)	Loss Reduction Due to MHPs (kW)	Generation {EG} (Amps)	L/EG %
0.25	92	36	64	269	-2.72	-233	154	59.74
0.5	113	71	46	262	-2.23	-191	154	73.38
0.7	133	118	30	268	-1.75	-150	154	86.36
1	154	179	24	285	-1.24	-106	154	100.00
					-2.11	-180.67		

Similarly the above analysis was repeated for other PFs, i.e. 60%, 40%, 25% and 15%.
The results of the simulations are shown graphically, i.e. the loss variation with respect to (L/EG%).

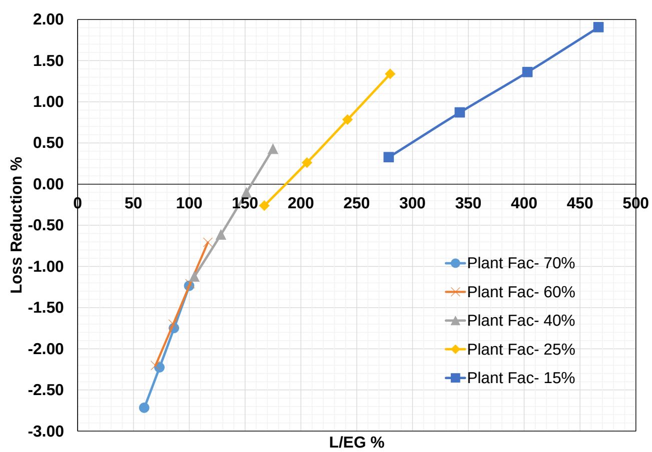


Figure 9: Loss reduction as a % of EGs

From the figure 9 it could be seen that the embedded generation capacity that would result in the minimum losses in this selected feeder corresponds to a L/EG ratio of around 175%. In order to obtain the losses over a period of time, that is for one year, for each load block, and for each PFs the cumulative losses were calculated.

Further, Cumulative Losses per annum were also plotted with respect to Daily Demand Curve and PF Durations by months as below.

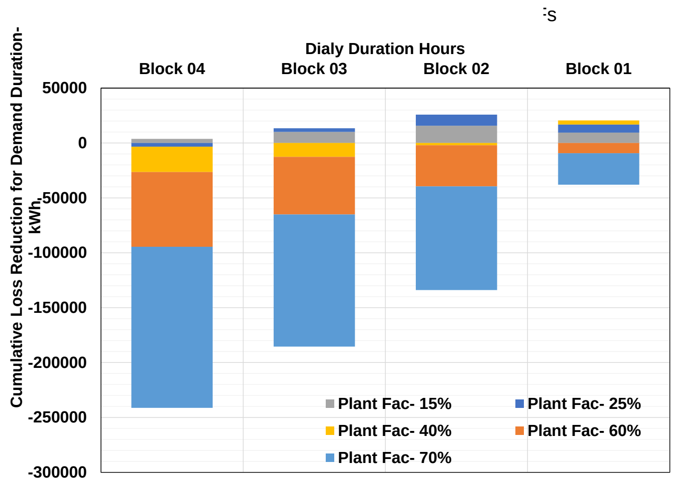


Figure 10: Cumulative loss in kWh

From the figure 10 it could be seen that, annual line losses increase due to addition of EGs, which is beyond the optimum EG value. In most of the cases L/EG <100%. As per the Standard Power Purchase Agreement (SPPA), metering point of EG shall be within power house premises. Hence, medium voltage line loss due to addition of EGs is not accounted for and it has to be borne by the CEB.

Currently, the average cost for kWh for MHPs is nearly Rs.14.25 for year 2014 and annual line loss boost due to EGs in above feeder is 7.6MLkr. (535,020.00kwh per annum (-0.56%) Line Loss Increment/EG %)

This methodology was repeated for other feeders at Rathnapura GSS to derive distribution losses, which are having EGs.

5.2 Rathnapura Durekanda feeder (F08)

In this case (L/EG) ratio for this feeder is around 145% respective annual loss increment due to EG is 8.4MLKR((589,620.00kwh per annum (-0.85%) Line Loss Increment/EG %).

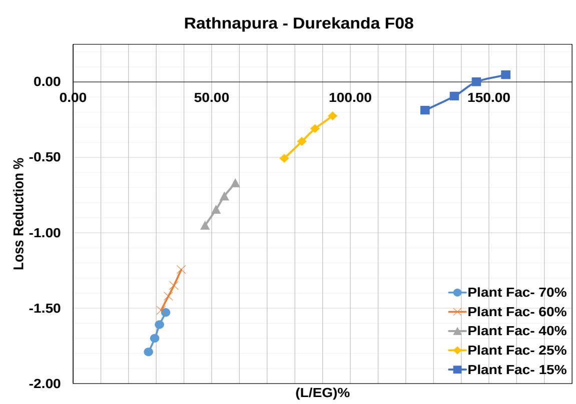


Figure 11: Loss reduction as a % of EGs

5.3 Rathnapura Kuruwita (F05)

Here, (L/EG) ratio for this feeder is again around 145% respective annual loss reduction due to EG is 2.3MLKR (160,170kwh per annum 1.47% Line Loss reduction/EG %).

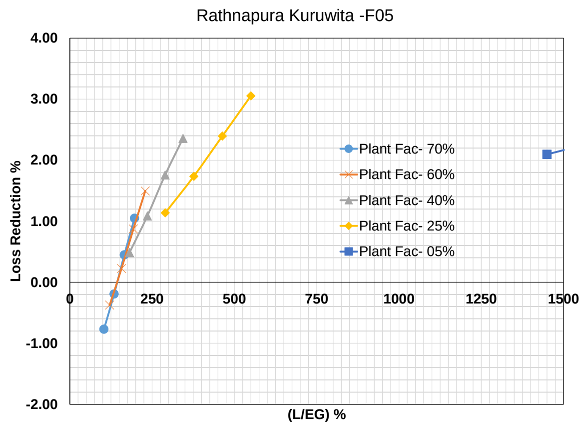


Figure 12: Loss reduction as a % of EGs

5.4 Rathnapura Nivithigala (F06)

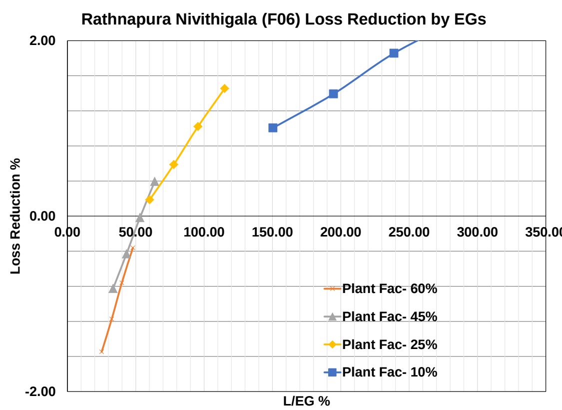


Figure 13: Loss reduction as a % of EGs

In this feeder almost, 9MW generation out of 12.25MWs are located near the Rathnapura GSS. But load is distributed among the feeder. Hence, excess power by EGs will flow to the GSS with minimum line length and less line losses as above. Hence, (L/EG) ratio for this feeder is 55% respective annual loss reduction due to EG is 0.8MLKR (57,030kwh per annum 0.52% Line Loss reduction/EG %).

In all other four feeders of Rathnapura GSS there are no commissioned EGs.

6. Cumulative summery of line losses

As per the above Analysis, Total Loss Reduction in 33kV feeders due to EGs are summarized in Table 2.

It is to be noted that above line losses will further increase with the addition of new plants and plant factors of commissioned EGs. Further, Mini Hydro plants are also running at its maximum capacity during rainy seasons, where CEB reservoirs are also at its spill levels. Since, there is no method to control the generation of EG plants, CEB main hydro Plants will have to generate depending on the system demand at that time.

Actual energy sent out from Rathnapura GSS in 2014 was - 29,602.00 MWh and monthly energy sent out is graphically shown in Figure 14.

Table 2: Total loss reduction

1	Rathnapura Durekanda Feeder (F08)	*41.25PF*	*(589,620.00) kWh*	*-8,402,085.00LKR*
II	Rathnapura –Eheliyagoda Feeder (F03)	*42.08 PF*	*(535,020.00) kWh*	*-7,624,035.00LKR*
III	Rathnapura Kuruwita (F05)	*38.33 PF*	*160,170.00 kWh*	*2,282,422.50LKR*
IV	Rathnapura Nivithigala (F06)	*27.92 PF*	*57,030 kWh*	*812,677.50* LKR
	Total Loss Reduction		*907,440 kWh*	*-12,931,020.00*LKR

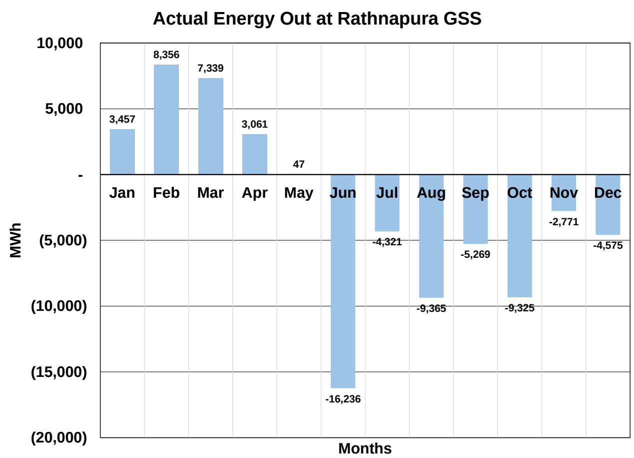


Figure 14: Actual energy sent out from Rathnapura GSS in year 2014

Figure 14 shows that, in most cases Demand in Rathnapura GSS is less than the EG. Hence, in most practical situations (L/EG < 100%) and results in higher distribution line losses in MV feeders.

7. Conclusion

The impact of EG on distribution line losses have been analyzed for variable daily demand and mini hydro penetration levels. In practical situations, (L/EG) ratio will fluctuate with the load demand variation, load dispersion, geographical dispersion of EG, and EG's plant factors. Most of the EGs are located in remote areas, that is, in rural areas where the consumer demand is very low. Further EGs are located generally at feeder ends and not at load centers. In such cases, it could be concluded that L/EG ratio shall be more than 100% to minimise the distribution line losses.

Excess penetration of EGs will lead to higher line losses as well as voltage rise at off-peak times. In order to develop a good plan for EG development, detailed studies need to be carried out taking into account the demand distribution, location of proposed DGs and also feasibility of storing excess energy during off peak hours and to utilize them during peak hours. Therefore, existing mini hydro plants have to be converted to hybrid plants in the longer term with suitable energy storing methods, which could enhance the excess penetration of Embedded Generation to the distribution network.

Acknowledgment

The author wishes to take this opportunity to thank Mr. J. Nanthakumar, D.G.M (Planning and Development) and Mr. S.H Walpita, Chief Engineer (Planning and Development) of Distribution Division 3 of CEB for their valuable suggestions, advice and continuous support in developing this paper.

References

Integration of Non-Conventional Renewable Energy Based Generation in to Sri Lanka Power Grid. 2015, Study Team, CEB.

Power Purchased from small power producers reports in year 2014 by Energy Purchase Branch, CEB.

System Control & Operations. Reports in year 2014 by System Control Branch Ceylon Electricity Board.

Víctor H., Quezada, M. and Abbad, J.R. Member, IEEE, and Tomás Gómez San Román, Member, IEEE, *"Assessment of Energy Distribution Losses for Increasing Penetration of Distributed Generation"*.

Hydrocarbon Exploration: Accomplishments, Opportunities and Challenges in the Mannar Basin, Sri Lanka

E.K.C.W. Kularathna[1*], H.M.T.G.A. Pitawala[2], A. Senaratne[2], B.S.M.C.K. Senevirathne[1], D.A.Weerasinghe[1]

[1]*Petroleum Resources Development Secretariat, Sri Lanka*
[2]*Department of Geology, University of Peradeniya*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Sri Lankan land mass is bounded by three sedimentary basins; Cauvery, Mannar and Lanka. After 25 years of pause, hydrocarbon exploration is being carried out successfully in the deep water Mannar basin since 2001. The basin has been proven for hydrocarbon potential with the discovery of gas from two wells named Dorado and Barracuda. These gas discoveries are needed to be appraised thoroughly by analyzing uncertainties associated with reservoir parameters. Interpreted plays and leads at multiple stratigraphic levels were enveloped in to the play levels as, Tertiary, Upper Cretaceous, Albian and Basement. Tectonic evolution, stratigraphy, play definition (both proven and unproven) and mature source rocks indicate of high potential for further exploration. High costs for drilling, development and production in deep water settings, poor seismic images due to intrusive and extrusive igneous activities, slow government procedures are the key challenges in further exploration of hydrocarbon in the Mannar basin.

Keywords: Hydrocarbon exploration, Mannar basin

1. Introduction

Three sedimentary basins, namely the Cauvery, Mannar and Lanka basins are located surrounding the Sri Lankan land mass (Kularathna et al., 2015, see Fig 1). The Mannar basin is located from Southwest to Northwest Sri Lanka, Southeast of India and South to the Cauvery basin. In terms of size, the Sri Lankan side of the Mannar basin approaches in an area of approximately 50,000 square kilometers. The basin is an offshore basin and water depths are ranging approximately from 500m to 3500m (Figure 1).

1.1 History of the oil exploration in Sri Lanka

Efforts for oil and gas Exploration in Sri Lanka can be recognized in two periods as old and new. Old period of oil exploration activities in Sri Lanka dates back to late 1950 s' and activities were mainly confined to the shallow water portion of the country. During this period the total length of approximately 9030km line of 2D seismic data was acquired and seven wells were drilled (CPC - report., 2001). Despite the gas shows in Pesalai-1 well, old period was continued until 1984 and was ruined without any useful results (U.S.S.R - report., 1976). Recent exploration activities have been begun in the deep water in the Mannar basin in 2001. Two 2D seismic data acquisition programs were done consecutively in 2001 and 2005, and in the year 2007, the block no "2007-01-001" was awarded to Cairn Lanka pvt Ltd (Figure 2). Two 3D seismic data acquisition programs and exploration of four wells such as Dorado, Dorado North, Barracuda and Wallago were performed by Cairn, and discoveries of gas from Barracuda and Dorado wells (Figure 2) were recorded. However, a major portion of the Mannar basin still remains underexplored.

1.2 Generalized stratigraphy

The N-S trending Mannar Basin is a pericratonic failed-rift basin and it is divided in to three main tectonic phases such as pre-rift, rift and post-rift. Lower and middle Jurassic pre-rift section with possible Karoo series rocks have been deposited in continental to lacustrine environment (Sundaram et al., 2001; Rao et al., 2010; Shaw, 2002; Kularathna et al., 2015). Rift phase has been divided in to two as early syn-rift and late syn-rift. Early syn-rift phase appears to have started in the late Jurassic, as a result of extension between Africa and Antarctica. During the period, sediments may have deposited in lacustrine to shallow marine environments. The late-syn rift phase, associated with India Antarctica-

*Correspondence: kularathna@prds.lk
ISSN 2478-0669 Print

Australia rifting, presumably began in the early Cretaceous, causing more extension in the Mannar basin. Shallow to deep marine depositional environment has been interpreted for the sedimentary formation. During the late Cretaceous and the Oligocene to Miocene Post-rift phase occurrences of thermal sagging under deep marine depositional environment is interpreted The basin was subjected to igneous activities during the post rift thermal sag phase (Shaw, 2002).

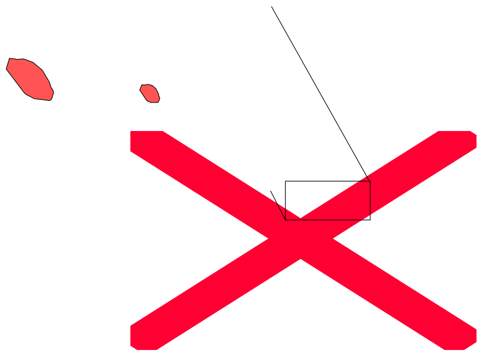


Figure 1: A Map showing; 2D and 3D seismic data coverage with in the Sri Lankan jurisdiction, Well Locations (*Dorado, Dorado North, Barracuda and Wallago*), Two gas discoveries (*Dorado and Barracuda*), Exploration blocks in Cauvery basin and Mannar basin, Blocks for Joint studies

This paper aims to briefly discuss the Dorado and Barracuda discoveries, identified potential for future exploration and challenges faced in hydrocarbon exploration in the Mannar basin Sri Lanka.

2. Methodology

Available data at Petroleum Resources Development Secretariat (PRDS), Colombo were incorporated for the study. Petrel 2011.2.4 / 2012.1 and Kingdom suit 8.3 exploration and production software platforms were mainly used for geophysical and well data interpretations. Arc GIS software platform was utilized for the preparation of maps and data analysis. Previous interpretations reports, well reports and other available information were also utilized for the study.

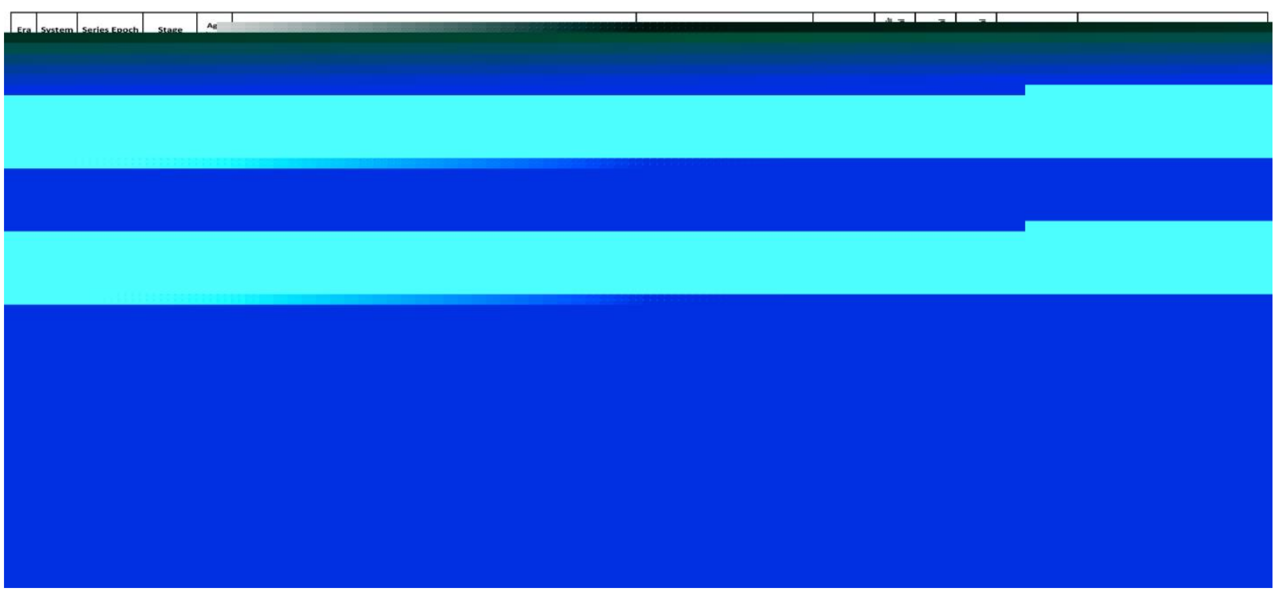


Figure 2: Generalized stratigraphic chart for the Mannar basin showing occurrences of petroleum system elements (Kularathna et al.,2015)

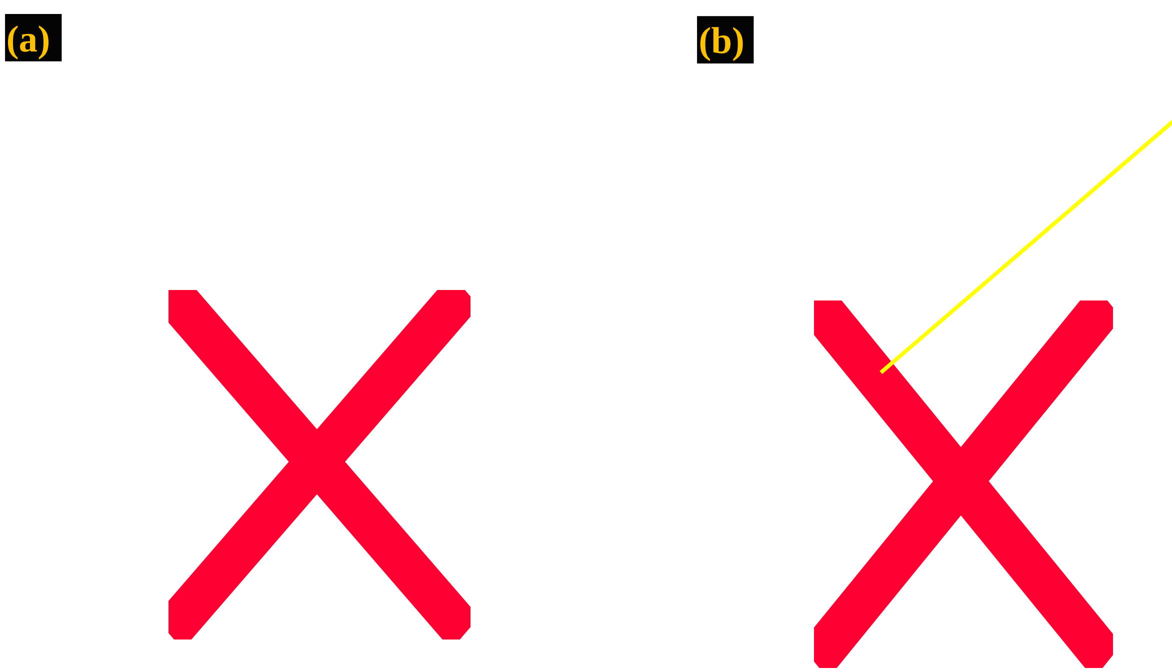
3D seismic and well data pertaining to block SL 2007-01-001 were interpreted to obtain information regarding the Dorado and Barracuda gas / condensate discoveries and unexplored prospects, while 2D seismic data acquired in 2001 and 2005, covering significant area of the Mannar basin were interpreted to extract information regarding the future hydrocarbon potential of the basin (Figure 1).

3. Results and Discussion

3.1 Dorado and Barracuda gas discoveries

Dorado discovery is located approximately 30km from the western near shore line of Sri Lanka (Figure 1) and the water depth is approximately 1350m and the reservoir top depth is 3010 m (total vertical depth sub-sea (TVDSS)).The discovery was made in a forced fold structure formed above an igneous intrusive (Hansen et al.,2006) and the reservoir is Early Campanian feldspathic - arenite deep water sands (Ichron.,2012) with average porosity and moderate permeability (Beard et al.,1973) (Figure 3). Encountered two reservoir sand levels are separated by a 30m shale; however, pay is evident only in the upper sand layer at the well location. Shale sequence above the upper sand layer provides sealing to the reservoir. According to results of the rock physics analysis the prospect is having Class III type AVO response, which is typical of gas sand. A bright amplitude anomaly associated with an apparent flat event is seen to be draped over igneous sills. The polarity of this reflection event is opposite to that of the sea floor, suggesting a soft seismic response at top reservoir (Malkani et al., 2015). Distinct gas water contact (GWC) can be interpreted from the MDT data and therefore pool limits were able to be determined with high confidence. According to the fluid analysis results, discovery is dominated with dry gas (approximately 96% methane with little condensates).

Barracuda discovery is located approximately 66km from the western near shore line of Sri Lanka and the water depth is approximately 1500m. The Barracuda discovery is located in a four way broad anticlinal feature and the gas was encountered in three intra volcanic sand layers located at approximate depths of consecutively 4040m, 4140m and 4170m (from TVDSS) (Figure 4).These sand layers are feldspathic to subfeldspathic - arenites with abundant mafic minerals and porosities are consistent with variable permeabilities. The age of the volcanic layer and the intra-volcanic sand layers is Maastrichtian inferred from Ar-Ar dating of the volcanic rocks and paleontological interpretations of the microfossils from sandstone interval (Ichron., 2012). Although mapping of intra-volcanic sands is the major technical challenge, it is apparent on seismic data that the flood volcanic layer together with intra-volcanic sand layers is pinching out towards the basin margin s).



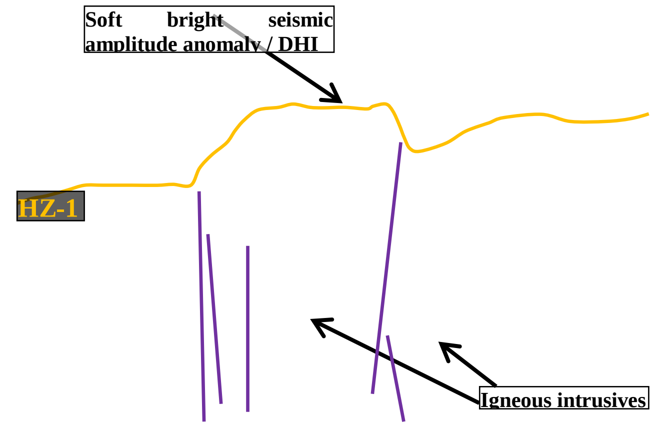


Figure 3: (a) Seismic section through the Dorado gas discovery showing the forced-fold structure and the direct hydrocarbon indication (DHI) (b) Depth structure map of the horizon HZ-1 showing: location of the seismic section “a” (in yellow colour) and RMS – amplitude extraction (search window of 60m above and below the event HZ-1)

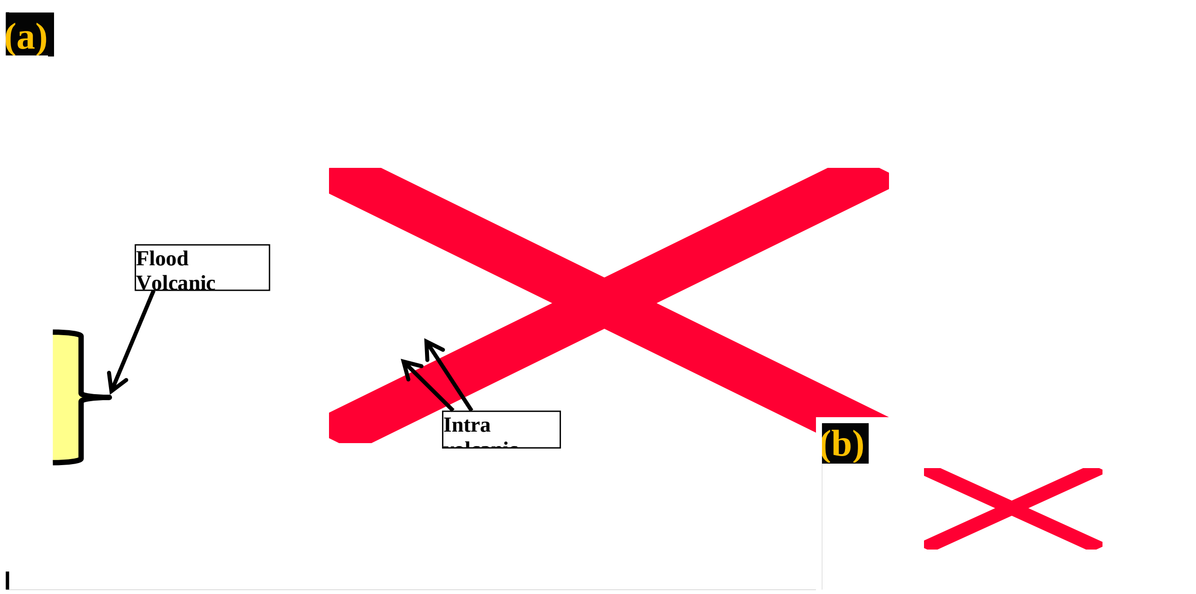


Figure 4: (a) Seismic section showing: the Barracuda gas discovery, flood volcanic layer and the well tops. (b) A map showing the location of the seismic line “a”

3.2 Future exploration potential

Mannar basin is still an underexplored basin with limited well control and five wells have been drilled thus far in the northern portion of the basin. Therefore recognized proven plays for hydrocarbon are limited. However, 2D seismic data acquired in 2001 and 2005 (Figure 1) have disclosed significant potential in the unexplored area with new plays. Based on the seismic interpretation results, together with regional and local information five major play levels were defined and interpreted plays and leads were then enveloped into these play levels as; Tertiary plays (Fans/ Channels/ Mounds/ roll over anticline), Upper Cretaceous (Forced folds/ intra-basalt turbidite sands/ sub volcanic clastics), Albian - Aptian (Fans/ reefs/ mounds), Early - Syn rift (fans) and Basement (weathered basement) (Figure 5).

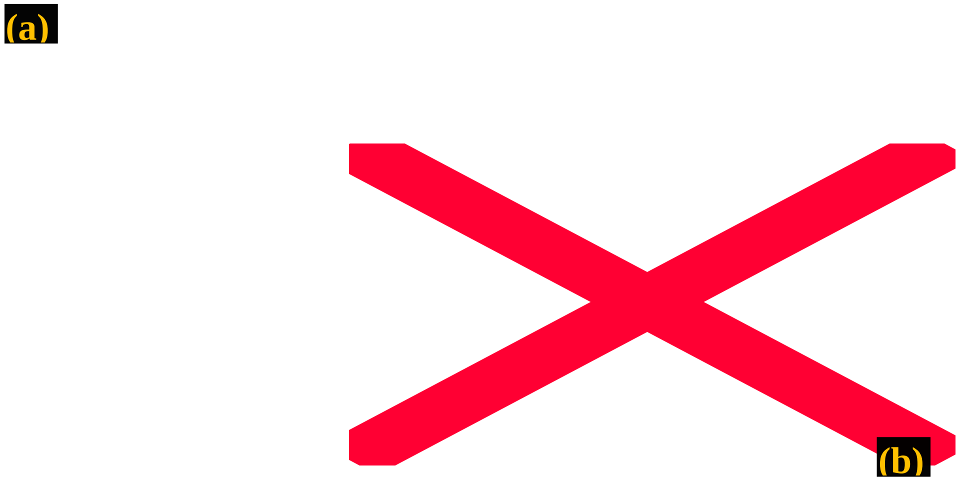


Figure 5: (a) 2D seismic line SL 05-57showing; key seismic horizons (Sea bottom, Oligocene, Eocene, Flood volcanic top, Flood volcanic bottom/ Cretaceous top, Albian-Aptian/ top late syn-rift, top early syn-rift / Late Jurassic top and basement) and interpreted major plays (b) A map showing the location of the seismic line "a"

Possible source rock regimes applicable to the Mannar basin was defined connecting to the tectonic evolution of the basin and the available data from the drilled wells, regional and local information were utilized for the source rock type prediction. Four source rock regimes were defined as given below.

- Pre Rift phase source rocks; There are no direct evidences from well data but Karroo-type coals and lacustrine shale sources of type I and type III can be interpreted with reference to the tectonic evolution of the basin. Kerogen types I & III are possible (Shaw, 2002). (Occurrences: proto-Somali BasinGodavari-Krishna Basin and Madagascar (TGS, 2005)).

- Early Syn-rift phase source rocks; There are no direct evidences from well data, but coals and lacustrine shale sources can be interpreted with reference to the tectonic evolution of the basin. Kerogen types I & III are possible (Shaw, 2002) (Occurrences: Andigama and thabbowa (Cooray.,1984), proto-Somali Basin, Godavari-Krishna Basin and Madagascar (TGS, 2005))

- Late Syn-rift phase source rocks; Marine shales of kerogen type II are proven for this phase and direct evidences are coming from the well Pesalai-1, which has penetrated oil-prone Albian source rocks of 600m thick. (Occurrences: Sattapadi formations in the Cauvery Basin (Berry et al.,1990), Mannar basin (USSR.,1976))

- Post rift phase / Thermal sag period source rocks; Source rocks of both type II and type III were encountered in the wells Dorado, Barracuda and Wallago confirming the existence of Marine shales of kerogen type II in the Mannar basin (Ichron.,2012). However Post rift phase / Cenozoic sedimentary section source rocks are immature for hydrocarbon generation (Kularathna et al.,2015).

Major seal rocks are claystone, mudstones and shales, which are prevailing above the reservoirs. Flood volcanic layer act as a regional seal and provides sealing particularly for intra-volcanic sands and reservoir facies below the bottom of the flood volcanic layer.

3.3 Exploration challenges

The major exploration challenges of the Mannar basin faced by any Exploration and Production company are listed below. These challenges can also be recognized as geological, operational, regulatory and other.

- Geophysical data acquisitions in deep water basins, such as Mannar basin, are comparatively effortless and low-cost. However, nowadays deep water drilling is done at a very high cost. Similarly, deep water development and production costs are very high.

- A flood volcanic layer prevailing at the KT boundary of the Mannar basin covers more than two thirds of the basin area. Seismic imaging below this flood volcanic layer is being hindered by its high acoustic impedance. Therefore petroleum system definition below the KT boundary of the Mannar basin has been a major challenge. In addition to this, for identified plays their indigenous geological risk factors have to be considered.

- Although the basin is still proven only for dry gas, several petroleum system modeling results have revealed a substantial oil potential adjacent to the Mannar basin margin, (Kularathna et al., 2015). Uncertainties present with the deep water gas development, gas prizing and gas market opportunity E&P companies may be reluctant to make investment decisions.

- E&P industry is an extremely dynamic, fast growing industry where advance technology is applied .Therefore, slow government procedures in block awarding, getting approvals and singing contracts are major issues. Especially, the hydrocarbon exploration is being done in high risk basins, like Mannar basin. In addition, flexible, attractive terms and conditions must be included in to the agreements in order to attract E&P companies.

4. Conclusion

Mannar basin has a proven petroleum system and it has been confirmed by the potentially commercial recent discoveries. An appraisal program must be carried out to identify uncertainties associated with the gas discoveries of Dorado and Barracuda. Tectonic evolution, stratigraphy, play definition (both proven and unproven) together with good source potential show huge upside potential for further exploration activities in the basin. Remedial measures must be taken to overcome above discussed challenges in order to create an Exploration and Production industry in Sri Lanka.

References

Allen, P.A., and Allen, J.R., 2005. Basin analysis, principles and applications. Second edition, Blackwell publishing ltd, ISBN-0-632-05207-4, 405-474 .

Beard, D.C., and Weyl, P.K., 1973. Influence of Texture on Porosity and Permeability of unconsolidated Sand. AAPG Bulletin 57: 349-369.

Berry, C.M., and Rawat, M.S., 1990. Organic Matter Type, Maturation and Source Potential in Offshore of Cauvery Basin.Bulletin of the Oil and Natural Gas Commissiion. V. 27(2): 79-90.

Cantwell, T., Brown, T. E., Mathews, D. G., 1977. Petroleum Geology of the Northwest Offshore area of Sri Lanka. CPC (Ceylon Petroleum Corporation)., 2001. Sri Lanka's Petroleum Exploration Concessions, 5-13

Cooray, P.G., 1984. An introduction to the Geology of Sri Lanka, 117-132.

Gomes J. S., and Alves F. B., 2007. Universo da industriapetrolifera. CalousteGulbenkian Foundation, Lisbon, Portugal. ISBN 978-972-31-1228-3; 2nd edition.

Hansen, D.M., and Cartwright, J.A., 2006. The three-dimensional geometry and growth of forced folds above saucer-shaped igneous sills. *Journal of Structural Geology* - vol. 28: 1520-1535.

Ichron limited., 2012. A biostratigraphical evaluation and petrographical, diagenetic and reservoir quality assessment of well Dorado-91H/1Z, Block SL 2007-01-001, Mannar Basin, Sri Lanka. Prepared for Cairn Lanka Pty Limited by Ichron Limited.

Ichron limited. ,2012. A biostratigraphical evaluation and petrographical, diagenetic and reservoir quality assessment of well Barracuda-1G/1, Block SL 2007-01-001, Mannar Basin, Sri Lanka. Prepared for Cairn Lanka Pty Limited by Ichron Limited.

Isis Petroleum Consultants Pty Ltd and TGS nopec., 2005. Hydrocarbon Prospectivity Review of the SL04 Marine Seismic Survey Gulf of Mannar Basin, Sri Lanka, Final Report. Perth, Western Australia.

Malkani,A., Prabir Routray., Prem Kumar., BiswanathGhosh., SomanChacko., Michael Quinn., 2015. Applying Rock Physics Analysis to De-risk Exploration Prospects in Mannar Basin, Sri Lanka. EAGE Seismic Driven Reservoir Characterization and Production Management Symposium Kuala Lumpur, Malaysia.

Rao, M.V., Chidambaram, L., Bharktya, D., Janardhanan, M., 2010. Integrated Analysis of Late Albian to Middle Miocene Sediments in Gulf of Mannar Shallow Waters of the Cauvery Basin, India: A Sequence Stratigraphic Approach.

Shaw, R.D., 2002. Interpretation Report on Offshore Sri Lanka Seismic Survey, TGS-NOPEC, 1-88.

Sundaram, R., Henderson1, R., Ayyasami, K., and Stilwell, J. D., 2001. A lithostratigraphic revision and paleo environmental assessment of the Cretaceous System exposed in the on shore Cauvery Basin, southern India, Cretaceous Research 22: 743-762.

VsesoyuznoeExportnoimportnoeObjedinenie “Technoexport” (U.S.S.R) report., 1976. Report on Rendering Assistance in Drilling Three Deep Wells at Mannar Island in the Republic of Sri Lanka, 30-37.

Optimizing the Cable Designs for Wind Energy Applications

M.W.B.K. Wickramagedara, A.H. Wijethunga, J.B. Ekanayake*

Department of Electrical and Electronic Engineering, University of Peradeniya

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Wind power will play a major role in the future power system. In order to promote more and more wind farm connections, the capital cost (CAPEX) should be minimised. Even though the cost of the collector cable network is about 5% of the total CAPEX of the wind farm, any reduction of Cu or Al use for cables is welcomed both by both environmental and cost point of views In this paper, a method of reducing the size of the cables used for a wind farm is presented. A case study was used to validate the proposed method. The results show a great reduction of cable size used for the collector network.

Keywords: wind power, cable design

1. Introduction

Generating electricity from the wind is one of the most cost effective ways of using renewable energy. By 2014 there was more than 350 GW of wind turbine capacity installed worldwide. According to the Sri Lankan Government's energy sector targets published in 2015, the Government aims to "increase the share of electricity generation from renewable energy sources from 50% in 2014 to 60% by 2020 and finally to meet the total demand from renewable and other indigenous energy resources by 2030". It is anticipated that wind power will play a major role when achieving the Government's ambitious energy sector targets.

Wind turbines generate power at a relatively low voltage, usually below 1000 V. Some larger turbines (>3 MW) use a higher generator voltage, up to around 3-5 kV, but at this increased voltage the safety requirements are more onerous. With these generator voltages it is necessary for each turbine to have an individual transformer either within or adjacent to the tower. This increases the voltage for connection to the power collection network, for example to 33kV. Each turbine also requires some form of switchgear (circuit breaker, isolators and perhaps fuses). Many wind turbine manufacturers now include the transformer and switchgear as part of the turbine supply.

A typical onshore wind farm connection is shown in Figure 1. A number of strings of wind turbines are connected to the collector bus bar at 33 kV. A central wind farm transformer steps up the voltage to 132 kV for connection to the public network. In many wind farms, the same cable is used from the end to the beginning of each string. However, towards the end of the string power from a few turbines is flowing whereas at the beginning power from the entire string is flowing. For example if each wind turbine is 2 MW and a string has 10 wind turbines, the last line section between the 10^{th} and 9^{th} wind turbines will carry a maximum power of 2 MW, whereas the line section between 9^{th} and 8^{th} wind turbines carries 4 MW and so on. Therefore, it is more economical to use tapered power cables where the area of cables towards the end of the string is much less than that of the beginning of the string. This is illustrated in Figure 1.

This paper discusses a concept which could further reduce the size of the cables beyond the tapered cable design. The new concept is based on the fact that the current carrying capacity of a cable depends on the heat balance on the cable and when the wind blows more heat is taken away from a cable quickly. Therefore when the wind speed is high, even under high currents flowing through the cable the heat produced by the copper (I^2R) losses of the cable will not increase the temperature of the cable beyond the permissible level. This in turn increases the current carrying capacity of the cable. As current flowing through a collector cable within a wind farm is directly related to wind speed, the above phenomena was used to further reduce the cross sectional area of the collector cables.

* *Correspondence: jbe@ee.pdn.ac.lk*
ISSN 2478-0669 Print

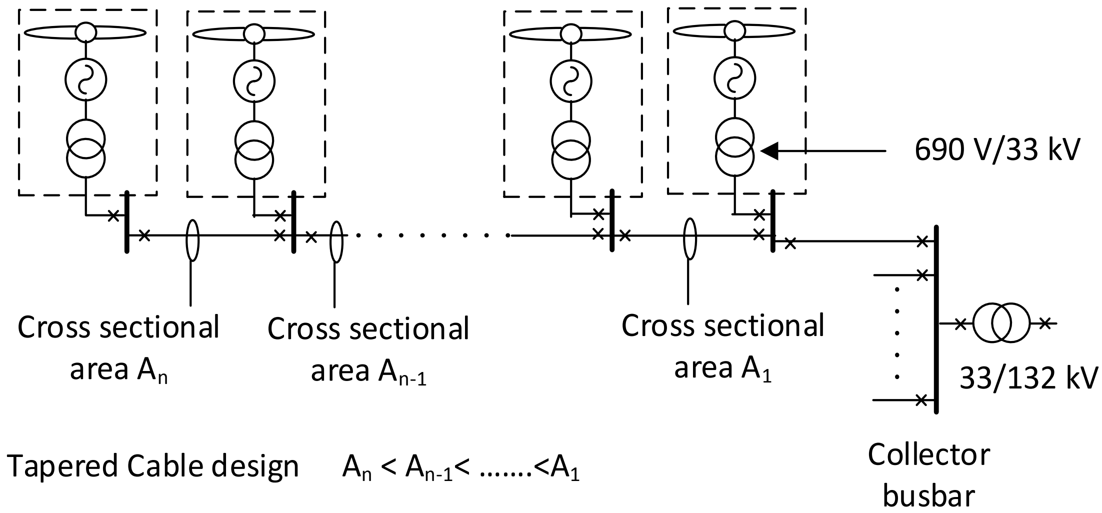


Figure 1: Typical wind farm connection

2. Methodology and Results

The wind speed, ambient temperature, wind direction, solar radiation, emissivity factor, and solar absorption factor have a significant effect on the current carrying capacity of a cable [1], [2]. The current-temperature relationship of a bare overhead conductor is addressed in the IEEE 738 standard. In response to changes in conductor current and weather, the conductor temperature value changes and affects to the dynamic current carrying capacity of the conductor at the particular temperature [2].

Non-steady state heat balance equation for power line can be defined as in equation (1), where q_s is the heat input due to solar radiation, q_c is the heat output due to convection (a function of wind, ambient temp, conductor temp), q_r is the loss of the radiation heat (a function of ambient temp and conductor temp), $I^2R_{ac}(T_c)$ is the heat input due to line current (R_{ac})is a function of conductor temperature), m is the mass density and C_p is the specific heat capacity of the conductor [2].

$$q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R_{ac}(T_c) \qquad 1$$

Here R_{ac} is calculated using equation (2) where T_c is the conductor temperature and T_o is the initial temperature.

$$R_{ac} = R_{dc}[1+\alpha_0(T_c - T_0)] \qquad 2$$

A spreadsheet was developed to calculate the current carrying capacity of a cable using the above equations. This spreadsheet was used to calculate the current carrying capacity under a wind speed of 6 m/s (which is considered as the most prevailing wind condition within a wind farm in many part of Sri Lanka).

The network shown in Figure 2 was used to demonstrate the effectiveness of new cable calculation method. Each turbine was assumed to be 2.5 MW and one string has 7 wind turbines and the other has 6 wind turbines. In order to design a tapered cables, four cable sections as shown in figure was selected. The sizes of the cables were first determined only using the cable data available in the manufactures data sheet. Then the spreadsheet developed to determine the cable rating based on the heat balance with a wind speed of 6 m/s was used to determine the cable rating when wind is blowing through the site. Table 1 compares the sizes of the cables required based on two design techniques.

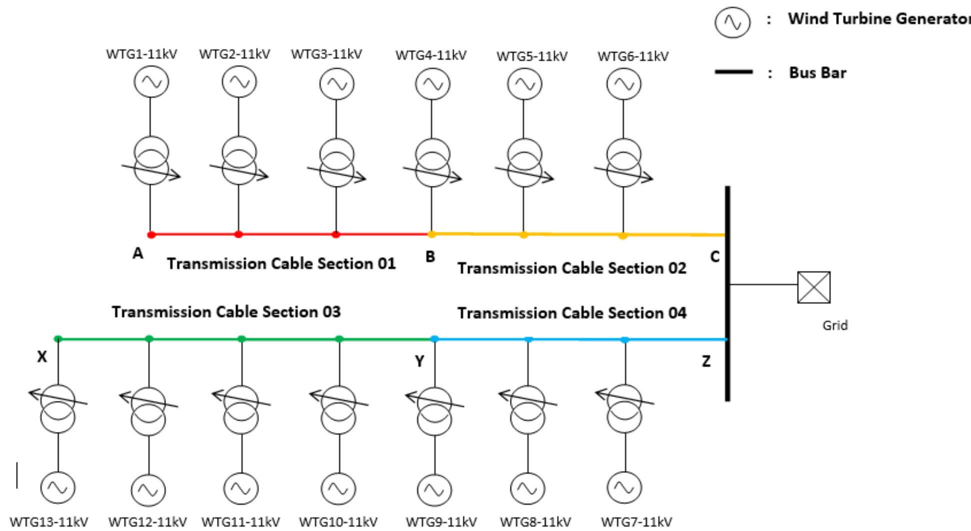


Figure 2: Case study considered

Table 01: Comparison of sizes of cables required

Tapered Cable Section	Required Current Rating(A)	Conventional Method		New Method	
		Nominal Size of Cable (mm^2)	Current Rating of selected Cable (A)	Nominal Size of Cable (mm^2)	Current Rating of selected Cable (A)
01	162	33.63	184	13.3	105
02	324	107.22	357	33.63	184
03	216	53.51	242	21.15	140
04	378	135.19	449	42.41	212

From Table 01, it is clear that the new technique developed provides optimum sizes of the cable for wind farm collector network. These cable sizes are much small than the cables designed using the conventional approach.

3. Conclusion

A novel method of reducing the size of the collector cables required for a wind farm is presented. From a case study it was shown that the size of the collector cables could be reduced by 50 - 75% of a tapered cable design.

Acknowledgement

The authors would like to acknowledge the financial support provided by the National Science Foundation, Sri Lanka under the research grant RG/2014/EA & ICT/01.

References

Cigr´e Working Group 22.12 (2002, August). *Thermal behaviour of overhead conductors*, Cigr´e Brochure 207.

IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors (1993, November 8). IEEE Std 738-1993.

Energy Efficiency Benchmarking of Pumps in Water and Waste Water Industries

M. Abeysekera*, B.G.A. Dinesh, L.K. Bogahapitiy

National Water Supply & Drainage Board, Galle Road, Ratmalana, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

1. Introduction

Conveyance of water and waste water in the National Water Supply & Drainage Board (NWSDB), Sri Lanka is mainly carried out by pumping. Pumps used are of rotodynamic type.

NWSDB consumes 237 Mill. KWh. Annually for the pumping needs of the water and waste water systems. With the new mandatory regulations regarding energy efficiency coming into effect in Sri Lanka in the recent past, as well as the awareness created regarding efficiency related issues that appear to exist in the NWSDB pumping systems, NWSDB undertook a study programme.

The programme mainly consisted of carrying out energy audits of water supply systems in the island, analyzing the data collected and finding the causes of inefficiencies. Depending on the nature and the extent of the causes of inefficiencies, appropriate remedial actions were carried out.

Main cause of the energy wastage in pumping is the lower efficiencies at which the pumps are operated. This is revealed in the energy audits carried out in the pumping stations. Pumps used in the water and waste water systems, vary in size from 850 Kw to 1.5Kw. Because of the inherent characteristics of the pumps their achievable highest efficiency is dependent on size, in addition to several other factors.

There is no reliable way to gauge the acceptable efficiency of the pumps in order to determine whether pumps are wasting energy unduly. As a redress to this problem NWSDB commenced to establish an efficiency benchmarking program. An empirical system based on data published by reputed bodies, was established and used to determine the empirically possible highest efficiency for the pumps operating in the field.

And the comparison was done between the above efficiency and the operating efficiency of the pumps in the field. This exercise facilitated in the determination of whether the pumps are working at the highest possible efficiency or wasting energy by working at sub optimal efficiencies.

In case they are working at suboptimal efficiencies, further investigations can be carried out to find out the causes. Subsequently the remedial solutions can be determined for implementation and saving energy.

2. Methodology

Efficiency of a pump is expressed in different forms, Overall Pump Efficiency, Pump Hydraulic Efficiency. Motor efficiency also comes into the picture when determining these pump efficiencies. Any pump will have a single operating point where it exhibits the maximum efficiency of the particular pump, in its range of efficiencies, see Figure 1. An operating point is any point on the Head vs. Flow rate curve on which the pump operation range lies.

The maximum efficiency point is termed Guaranteed Duty Point in the industry. At operating points away from this point on either side will reduce the efficiency thus increasing the wastage of energy. Therefore in any effort to do away with the energy wastage or to optimize the efficiency, we must cause the pump to function on the guaranteed duty point or as close to it as possible.

* *Correspondence: nwsdbmne@gmail.com*

ISSN 2478-0669 Print

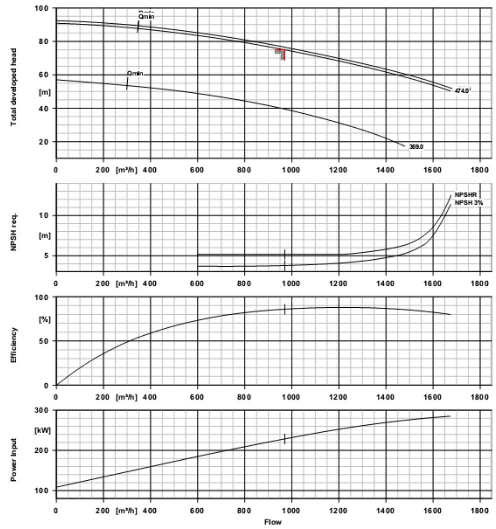


Figure 1: Typical manufacturer published characteristics of a pump

Overall pump efficiency defines how efficiently the pump unit uses the electrical power drawn from the utility grid in the pumping operation and the equation for it is,

$$Overall\ efficiency = \frac{Power\ absorbed\ by\ the\ water}{Power\ drawn\ from\ the\ grid} \qquad 1$$

Where;

$$Power\ Absorbed = \frac{q\ \rho\ g\ h}{3.6 \times 10^6} \qquad 2$$

q = *flow capacity* (m^3/h)

ρ = *density of fluid* (kg/m^3)

g = *gravity* ($9.81\ m/s^2$)

h = *differential head* (m)

$$Pump\ hydraulic\ efficiency = \frac{Power\ absorbed\ by\ the\ water}{Shaft\ power\ required\ driving\ the\ pump} \qquad 3$$

Motor efficiency deterioration over time is rather slow compared to the deterioration of the pump efficiency due to the fact that wear and tear phenomina associated with pumps are relatively absent. Also the motors are built with narrow and accurate efficiency tolerances. However in this exercise for benchmarking we determine the actual operating efficiency of the motor also. For this we use typical motor characteristics published by IEC 60034-30 (2008), see Figure 2.

Instantaneous pump efficiency is directly related to the instantaneous flow rate through it. This is evident from the manufacturer's characteristic curves issued for the performance of any particular pump, see Figure 1.

Yet at the same time rotodynamic pump exhibits an inherent design characteristic termed Specific Speed which is directly related to the achievable efficiency as well as defining the configuration of the pump structure within the rotodynamic category.

Table 1 Table with efficiency classes: IE 60034-30 (2008)

kW	HP	IE-1 - Standard efficiency						IE2 - High efficiency						IE3 - Premium efficiency					
		2 pole		4 pole		6 pole		2 pole		4 pole		6 pole		2 pole		4 pole		6 pole	
		50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz
0.75	1	72.1	77.0	72.1	78.0	70.0	73.0	77.4	75.5	79.6	82.5	75.9	80.0	80.7	77.0	82.5	85.5	78.9	82.5
1.1	1.5	75.0	78.5	75.0	79.0	72.9	75.0	79.6	82.5	81.4	84.0	78.1	85.5	82.7	84.0	84.1	86.5	81.0	87.5
1.5	2	77.2	81.0	77.2	81.5	75.2	77.0	81.3	84.0	82.8	84.0	79.8	86.5	84.2	85.5	85.3	86.5	82.5	88.5
2.2	3	79.7	81.5	79.7	83.0	77.7	78.5	83.2	85.5	84.3	87.5	81.8	87.5	85.9	86.5	86.7	89.5	84.3	89.5
3		81.5	–	81.5	–	79.7	–	84.6	–	85.5	–	83.3	–	87.1	–	87.7	–	85.6	–
3.7	5	–	84.5	–	85.0	–	83.5	–	87.5	–	87.5	–	87.5	–	88.5	–	89.5	–	89.5
4		83.1	–	83.1	–	81.4		85.8	–	86.6	–	84.6	–	88.1	–	88.6	–	86.8	–
5.5	7.5	84.7	86.0	84.7	87.0	83.1	85.0	87.0	88.5	87.7	89.5	86.0	89.5	89.2	89.5	89.6	91.7	88.0	91.0
7.5	10	86.0	87.5	86.0	87.5	84.7	86.0	88.1	89.5	88.7	89.5	87.2	89.5	90.1	90.2	90.4	91.7	89.1	91.0
11	15	87.6	87.5	87.6	88.5	86.4	89.0	89.4	90.2	89.8	91.0	88.7	90.2	91.2	91.0	91.4	92.4	90.3	91.7
15	20	88.7	88.5	88.7	89.5	87.7	89.5	90.3	90.2	90.6	91.0	89.7	90.2	91.9	91.0	92.1	93.0	91.2	91.7
18.5	25	89.3	89.5	89.3	90.5	88.6	90.2	90.9	91.0	91.2	92.4	90.4	91.7	92.4	91.7	92.6	93.6	91.7	93.0
22	30	89.9	89.5	89.9	91.0	89.2	91.0	91.3	91.0	91.6	92.4	90.9	91.7	92.7	91.7	93.0	93.6	92.2	93.0
30	40	90.7	90.2	90.7	91.7	90.2	91.7	92.0	91.7	92.3	93.0	91.7	93.0	93.3	92.4	93.6	94.1	92.9	94.1
37	50	91.2	91.5	91.2	92.4	90.8	91.7	92.5	92.4	92.7	93.0	92.2	93.0	93.7	93.0	93.9	94.5	93.3	94.1
45	60	91.7	91.7	91.7	93.0	91.4	91.7	92.9	93.0	93.1	93.6	92.7	93.6	94.0	93.6	94.2	95.0	93.7	94.5
55	75	92.1	92.4	92.1	93.0	91.9	92.1	93.2	93.0	93.5	94.1	93.1	93.6	94.3	93.6	94.6	95.4	94.1	94.5
75	100	92.7	93.0	92.7	93.2	92.6	93.0	93.8	93.6	94.0	94.5	93.7	94.1	94.7	94.1	95.0	95.4	94.6	95.0
90	125	93.0	93.0	93.0	93.2	92.9	93.0	94.1	94.5	94.2	94.5	94.0	94.1	95.0	95.0	95.2	95.4	94.9	95.0
110	150	93.3	93.0	93.3	93.5	93.3	94.1	94.3	94.5	94.5	95.0	94.3	95.0	95.2	95.0	95.4	95.8	95.1	95.8
132		93.5		93.5	–	93.5	–	94.6	–	94.7	–	94.6	–	95.4		95.6	–	95.4	–
150	200	–	94.1	–	94.5	–	94.1	–	95.0	–	95.0	–	95.0	–	95.4	–	96.2		95.8
160		93.8		93.8	–	93.8	–	94.8	–	94.9	–	94.8	–	95.6	–	95.8	–	95.6	–
185	250	–	94.1	–	94.5	–	94.1	–	95.4	–	95.4	–	95.0	–	95.8	–	96.2	–	95.8
200		94.0	–	94.0	–	94.0	–	95.0	–	95.1	–	95.0	–	95.8	–	96.0	–	95.8	–
220	300	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
250	350	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
300	400	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
330	450	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8
375	500	94.0	94.1	94.0	94.5	94.0	94.1	95.0	95.4	95.1	95.4	95.0	95.0	95.8	95.8	96.0	96.2	95.8	95.8

Figure 2: Motor characteristics

When the specific speed of a particular pump is determined, it is possible to find out the maximum achievable efficiency for that pump using the flow rate through the pump and empirical data published by a recognized body, in our case we used the data published by the Hydraulic Institute (HI), USA, see Figure 3.

Equation for the specific speed is;

$$N_s = \frac{N \times Q^{0.5}}{H^{0.75}} \qquad 4$$

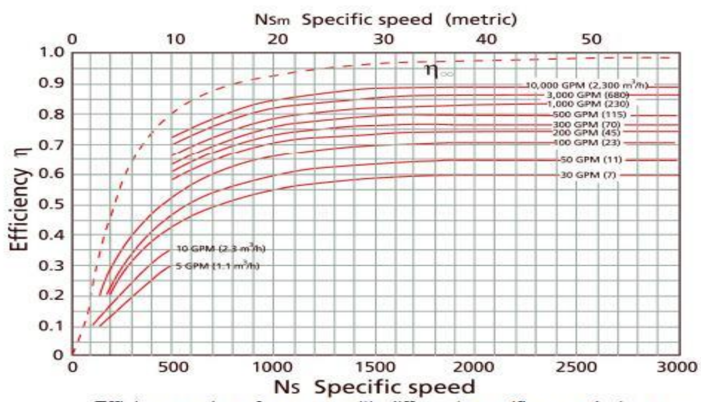
Where;

N_s = Specific speed

N = Rated rotational speed in revolutions per minute

Q = Rated flow rate in m^3/s (Q/2 for double suction pumps)

H = Rated total dynamic head of the pump in m. (per one stage for multi stage pumps)



Efficiency values for pump with different specific speeds (source: The Pump Handbook published by McGraw Hill).

Figure 3: Empirical data

Therefore the achievable optimal efficiency of a pump under particular operating conditions, is dependent on the actual flow rate through it and the specific speed of the particular pump.

In this programme we end up with an extended parameter termed Specific Energy Consumption (SEC) which is the total amount of energy consumed per one cubic meter of water pumped. It is obvious that higher the efficiency figure for a pump, the lower the SEC which what we are striving for.

The process of this programme is to benchmark efficiency of the NWSDB pumps using the empirical method described here and at the same time to find the actual operating efficiencies of the pumps. And if the actual operating efficiency is lower than the benchmark, then it is subjected to further investigation action as well as remedial measures. As the core of the process, the benchmark efficiency or the achievable optimal efficiency has to be determined.

First step of the process would be the determination of the Specific Speed of the pump. The equation given above is used, and design or rated values of the Q and H are used in the calculation. These Q and H values are the values corresponding to the guaranteed duty point.

Once the specific speed is calculated, achievable optimal hydraulic efficiency of the particular pump is determined from the HI diagram. Next the actual power drawn by the pump is determined by the following formula,

$$Shaft\ power = \frac{Hydraulic\ power}{Pump\ efficiency} \qquad 5$$

To make corrections for the actual operating efficiency of the motor due to the extent of instantaneous under loading, Load Factor of the motor has to be determined.
Equation for the load factor is,

$$Load\ factor = \frac{Shaft\ power}{Motor\ rated\ power} \qquad 6$$

Where;
Motor rated power is the rating mentioned on the manufacturer's data plate on the motor. Find the achievable optimal power consumption of the motor form the following formulae.

$$Optimal\ power\ consumption\,(kw) = \frac{Shaft\ power}{Motor\ efficiency\ at\ the\ load\ factor} \qquad 7$$

Benchmark specific energy consumption (BSEC) is determined form the equation,

$$BSEC = \frac{Optimal\ power\ consumption\,(kW)}{Flow\ rate\,(m^3/h)} \qquad 8$$

This is the maximum allowable energy consumption by the particular pump to deliver 1 m^3 of water under the operating conditions encountered during the study. During the programme NWSDB has benchmarked 500pumps so far and compare the actual operating efficiencies of 200 pumps.

3. Results and Discussion

From the data it is evident that 127 Nos. pumps show excessive SEC figures over the benchmark SEC's. These pumps are clearly using excessive power than necessary or plainly, are wasting energy.

The energy wasting pumps should be investigated further with guaranteed efficiencies of a few compatible pumps in the market also as an additional check on the achievable efficiency. This step of the analysis though an essential one is yet to be commenced. After commencement changing or improving efficiency data will be used to modify the HI diagram for achievable efficiencies. Only then NWSDB will be able to provide the analysis on this aspect. As this is mainly an empirical exercise the results and deductions from the data must be compared with the achievable efficiency of compatible pumps in the same specific speed range. This might reveal necessary adjustments to HI data being used in this programme or adjustments elsewhere.

Pumps in the same specific speed range and operating in the same Head/Flow Rate ranges may show varying efficiencies because the detailed design of the pumps varies from manufacturer to manufacturer. Some manufacturers are able to achieve comparably higher efficiencies due to innovativeness and R&D strength. Therefore the adjustment process must be a continuous process whenever necessary.

A considerable problem in the analysis results is that sometimes seemingly inconsistent results are generated as regards the SEC value. There are cases when SEC should show higher values theoretically, favorable results or lower SEC's result. For example when operating well away from the guaranteed optimal efficiency point, mostly on the higher flow rate side. This is due to the non linear, different behavior of the characteristics of the power, H – Q etc. of the pumps, which is again the result of marginal design improvements of similar pumps among different manufacturers. This peculiarity is interpreted case by case with the actual characteristics of the particular pumps.

4. Conclusion

The programme is greatly useful as an indicator to identify the possible energy wasting pumps. Thus this tool is very useful in screening problematic pumps. However, once identified they must be subjected to further investigations including an Investment Grade Energy Audit to find out the status of the performance of the pump. Depending on the results of such studies remedial action could be taken, if necessary.

Also it must ensure to compare the achievable efficiency level of compatible pumps from a few manufacturers in the market, in order to validate or calibrate the HI Efficiency diagram or other aspects of this tool to make it more accurate. Also the tool must be subjected to any necessary changes depending on the verification process. This must be an ongoing process to reflect the technological and other changes in the market etc.

References

Ebara Pump system Engineering Handbook: Ebara Corporation, 2001.
Garr M. Jones , PE : Pumping Station Design – Third Edition , 2006.
Hydraulic institute Standards for Centrifugal, rotary and reciprocating pumps. 1983.
Karassik , I.J., Messina, J.P., Cooper, P. and Heald, C.C. 2004. Pump Hand Book –Fourth Edition
Pumping Station Engineering Handbook: Japan Association of Agricultural Engineering Enterprises, Tokyo, 1991.

Development of “Biomass Fuelled Rotary Type Bakery Oven”

D.M. Punchibanda*

National Engineering Research & Development Centre

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Temperature controllable rotary type bakery ovens are normally run on diesel, kerosene or furnace oil. Bakery ovens run on fuel wood, with accurate temperature controlling are not seen in the society. For quality rice flour bread baking, temperature controllability is very important. This requirement has been achieved by developing a biomass fuelled temperature controllable rotary type bakery oven. The newly developed bakery oven unit consists of six major components as biomass combustion chamber, vertical tube heat exchanger, oven chamber, rotating trolley unit, hot air circulating unit and temperature controller unit. Fuel used for the oven is fire wood pieces or fire wood sticks with diameter of less than 2 inches for efficient combustion. During the operation, fuel wood is fed manually in suitable intervals. The hot air generated in heat exchanger unit is directly sent to the oven chamber from the bottom and sent out from the top after passing through the rotating bread trays. Efficient utilization of heat is achieved by circulation of air in a closed cycle through the heat exchanger and the oven chamber. In this oven, total circulation of hot air reduces the fuel consumption and baking occurs efficiently without drying. Air circulation within the oven chamber has been arranged so that there is a reasonably uniform temperature distribution within the oven. Temperature within the oven chamber is controlled accurately (set value ±2 ^{0}C) by a specially designed valve unit which releases part of hot air, to surrounding as set temperature is achieved. The valve has been fixed in the inlet hot air duct just outside the oven. Capacity of the oven is 80 loaves per batch and average baking time is 55 minutes. It takes nearly 45 minutes for initial heating up to set temperature of 240 ^{0}C and consumes nearly 20 kg of fuel wood; while consuming 8 – 10 kg for baking of each consecutive batch. In addition to the baking of bread, other bakery products such as buns, bread rolls etc. can be baked in this oven with residue heat or addition of small quantity of fuel, as they require lower temperatures for baking. Main advantages of this novel technology are, accurate temperature controllability, ability to operate with sustainably grown wood pieces such as glidiceria instead of large fire wood logs which are used in traditional bakeries, low specific fuel consumption of 200g of fire wood/bread which saves 60% of firewood in comparison with traditional biomass bakery, portability, avoiding the use of skilled labor for operation etc. the other major advantage for this bakery oven is decrease of labor requirement by about 50% when compared to traditional bakery. The other special features of this oven is introduction of a specially designed hot bread unloading trolley which avoid taking out heated bread trolley which normally happens in any rotary type ovens.with this new device, all bread trays can be loaded or unloaded at once and quickly minimizing the heat loss from the oven during the opened period while loading/ unloading.

Keywords: bakery oven, biomass

1. Introduction

There are about 9000 bakeries operated in the country; out of which about 7000 are traditional biomass fueled bakeries while the rest is operated on diesel; LPG, electricity and kerosene as the source of energy. In recent years; interest has increased for production of bread and other bakery products using rice flour instead of wheat flour by food technologist and other parties engaged in bakery industry. According to the available information, efforts have been successful to such an extent that 50% of wheat flour can be replaced by rice flour without degrading the quality of bread and other products. But the problem for implementation of this new finding is the requirement of temperature controllability of the bakery oven for production of breads with rice flour. Therefore traditional fire wood bakery ovens are unable to produce rice flour breads to expected quality. On the other hand; continuous prize increase of imported fossil fuels such as diesel; LPG and electricity severely effects on production cost. Further; improved diesel fueled bakery ovens are expensive.

* *Correspondence: bandara@nerdc.lk*
ISSN 2478-0669 Print

Traditional bakery ovens, which are scattered throughout the country, consume huge amount of jungle fire wood in the form of logs; which can cause for deforestation. Further, majority of these bakery ovens are inefficient due to low maintenance and substandard construction.

By addressing majority of above mentioned draw backs of traditional bakery ovens; and imported fossil fuel consuming imported diesel ovens; a new rotary type bakery oven unit with very similar features to those of diesel oven, but fuelled with fully biomass has been developed. Mainly the details of this newly developed technology and results of trials carried out are discussed in this paper.

2. Materials and Methods

It is not a development of a single technology; but covers several areas of technology mainly, technology for efficient combustion of biomass fuels in various types and sizes, hot air generation in portable, compact and efficient heat exchanger unit, controlling of hot air temperature of a biomass fuelled system, design and development of a compact bakery oven chamber with uniform temperature distribution and development of a new device for loading and unloading hot bread.
This newly developed bakery oven unit consists of biomass combustion unit, heat exchanger unit, bakery oven chamber with rotating trolley, temperature controlling unit and hot bread loading / unloading device.
Which is shown in the figure 01 below.

Figure 1: New bakery oven in operation

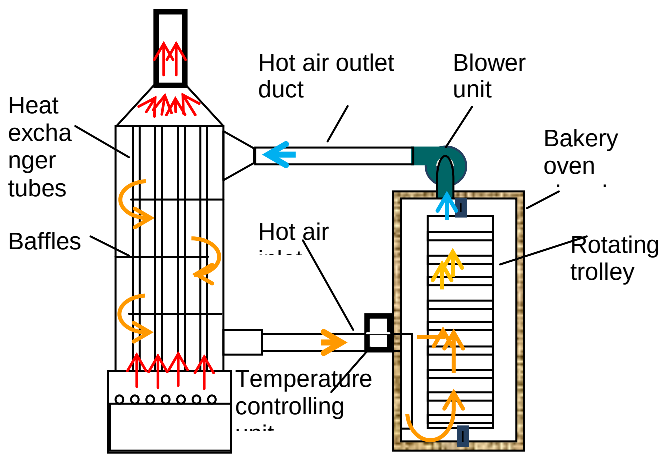


Figure 2: Cross section of the newly developed bakery oven unit indicating hot air flow paths.

2.1 Baking process in brief

The baking process of this bakery oven unit is very similar to that of rotary type diesel fuelled bakery oven. But, air is heated using fire wood as the fuel. In this new technology, Hot air generated in a vertical tube cross flow heat exchanger is circulated through the oven chamber and the exit air blows through the heat exchanger. Further, the hot air temperature is controlled by releasing heat to the surroundings when reached to the set value. When temperature falls below set value, the valve closes down automatically allowing hot air to enter oven chamber.

Initially, the required temperature is set on the display and burning of fire wood in the combustion chamber starts with the oven doors closed with air circulating blower in off position. After about 10 min of firing, blower is switched on. Then keep on feeding fire wood in suitable regular intervals depending on quality of fire wood. (present practice is firing starts with 04 KG of gliricedia sticks and then feed 02KG in 5min intervals. After reach of set temperature, blowers and rotating motor are switched off and doors are opened. Then using the unloading device, baked breads are removed. This procedure continues for any no. of consecutive batches.

2.2 Description of components

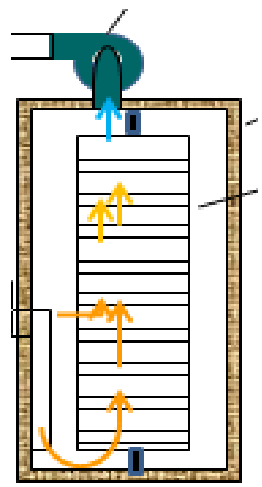
2.2.1 Biomass Combustion Unit

Biomass combustion unit is shown in the figure 03 and it is a simple and portable unit with a perforated pipe which has been fixed underneath fire grate to supply primary forced air. The combustion unit consists of fire grate, ash tray, front doors covered with refractories, outer walls covered with insulation bricks and a blower to supply combustion air. Maximum capacity of this combustion unit is nearly 04 KG of normal fire wood sticks or wood chips.

Figure 3: Biomass combustion unit located underneath the heat exchanger unit

2.2.2 Bakery oven chamber

Figure 4 shows the inside view of bakery oven chamber.



Basically bakery oven chamber has been designed very similar to that of diesel oven chamber but with some improvements.

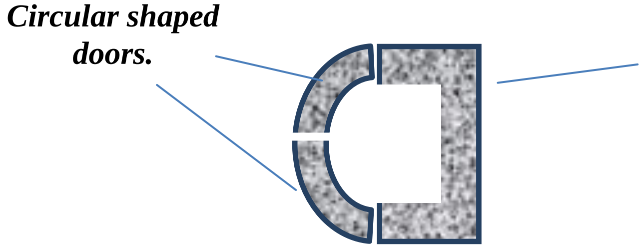


Figure 5: Cross section of oven chamber

As shown in the figure 5, stationary part of the main body has been constructed with rectangular shape while the doorse are semicircular in shape when closed. This shape has been provided in order to minimize the inside space and hence to maximise the hot air contact with baking bread.

Figure 6: Front view of oven chamber

2.2.3 Heat exchanger unit

As shown in the figure 7, it is simply a vertical tube heat exchanger where flue gas directly flows through the tubes to the chimney and exhaust air from the bakery oven is blown from top side of tubes in perpendicular direction to the tubes as indicated by arrows. Top part of the heat exchanger (chimney part) has been designed in such a way that, with the ability for cleaning of tubes. The mechanism incorporated is sliding of top part horizontally whenever necessary. The heat exchanger unit has been mounted on the biomass combustion unit so as to pass flame and flue gas through the heat exchanger tubes to the chimney by natural draft.

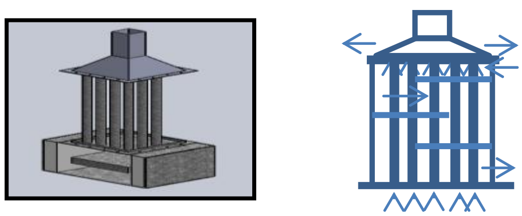


Figure 7: Cross section of the Heat exchanger unit

2.2.4 Rotating trolley

In any rotary type bakery ovens, rotating trolley is available for stacking bread trays for baking process. In traditional diesel ovens this trolley is taken out and load trays with unbaked or raw bread and then insert into the oven chamber. After baking process is completed, hot trolley with baked bread is taken out and new trolley is inserted for the new cycle. In this procedure, heat absorbed by trolley is wasted to the surrounding and additional energy is required to heat the new trolley. But in new design, rotating trolley has been permanently fixed inside the oven chamber and only bread trays are taken out by using a new device called hot bread loading / unloading device.

Figure 8: Rotating trolley is mounted permanently inside the oven chamber

2.2.5 Hot bread loading Unloading Device

This is a novel concept for the bakery industry and function of it is to take out all the trays once from rotating trolley or load all raw bread trays to trolley for baking. The new device has been constructed with similar no. of arms to the no. of tray holders in the rotating trolley. As shown in the figure, the device can be inserted into and outwards the rotating trolley and about 03 inches can be moved up and down by means of a hydraulic jack mounted at the bottom.

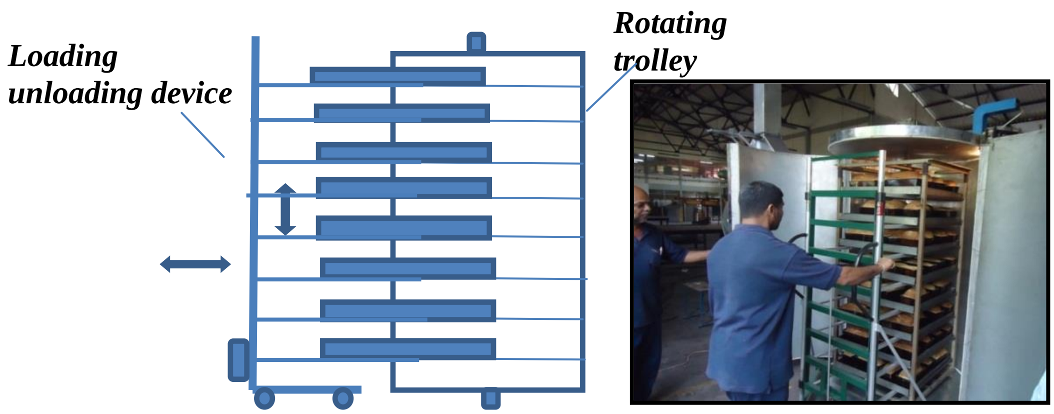


Figure 9: Bread loading/ unloading device and rotating trolley

2.2.6 Hot air circulating unit

Hot air circulating blower unit has been mounted on top of the bakery oven and it is shown in the photograph below. Hot air circulating path has been clearly indicated in the sketch below. The blower has been fabricated to withstand an elevated temperature of 300 ^{0}C. The blower impeller has been connected to the motor by an extended shaft to protect it from heat. In this system 01 hp, 2850 rpm induction motor has been used to drive blower impeller.

Figure 10: The blower unit has been mounted on top of the bakery oven chamber

2.2.6.1 Hot air circulation and Controlling of temperature.

In this system, hot air is circulated in a closed cycle. Air heated through the heat exchanger is sent to the bakery oven chamber from the bottom and moves up through the rotating bread trolley and then sucked by the inlet of air circulating blower mounted on top of the oven chamber. The same air is sent to the heat exchanger and cycle continues.

2.2.6.2 Temperature controller unit

According information available, maintaining the baking temperature is very important; especially for baking rice flour bread. But it is a very difficult task in a biomass fuelled oven due to many reasons.

- Response time from combustion chamber to oven chamber is very high when compare to 40 – 50 min. which is baking time per batch of bread.
- Parameters such as density, type, moisture content, size and shape of biomass are not consistent throughout the operation.
- Fuel feeding is done manually.

Due to above reasons it is very difficult to achieve a constant temperature throughout by controlling fuel feeding. Therefore most suitable method is that, controlling temperature by controlling hot air entrance to the oven chamber. This method is introduced to the bakery oven successfully by releasing part of hot air to the surrounding (can be used for pre-heating primary combustion air) by a flap valve which is operated by a digital thermometer/ thermo couple unit.

2.2.6.3 Specifications

Table 01: Specifications of new bakery unit

	Particulars	Values
01	Dimensions	10' x 5' x 8'
02	Capacity of oven chamber	80 loaves /batch
03	Type of fuel	Biomass pieces or sticks.
04	Type of burner	Direct burning on a grate with forced air supply.
05	Type of heat exchanger	Vertical fire tube cross flow type heat exchanger.
06	Portable	
07	Oven temperature	150^0C -250 ^{0}C - Controllable

Table 02: Results of performance evaluation trial

	Particulars	Values
01	Fire wood consumption	810 g/Kg of flour
02	fire wood consumption	270 g /bread
03	Energy cost	Rs.1.35/ bread
04	Average fuel consumption for initial heating	20 kg of wood chips
05	Set temperature	240 ^{0}C
06	Average initial heating time.	45 -55 min
07	Average baking time	50 -60 min
08	Average electrical energy consumption / batch	0.5 units

Figure 11 shows Temperature variation in bakery oven chamber for six consecutive baking trials

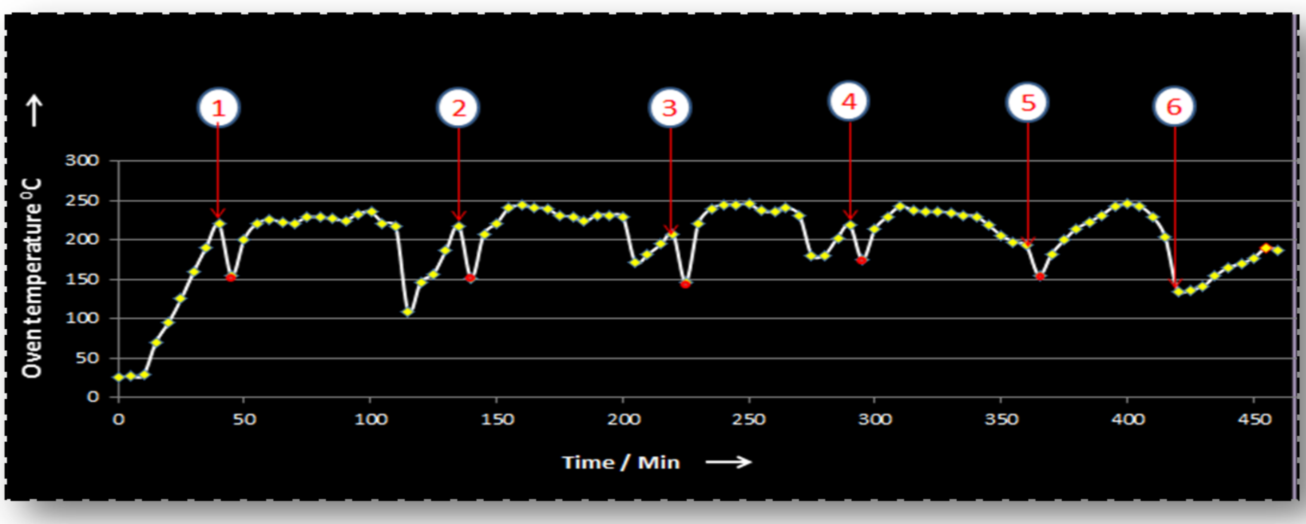


Figure 11: Temperature variation in bakery oven chamber for six consecutive trials

3. Discussion

3.1 Baking temperature

Most important parameter of bread baking is the oven temperature. It was observed that different temperatures are used in different bakeries where hot air is used for baking process. According to records of operators the range varies between 175^{0}C-240^{0}C. But ideally the temperature should be around at set temperature throughout the oven. Normally in traditional firewood bakeries, there are no temperature controllers or thermo meters installed. For rotary type diesel, kerosene or gas fuelled bakeries, temperature sensor or thermocouple has been fixed in one point. But no idea about temperature profile of oven chamber. However, it can be observed that full batch of bread is uniformly baked throughout. This may be due to the rotary action and hot air movement inside the oven chamber.

According to the figure 11, the variation of bakery oven inside temperature, maintains within the suitable range with slight deviation from set temperature (240^{0}C in this case). After starting the fire, it reaches the set temperature within short period of 45-55 min. as soon as the set temperature is achieved, doors are opened for loading. The loading period should be maintained as short as possible to minimize the temperature drop. This temperature drop can be observed in the figure 11. After loading, doors are closed causing the temperature to increase. The initial heating up occurs fairly at a lower rate due to loading of wet bread. In this oven, dropping of temperature below the required level is avoided by feeding of fuel at suitable intervals. The last trial of the series shows the baking of other bakery items such as buns, bread rolls etc. using residual heat as they require lower baking temperature than bread.

4. Conclusion

Sustainably grown fuel wood chips (Gliricidia) can be ideally used in new biomass bakery oven unit as the fuel, instead of large wood logs in traditional ovens.

Temperature controllability with a biomass fuelled bakery oven is a major achievement for bakery industry.

- 100% hot air circulation reduces the fuel consumption and ensures baking with controlled dehydration.
- Rotary action of the trolley can be eliminated by introducing new features such as, perforation in trays, new method of hot air distribution, and minimizing oven volume
- Introduction of the bread loading / unloading device is a novel concept for the bakery industry and it provides many advantages for the bakery oven.
- The specific fuel wood consumption using sustainably grown fuel wood (*Gliricidia*) is approximately 260 g/bread.
- The results of trials show that temperature controllability for baking rice flour mixed bread is not a strict requirement.

References

Manhika, F. A. and Lucas C. Wood consumption and analysis of the bread baking process in wood - fired bakery ovens, University of Boras, Sweden.

Effective Use of DC Energy Storage Schemes for Mitigating Long Duration Voltage Sag/Swell in the Power System

U.N. Sanjaya[1*], J.P. Karunadasa[2], H.M. Wijekoon[1]

[1]*Ceylon Electricity Board*
[2]*Department of Electrical Engineering, University of Moratuwa*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Present Power quality problems in the distribution systems have been increased due to the increased utilization of sensitive and critical equipment in the system. Power quality issues may contain transients, voltage sags, voltage swells, under voltage, overvoltage, harmonics distortion, flicker and voltage imbalance, etc. DC Energy storage technologies can be effectively used to overcome voltage sag/swell conditions in the power system. Dynamic Voltage Restorer (DVR) is one of the economical equipments which can utilize the DC energy storage schemes to rectify the said problems. The DVR injects an appropriate voltage in series with the grid voltage, in order to avoid loss of power as it can maintain the load voltage at its nominal magnitude and phase by compensating the particular voltage sag/swell. Therefore, energy storage is the key factor in deciding the capability of DVR. Battery storage is the most traditional storage used in DVR and a number of studies had been carried out to use new energy storage technologies in DVR. In this paper, responses of the DVR in compensating long duration voltage sag/swell conditions are discussed with Super Capacitor based storage, an emerging technology and the same is compared with battery storage as well. MATLAB simulations have been used to model the storage schemes as well as to analyze the responses of DVR. In addition, an economic analysis has been done to compare the two energy storage schemes in compensating the sag/swell conditions.

Keywords: volatage sag, DC energy

1. Introduction

Power distribution network experiences a wide range of different disturbances such as voltage sags, swells harmonic distortion, flickers, interruptions, etc. Among these issues, voltage sags can occur at any instant of time with amplitude ranging from 10% to 90%. Duration of such voltage sags may last for 0.5 cycles to 1 minute. On the other hand sudden increases in the rms voltage or current which are called voltage swells may last for some duration. Among the various solutions, Dynamic Voltage Restorer (DVR) connected with a precise energy storage scheme can be effectively and economically used to overcome these disturbances. A DVR employs a series of voltage boost technology using solid state switches for compensation of voltage sags/swells. The shunt converter of the DVR, converts this energy to feed the line in a disturbance. Several DC energy storage systems are used with DVR such as Fly wheels, lead acid batteries, Fuel Cells, Conventional Capacitor banks, Super capacitors, etc… The performance, economics and sizing of DVR will depend upon this DC energy storage. In this study, only the battery storage and Super capacitor storage were considered.

1.1 Conventional system of DVR

The basic operating principle of the Dynamic Voltage Restorer is to inject an appropriate voltage in series with the supply through an injection transformer whenever voltage sag or voltage swell is detected. DVR is located on approach of sensitive loads. If a fault occurs on other lines, DVR insert series voltage and compensates load voltage to pre-fault value. Any differential voltage caused by the disturbances in the distribution feeders will be compensated by an equivalent value generated by the voltage source converters there and injected through the booster transformer. Simplified block diagram to demonstrate this operation is given in figure 1.

[*] *Correspondence: sanjayaun1983@gmail.com*
ISSN 2478-0669 Print

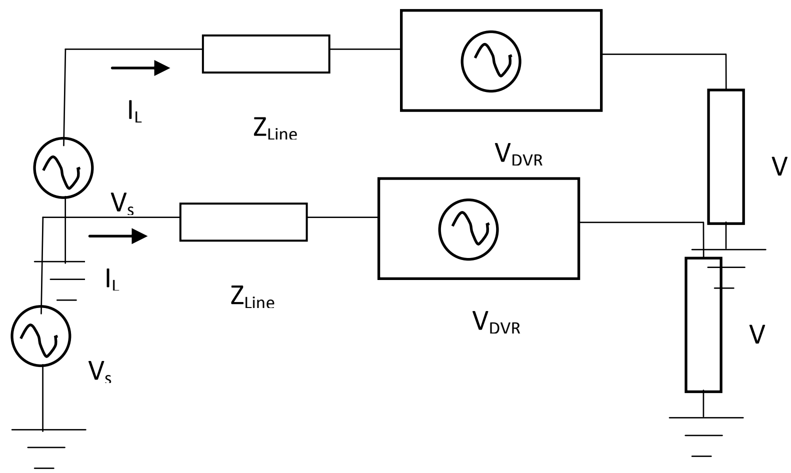


Figure 1: Conventional ssystem of DVR

When the system voltage (V_S) drops, the DVR injects a series voltage (V_{DVR}) through the injection transformer, so that the desired load voltage magnitude (V_L) can be maintained. The series injected voltage of the DVR can be written as

$$V_{DVR} = V_L + Z_{Line}\, I_L - V_s \qquad 1$$

Where;

V_L = The desired load voltage magnitude

Z_{Line} = The line impedance

I_L = The system voltage during fault condition

V_s = The load current

Batteries are electrochemical devices which convert chemical energy into electrical energy during discharge time. The total energy stored and the weight of the battery unit is considered to be important technological aspects. Another important factor is the cost of the batteries. The total energy that can be stored in a battery usually follows the weight and volume more or less linearly. Among the different battery types in the market today for high power applications, there are two major technologies of interest, namely the Ni-MH and the Li-Ion.

A super capacitor is a component which has relatively high specific power ability in comparison to batteries much like a capacitor, while it has a much higher specific energy than a conventional capacitor, more like a battery. The main difference between the super capacitor and the ordinary electrostatic capacitor is that the electrolyte in the super capacitor contains free charges in the form of ions. The ordinary capacitor does not have this type of free charges. In a super capacitor the electrodes consist of a porous micro structure. When the super capacitor is charged, the electrons at the cathode attract positive ions and on the anode the vacancies for electrons attract negative ions in order to locally obtain a charged balance. This attraction of ions leads to a capacitance being formed between the ions and the surface of the electrode. The layer closest to the electrode acts as a dielectric and the layer outside the first layer holds the charges. This occurs at both electrodes in the super capacitor and the total capacitance consists of these two capacitances connected in series.

1.2 Battery and super capacitor energy storage

Batteries are electrochemical devices which convert chemical energy into electrical energy during discharge time. The total energy stored and the weight of the battery unit is considered to be important technological aspects. Another important factor is the cost of the batteries. The total energy that can be stored in a battery usually follows the weight and volume more or less linearly. Among the different battery types in the market today for high power applications, there are two major technologies of interest, namely the Ni-MH and the Li-Ion.

A super capacitor is a component which has relatively high specific power ability in comparison to batteries much like a capacitor, while it has a much higher specific energy than a conventional capacitor, more like a battery. The

main difference between the super capacitor and the ordinary electrostatic capacitor is that the electrolyte in the super capacitor contains free charges in the form of ions. The ordinary capacitor does not have this type of free charges. In a super capacitor the electrodes consist of a porous micro structure. When the super capacitor is charged, the electrons at the cathode attract positive ions and on the anode the vacancies for electrons attract negative ions in order to locally obtain a charged balance. This attraction of ions leads to a capacitance being formed between the ions and the surface of the electrode. The layer closest to the electrode acts as a dielectric and the layer outside the first layer holds the charges. This occurs at both electrodes in the super capacitor and the total capacitance consists of these two capacitances connected in series.

2. Methodology

A DVR circuit with general DC storage installed at the Low Voltage (LV) side of a 33kV/400V distribution transformer was modeled in MATLAB as indicated in the figure 2. Following parameters were used for the model.

Table 1: Parameters used for the DVR, 33kV Feeder and 33kV/400V Transformer model

33kV Feeder bay	Phase to phase voltage and frequency=33kV,50Hz
	Three phase short circuit level =463MVA
	Internal connection=Yg
	X/R ratio=10
33kV Feeder parameters	R=1.78Ω, L=0.01035 H (for 10km length)
Distribution Transformer	Vector Group=Dyn11
	Nominal power and frequency=160MVA, 50Hz
	Primary Winding Voltage=33kV
	Primary Winding R (pu)=0.0001
	Primary Winding x (pu)=0.045
	Secondary Winding Voltage=400V
	Secondary Winding R (pu)=0.0001
	Secondary Winding X (pu)=0.045
Sensitive load	Configuration= Y
	Active Power=2kW
	Line Voltage and frequency=400V,50Hz
Voltage Sag condition	Fault resistance=4.6Ω
	Ground resistance=0.1Ω

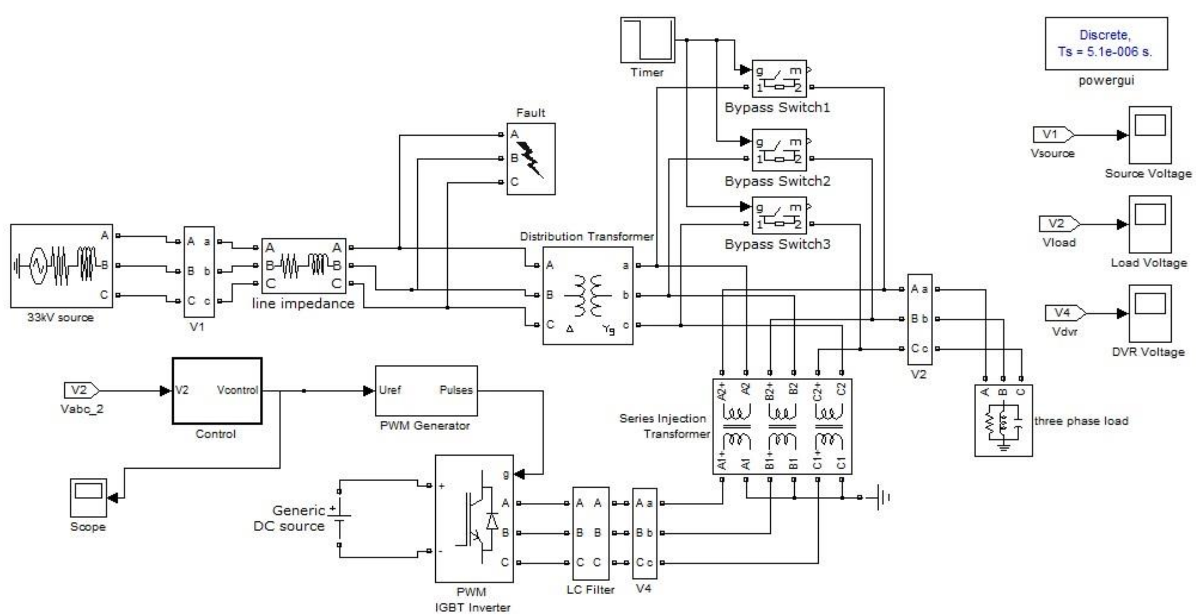


Figure 2: DVR and 33kV feeder modeled in MATLAB

DVR was tested for sag conditions with general energy storage. Battery Energy Storage model in MATLAB was validated by simulating its constant current charging characteristics and comparing with battery manufacturer data. Further, based on the characteristics of super capacitor, the model illustrated in figure 3 was developed in MATLAB and simulated its constant 1A current charging characteristics. Parameters were selected as capacitance=9F/3V, ESR=0.2kΩ anf EPR=2.7kΩ

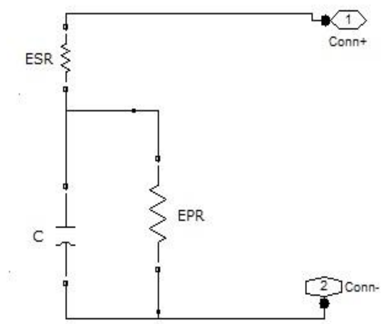


Figure 3: MATLAB model of super capacitor

Results were compared with its Practical constant current charging/discharging characteristics. After the above model verifications, each of the energy storage option was independently connected to the DVR model and responses for sag conditions were plotted for each storage option.

3. Results

Voltage sag created at the source side of the DVR is illustrated in figure 4.

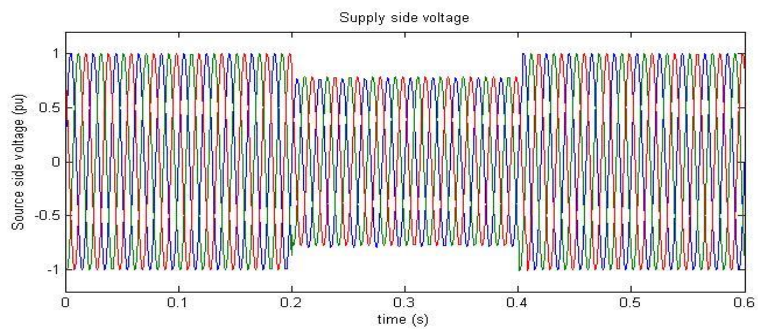


Figure 4: Voltage sag created at the source side

Voltage Injected by DVR at the LV side of the injection transformer to compensate the above sag condition is plotted in the figure 5

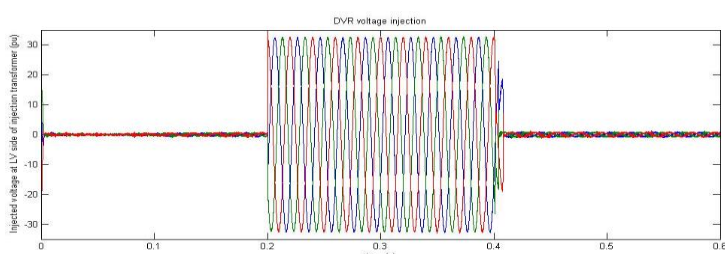


Figure 5: Voltage injected by DVR at the LV side of the injection transformer

It was noted that the Voltage at the sensitive load side was not affected by this sag as it has been fully compensated by the DVR as indicated in the figure 6.

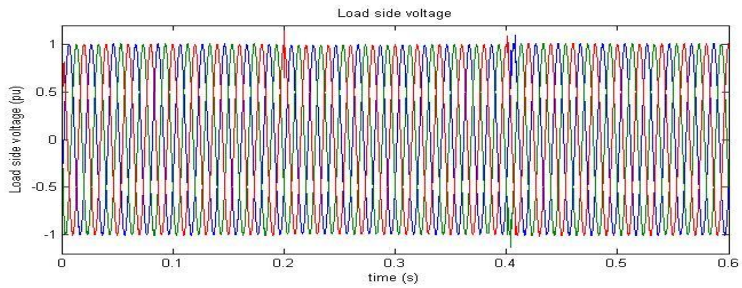


Figure 6: Voltage at the sensitive load side

In order to validate the Ni-MH battery energy storage, its constant 1A current charging characteristics were simulated using MATLAB and results are indicated in Figure.

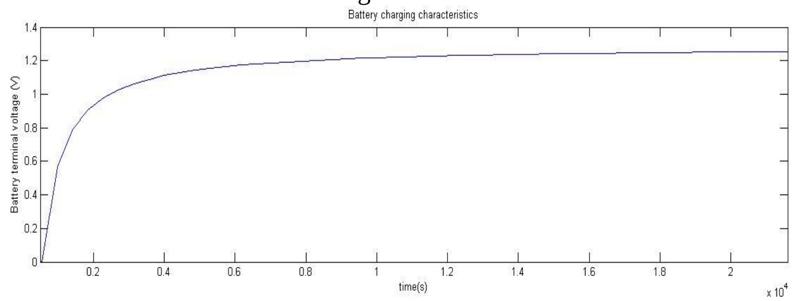


Figure 7: Constant current charging characteristics of Ni-MH battery simulated in MATLAB

Constant current (1A) charging characteristics of a 9F/3V Super capacitor storage model was obtained from MATLAB simulation.

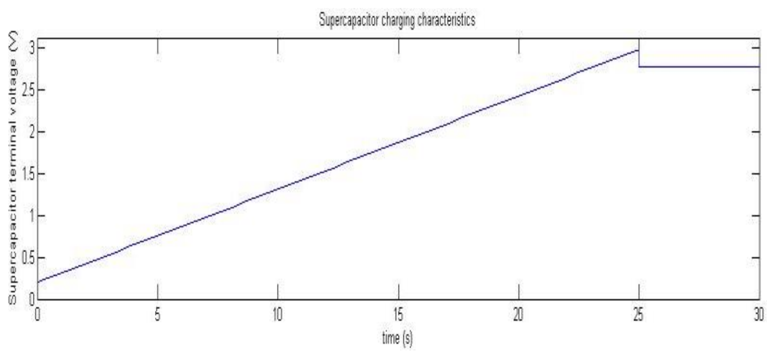


Figure 8: Constant current charging characteristics of supercapacitor simulated in MATLAB

Same characteristics were observed in practical constant current charging test which was carried out for 9F/3V super capacitor for 1A constant current.

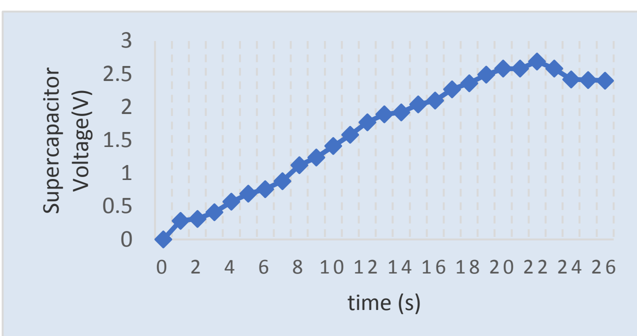


Figure 9: Test carried out for constant current charging characteristics of battery

Variation of the status of charge (SOC%) of the Ni-MH battery model for a 50% sag condition exists for 1 second duration was monitored as in the figure 10.

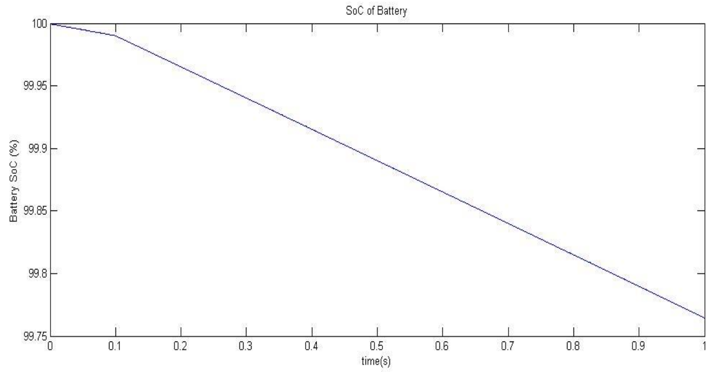


Figure 10: Variation of SOC of battery with time during 50% sag

Further, mean power variation of the battery monitored during the above sag period is in figure 11.

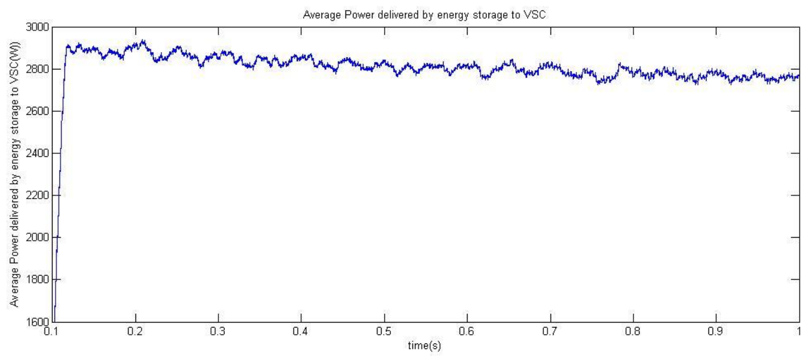


Figure 11: Mean power variation of the battery during sag

Variation of the status of charge (SOC%) of the 1F supercapacitor model for the above 50% sag condition exist for 1 second duration was monitored as in the figure 12.

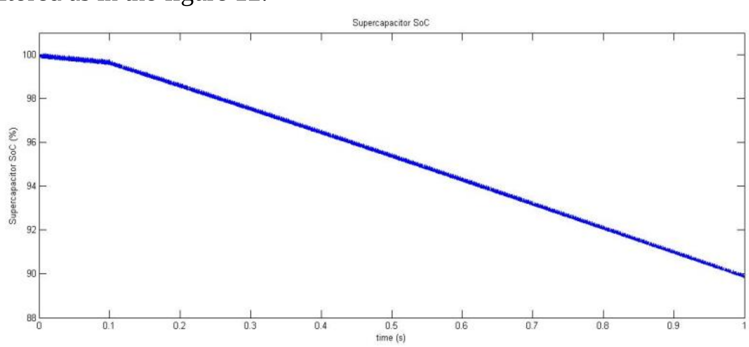


Figure 12: Variation of SOC of battery with time during 50% sag

Further, mean power variation of the super capacitor monitored during the above sag period is in figure 13.

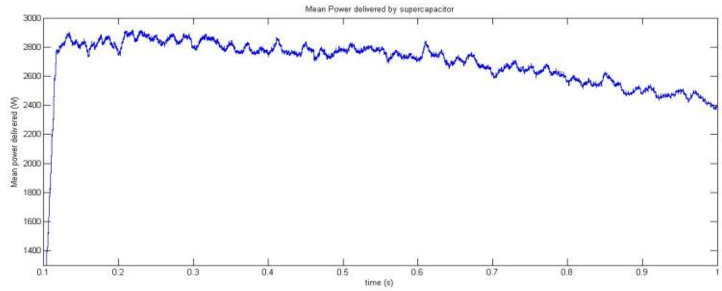


Figure 13: Mean power variation of the super capacitor during sag

Total harmonic distortion measured at the injected voltage of DVR for battery storage and super capacitor storage are illustrated in the figure 14.1 and 14.2.

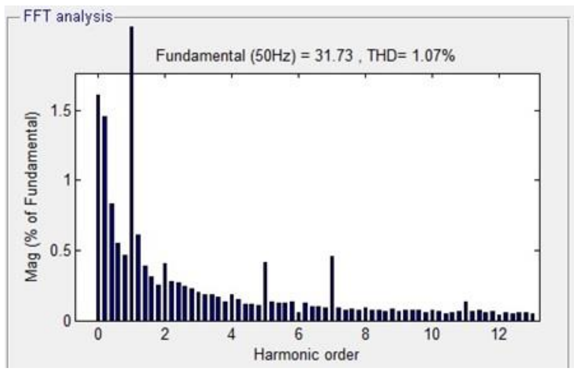


Figure 14.1: Total harmonic distortion measured at the injected voltage for battery

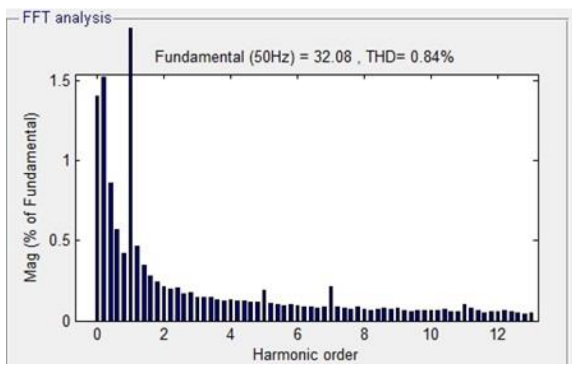


Figure 14.2: Total harmonic distortion measured at the injected voltage for super capacitor

4. Discussion

It was observed that even for a 50% sag, at the end of sag condition at 1s, the battery SOC was reduced only by 0.24%. It means that charges were released to the VSC from the battery in a very slower manner. This is because of low power discharge efficiency of the battery storage. Mean power delivered through the battery during the sag condition was monitored and it was noticed that the battery can maintain the power delivery to the converter in a nearly constant manner during sag condition. This is because of the low discharge efficiency of the battery storage. In the figure 10 it was observed that sag of 50% the SOC of the battery was reduced only by 0.24% at the end of sag at 1s. But under the same initial voltage, a 1F Super capacitor SOC% has been reduced approximately by 10% at the end of the sag duration which is illustrated in figure 12. This shows the rapid discharge characteristics of the Supercapacitor. It is capable of releasing a high amount of power to compensate even deeper sag effectively because of its high power density. However, even though it can release power efficiently, it cannot maintain the power levels for longer periods as the battery storage. Figure 13 shows that the released mean power level of the supercapacitor is rapidly reducing with time, while the battery is trying to maintain it at approximately constant level. For a three phase sag of 50% for 0.2s duration, Total Harmonic Distortion(THD) levels of the injected voltage at the primary side of the injection transformer for 5 no of cycles was monitored for the battery energy option and the 1F super capacitor storage, both at an initial voltage of 160V. Results are shown in the figures 14.1 and 14.2 respectively. It was noticed that there is a significant reduction in the THD levels for super capacitor energy storage.

Consider the DC power injection of 3000W for a period of 60seconds for a sag condition. Suppose the voltage of the storage is maintained at 160V. The cost of energy storage required for compensating that sag level can be analyzed as in table 2.

Table 2: Economic comparison of energy storage options

DC storage Option	Basic unit of the storage	No of units quired	Cost of a unit	Total Cost(USD)
1. Battery storage	1.2V Cell	134	3 USD	402
2. Super capacitor	9F/2.7V Supercapacitor	60	3 USD	180

Further, economics of the energy storages based on their cycle durability could be compared as indicated in table 3.

If the frequency of critical sags in a feeder is 20 per day,

No of critical sags in a year = 7300

No of critical sags in 10 years = 73000

Table 3: Cycle durability of energy storage options

Storage Option	Cycle durability	No of units to be replaced for 10 years
Ni-MH Battery	500 Cycles	15
Super capacitor	10^5 cycles	None

5. Conclusion

According to the results obtained for the two energy storage options discussed above, in connecting with DVR, Supercapacitor energy storage is suitable for compensating deeper sags which prevail for shorter durations. Rather than the battery storage, it can release higher amount of power in a shorter duration because of its high power density. This feature of supercapacitor increases the efficiency of the voltage source converter of the DVR. But it cannot store a large amount of energy in comparison with Battery storage. Therefore super capacitor storage cannot deliver power for a long duration. Therefore, for smaller sags prevailing for long durations, battery storage will be useful because of its high energy density. Other than the capability of releasing high power in milliseconds, super capacitor storage has the advantage of long durability. Since a super capacitor can survive even more than 200,000 charging discharging cycles, DVR can be operated without replacement of energy storage even for 5 years. But a battery life ends within 500 cycles. Also its life cycle becomes shorter with the depth of discharge. Therefore it cannot be used for high sag/swell locations. As it has the capability of recharging in few seconds, DVRs with super capacitor storage is suitable for the locations having frequent sags or swells in short durations. Another additional advantage of Super capacitor storage is it can improve the quality of the compensated voltage by reducing harmonic content.

References

Benachaiba, C. and Ferdi, B. 2008. Voltage Quality Improvement Using DVR, *Electrical Power Quality and Utilization*. 15(1).

Tiwari, H.P. and Gupta, S.K. 2010. DC Energy Storage Schemes for DVR Voltage Sag Mitigation System, *International Journal of Computer Theory and Engineering*. 2(3); 1793-8201.

Salimin, R.H. and Rahim, M.S.A. 2011. Simulation Analysis of DVR Performance for Voltage Sag Mitigation, *The 5th International Power Engineering and Optimization Conference* (PEOCO2011).

Gupta, R., Sharma, N.K., Tiwari, P., Gupta, A., Nigam, N. and Gupta, A. 2011. Application of energy storage devices in power systems, *International Journal of Engineering, Science and Technology*. 3(1); 289-297.

Omar, R., Rahim, N.A. and Sulaiman, M. 1991. Dynamic Voltage Restorer Application for Power Quality Improvement in Electrical Distribution System: An Overview. *Australian Journal of Basic and Applied Sciences*, 5(12): 379-396.

Rajani, S.V., Jha, R.C. and Prakash, P. 2012. Deeper and extended voltage sag mitigation by dynamic voltage restorer interfaced with ultra-capacitor, *International Journal of Advanced Engineering Technology* 3(1); 230-233.

Gupta, S.K. and Tiwari, H. P. 2012. Voltage Sag Compensation on Distribution Network Using DVR, *International Journal of Advanced Engineering Technology* 3(1); 230-233.

Thakur, T. and Singh, G. Modeling and simulation of DVR for power quality improvement, *International Journal of Engineering Sciences Research*-IJESR ISSN; 2230-8504;e-ISSN-2230-8512.

Fuyuan, Y., Languang, L., Yuping, Y. and He, Y. 2010. Characterization, Analysis and Modeling of an Ultracapacitor, *World Electric Vehicle Journal* Vol. 4.

Waste Stabilisation Ponds as an Energy Efficient Sustainable Wastewater Treatment Technique

D.N.De.S. Gunatilleke*, A. Anparasi

Planning & Design Section, National Water Supply & Drainage Board, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Waste Stabilization Ponds (WSP), often referred as oxidation ponds or lagoons, are holding basins used for wastewater treatment where decomposition of organic matter is processed naturally, i.e. biologically. The activity in the WSP is a complex symbiosis of bacteria and algae, which stabilize the waste and reduces pathogens. The result of the biological process is to convert the organic content of the effluent to more stable and less offensive forms. Many characteristics make WSP substantially different from other wastewater treatment techniques which include design, construction and operation simplicity, cost effectiveness, low maintenance requirements, low energy requirements, less sludge production and sludge disposal will arise after long operation periods, easily adaptive for upgrading and high efficiency.The activity in the WSP system is a complex symbiosis of bacteria and algae, which stabilize the waste and reduces pathogens. The result of the biological process is to convert the organic content of the effluent to more stable and less offensive forms by a natural treatment technique. Hence WSP systems do not require energy for its operation as it is a natural wastewater treatment technique compared to the 15-19 kWh/person-year required for aeration alone for Activated Sludge Extended Aeration Systems (Arceivala S.J.) which is typically used in Sri Lanka. The presence of algae in facultative ponds is important for treatment of wastewater but escape of algae cells from facultative ponds retard the performance efficiency of maturation ponds. Instead algae in the facultative pond effluent can be captured and utilized as energy source either as biomass for power generation or as biodiesel can produce 5,000-15,000 gal/ha/yr of oil.

Key words: algae, biodiesel, energy, waste stabilization ponds

1. Introduction

Waste Stabilization Ponds (WSP), often referred as oxidation ponds or lagoons, are holding basins used for wastewater treatment where decomposition of organic matter is processed naturally, i.e. biologically. The activity in the WSP is a complex symbiosis of bacteria and algae, which stabilize the waste and reduces pathogens. The result of the biological process is to convert the organic content of the effluent to more stable and less offensive forms. Many characteristics make WSP substantially different from other wastewater treatment techniques which include design, construction and operation simplicity, cost effectiveness, low maintenance requirements, low energy requirements, less sludge production and sludge disposal will arise after long operation periods, easily adaptive for upgrading and high efficiency.

The simplest of all wastewater treatment techniques available to treat sewage, involves holding the wastewater in shallow ponds for an adequate detention period to enable the natural stabilization of organic matter to occur through microbial decomposition. Major drawback of natural systems for wastewater treatment (ponds, wetlands) is the large area requirement (under tropical conditions > 2.5 m^2 / capita; compared to activated sludge < 0.5 m^2 / capita) (Van der Steen, 2004).

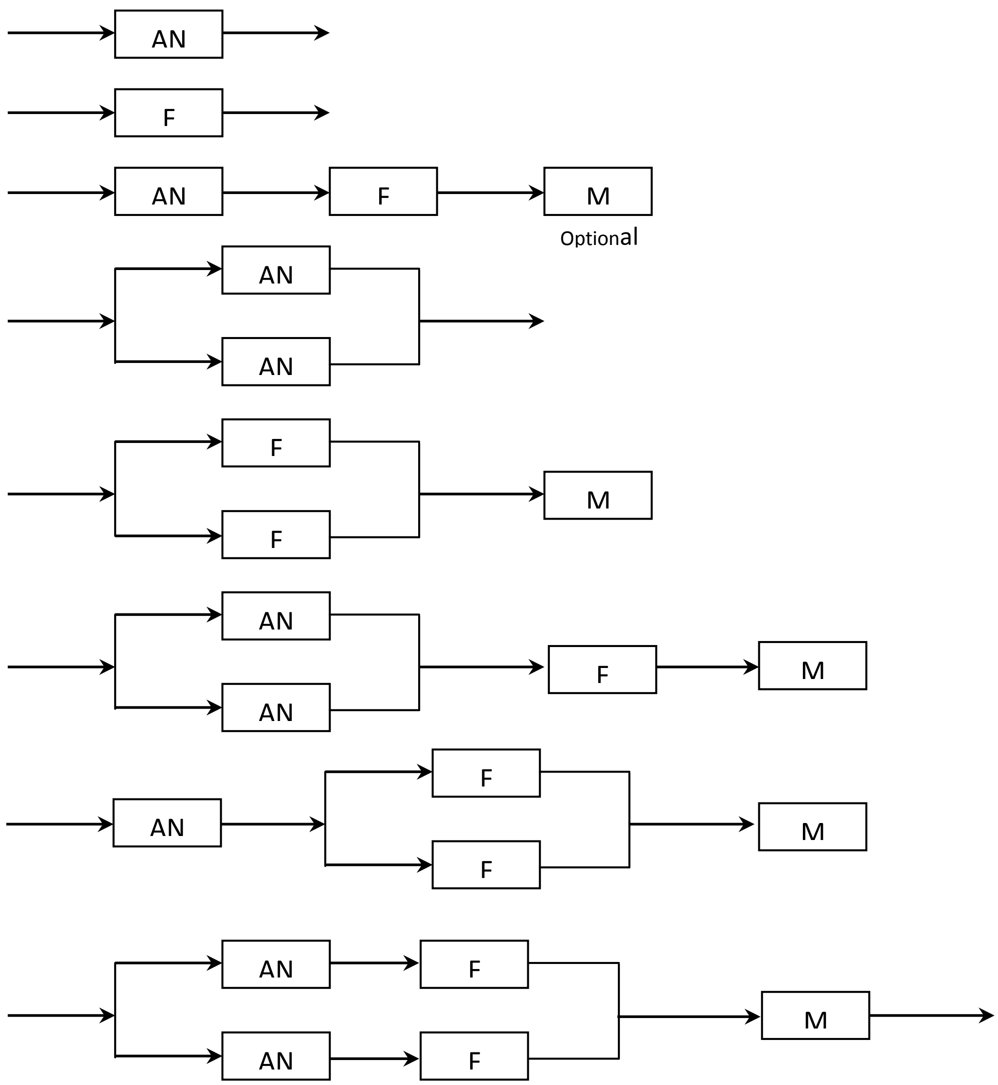
At present the National Water Supply Drainage Board, Sri Lanka (NWSDB) operate three WSP systems namely in; Kataragama sacred city - in operation since 1983, Mattegoda housing scheme - functioning from late 80's and the most recent at Hikkaduwa - commissioned in February 2006. The Central Engineering Consultancy Bureau (CECB) has also constructed WSPs around the island. In addition to existing WSP systems in operation, NWSDB is in the process of implementing WSP system under ADB/AFD assisted Jaffna City Wastewater Management Project and Hambantota Wastewater Management Project to re use treated wastewater for agriculture purpose. The wastewater treatment plant under construction for Defence Headquarters is comprised with maturation ponds to polish the effluent and to reduce

* *Correspondence: dgunatilleke@hotmail.com*
ISSN 2478-0669 Print

faecal coliform before discharging to natural drainage path that meets Diayawannawa. NWSDB also plans a WSP system to treat wastewater emanating from Batticalo town to inland surface discharge standards and intend discharge of treated effluent via a short sea outfall. In addition to that NWSDB has constructed WSP systems at IDP camps at Menik Farm and Vauniya to meet the emergency sanitation need and constructed several septage (septic tank sludge) treatment systems for towns that do not have wastewater treatment plants.

2. Methodology

WSP is highly recognized as a most appropriate wastewater treatment method as which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both in low cost and with minimal operational and maintenance requirements.



AN = Anaerobic Pond F = Facultative Pond M = Maturation Pond

(Pescod and Mara, 1988)

Figure 1: Stabilization pond configurations

Wastewater stabilization pond systems are designed to achieve different forms of treatment in up to three stages in series, depending on the organic strength of the input waste and the effluent quality objectives. For ease of maintenance and flexibility of operation, at least two trains of ponds in parallel are incorporated in any design. Strong wastewaters, with BOD_5 concentration in excess of about 300 mg/l, will frequently be introduced into first stage anaerobic ponds, which achieve a high volumetric rate of removal. Weaker wastes or where anaerobic ponds are unacceptable, even stronger wastes may be discharged directly into primary facultative ponds. Effluent from first stage anaerobic ponds will overflow into secondary facultative ponds, which comprise the second stage of biological treatment. Following primary or secondary facultative ponds, if further pathogen reduction is necessary, maturation ponds will be introduced to provide tertiary treatment. Typical pond system configurations are given in Fig. 1, though other combinations may be used.

WSP can be classified in respect of the types of the biological activity occurring in a pond. Three types are distinguished: anaerobic, facultative and maturation ponds. Usually a WSP system comprises a single series of the aforementioned three pond types or several such series in parallel. In essence, anaerobic and facultative ponds are designed for BOD (Biochemical Oxidation Demand) removal and maturation ponds for pathogen removal although some BOD removal occurs in maturation ponds and some pathogen removal in anaerobic and facultative ponds. In many instances only anaerobic and facultative ponds are required. In general, maturation ponds are required only when stronger wastewaters (BOD>150 mg/l) are to be treated prior to surface water discharge and when the treated wastewater is to be used for unrestricted irrigation (Irrigation for vegetable crops). Generally, in a WSP system, effluent flows from the anaerobic pond to the facultative pond and finally, if necessary, to the maturation pond. However, for better results wastewater flowing into an anaerobic pond shall be preliminary treated in order to remove coarse solids and other large materials often found in raw wastewater. Preliminary treatment operations typically include coarse screening and grit removal.

Effluent entering the facultative pond from the anaerobic pond is converted into carbon dioxide, water and new bacterial and algae cells in the presence of oxygen, i.e. aerobically. Algae populations within the aerobic pond require sunlight for their photosynthesis process. They develop and produce oxygen in excess of their own requirements. This excess oxygen is used by bacteria to further break down the organic matter present in the effluent.

The algal cells produced extensively in facultative ponds flow progressively to the maturation ponds and are ultimately discharged into water bodies. These effluents having considerable amount of algae cells retard the sunlight penetration in maturation pond thus retarding the natural disinfection power and contribute adversely on receiving waters such as lakes, estuaries and coastal waters to form algae blooms.

3. Results and Discussion

The activity in the WSP system is a complex symbiosis of bacteria and algae, which stabilizes the waste and reduces pathogens. The result of the biological process is to convert the organic content of the effluent to more stable and less offensive forms by a natural treatment technique. Hence WSP systems;

- Do not require energy for its operation as it is a natural wastewater treatment technique compared to the 15-19 kWh/person-year required for aeration alone for Activated Sludge Extended Aeration Systems (Arceivala S.J.) which is typically used in Sri Lanka. Therefore WSP systems do not contribute to consume non renewable energy.

- Extended aeration system does require considerable energy for sludge recirculation and waste activated sludge thickening, disposal to sludge drying bed or mechanical sludge dewatering in addition to the energy requirement for aeration

- Do not require skilled personnel to operate

- No mechanical devices to break nor to maintain

- No requirement to process control compared to activated sludge treatment. It is required to monitor Mixed Liquor Suspended Solids (MLSS), MLVSS, Sludge Volume Index (SVI), Food/Microorganism ratio (F/M) etc.

- Contribute to reduce green house gas emissions in the environment as algae present in the facultative ponds uptake CO_2 during photosynthesis process (in presence of sun light) and release molecular oxygen which will be utilized by the aerobic bacteria present in the facultative ponds while stabilizing the organic matter.

In addition to conservation of energy by implementation of WSP systems, considerable amount of energy could be generated from algae that flow along with facultative ponds effluent either as biomass or by producing biodiesel. Even though production of biodiesel has been discussed from specifically cultured algae using ponds no literature is found where algae from wastewater treatment plants is being used to produce biodiesel or as biomass and hence its possible application will be discussed in detail below.

The presence of algae in facultative ponds is important for treatment of wastewater but escape of algae cells from facultative ponds retard the performance efficiency of maturation ponds. Instead algae in the facultative pond effluent can be captured and utilized as an energy source while effluent having less algae cells tends to increase the natural disinfection ability of the maturation ponds due to more penetration of UV radiation of the sunlight and improving the water quality of the receiving waters.

Thus algae based wastewater treatment is a powerful avenue for sustainable wastewater treatment. Use of algae as the bioremediation agent enables to solve two key problems: minimize high energy costs associated with alternative advance wastewater treatment techniques while the extracted algae can be utilized as biodiesel to generate energy instead. An alternative fuel source that is renewable, economical and environmental friendly is necessary as fossil fuels are fast depleting. Biodiesel made from crops such as rapeseed and soybeans is one of the alternatives many people are aware of. Production of biodiesel from food sources and utilization of agricultural lands for production of biodiesel displace food and the amount of crops it takes to produce a gallon of oil. The yields of oil from algae are much higher than other land crops and algae can grow practically anywhere. Thus ensuring that there is no competition with food crops and are excellent bioremediation agents, they have the potential to absorb massive amount of CO_2 and can play an important role in wastewater treatment. The algae that are used in biodiesel production are usually aquatic unicellular green algae. This type of algae is a photosynthetic eukaryote characterized by high growth rates and high population densities.

Most common algae harvesting process are flocculation, micro screening and centrifugation. Once the algae are grown and harvested, it can be utilized to produce biodiesel or biomass which can be used to generate power. There are a different ways of extracting the oil. This oil is transformed into biodiesel through a process called 'transesterification'. Although algal biodiesel and fossil fuel are similar, the properties and energy efficiencies are comparable. Innovative technique for cultivation of algae in facultative ponds allows production of biodiesel to compete with or even replace fossil fuels.

The main algal species found in Sri Lanka are Chlorella, Pandorina, Spirulina and Oscillatoria. Chlorella is found in huge amount and has high oil content of 28-32% of dry weight. Under good conditions, green algae can double its biomass in less than 24 hours and can have huge lipid contents, frequently over 50%. Soybeans, rapeseed and palm oil can produce 48 gal/ha/yr, 127 gal/ha/yr and 635 gal/ha/yr of oil respectively while microalgae can produce 5,000-15,000 gal/ha/yr of oil. There are significant variations between oil yields from different strains of algae according to culture conditions. Oil content is only one criterion for selecting the species for cultivation. Growth rate, density, and survivorship must also be considered.

However, human exposure to algae derived toxins, allergens and carcinogens from existing and genetically modified organisms is an issue in algal biodiesel studies. At certain stages of lifecycle many algae species can produce toxins ranging from simple ammonia to physiologically active polypeptides and polysaccharides. Toxic effects can range from the acute (e.g. the algae responsible for paralytic shellfish poison may cause death) to the chronic. Toxin production is species and strain specific and may also depend on environmental conditions. The presence or absence of toxins is thus difficult to predict. From the perspective of producing biofuels, the most important issue is that where co-products are used in the human food chain, producers will have to show that the products are safe. From an economic perspective algal toxins may be important and valuable products in their own right with applications in biomedical, toxicological and chemical research. Instead of producing biodiesel, it may also be possible to use algae as biomass to be used in gasifiers, dendro power plants and boilers to produce energy

References

Comprehensive Oilgae Report, www.oilgae.com.

Matthew N Campbell, Biodiesel: Algae as a Renewable Source for Liquid Fuel, Guelph University, Guelph, Ontario, N1G 2W1, Canada.

Kalubowila S., Gunatilleke D.N.De.S., Jayaweera M. and Nanayakkara C.M. Floating Wetlands for Management of Algal Washout from Waste Stabilization Pond Effluent: Case Study at Hikkaduwa Waste Stabilization Ponds, Engineer, Vol:XXXXVI(04): 63-74.

Operation & Maintenance Manuel, Sewerage Division, NWSDB, 2009.

Energy Efficient Weft Insertion for Conventional Weaving Looms

K. Kamalaruban, K. Hamsathvanie, S. Selvalojini, T. Thiruvaran, S. Arunan

Faculty of Engineering, University of Jaffna

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

In the weaving industry, speed of the weft insertion is the key factor which determines the production rate, however, the energy consumption for weft insertion is significantly high. There are various techniques of weft insertion system implemented to increase the production speed and the quality of fabric, such as air jet, water jet, rapier, and projectile weft insertion even though, the large amount of initial cost for high speed modern weaving looms retreats the people in developing countries to involve in competitive weaving industry. The present study describes the energy efficient weft insertion in conventional weaving looms by electromagnetic force system, which can be portable and simply integrated with conventional shuttle weaving looms to increase the picking speed with low cost. Off grid solar batteries can also be used to empower weft insertion in conventional shuttle weaving looms, which enhance the small scale industries.

Keywords: electromagnetism, solenoid, projectile, weft insertion

1. Introduction

The production rate and quality of the woven fabric are determined by the type of weft insertion technique used. Hence that, weaving looms are categorized according to the type of weft insertion method. Weft insertion is the process to insert weft yarn across the loom's width through warp yarns. The development of weaving looms had been evolved to modern shuttle less looms from conventional shuttle looms and provide increase in the production rate and quality of the fabric. However, the weaving industry in the developing countries still belong to conventional looms such as hand looms and semi-automated looms. According to Pandit (2013) the weaving looms are used to produce woven fabric for last 850 years. Hari & Behera (1994) stated that, 85% of weaving industry are still covered by conventional shuttle weaving looms with considerable low weft insertion speed, i.e. speed varies from 6 m/s to 11 m/s.

The weft insertion speed in modern shuttle-less weaving looms such as air jet, water jet, rapier and projectile weaving looms varies from 10 m/s to maximum of 44 m/s (Pandit, 2013). The development of energy efficient weft insertion with high speed and low cost paves a concrete platform for weaving entrepreneurs in developing countries. Koc & Cincik (2010) state that in shuttle weaving looms, the weft insertion motion consumes 61% of the total energy.
This paper proposes an energy efficient electromagnetic weft insertion system. The prime motivation to develop the prototype is the possibility to achieve relatively high weft insertion speed with significantly low cost compared to the modern method. Mirjilini (2005) carried out the above method obtaining the maximum velocity of 8 m/s. This model was not further developed presumable due to the inability to improve the speed than conventional shuttle weaving looms.

The electromagnetic launching for weft insertion which was carried out for this paper achieved a speed of 14 m/s. The system consists of solenoid, projectile, high current DC power supply, PLC switching device and a yarn feeder mechanism.

2. Methodology

2.1 Theory behind the mechanism

The coil gun mechanism is used to develop the weft insertion model. The bullets of the coil gun are replaced by ferromagnetic projectile (Holzgrafe 2012). A high current is applied as a pulse to the solenoid coil by switching the high current DC power supply through the PLC.

* Correspondence:
ISSN 2478-0669 Print

2.1.1 Coil gun

A coil gun is an electromagnetic device to launch magnetically active projectiles to high velocity. A strong magnetic field will be formed, when a large current is pulsed through a solenoid. This strong field induces magnetization in the projectile, causing microscopic dipoles to align with the field and pull the projectile to the centre of the coil (Ali, 2001). If the current is stopped instantly, it continues to move out of the core at rapid speed (Holzgrafe, 2012). If the current was sustained indefinitely, after being accelerated from one side of the coil, the projectile would encounter an opposite gradient on the other side which would apply a force back towards the centre of the coil, slowing its motion. Thus in this paper, current is applied as a pulse.

2.1.2 Solenoid

A solenoid is used to produce magnetic field along the centre axis of the solenoid. The magnetic field strength depends on the number of turns of the solenoid, current and the diameter of the solenoid. Magnetic field in the solenoid is given by the following equations,

$$B = \mu \frac{N}{L} l \qquad 1$$

$$B = \mu n l \qquad 2$$

Where;

B = Magnetic flux density
μ = Magnetic permeability
N = Number of turns
L = Current
n = Turns density (turns/length)
I = Length of the solenoid

In the proposed weft insertion mechanism a part of the magnetic energy, generated by the solenoid is converted to kinetic energy, which determines the projectile speed. Therefore, inferring from equation (1) and (2) the number of turns and current in the coil determines the exit velocity of the projectile.

2.1.2 Projectile

The projectile is a ferromagnetic object containing velcro tail which carries the yarn across the loom. The factors to be considered for strong attractions of projectile by solenoid are permeability, dimension of projectile and the effect of eddy current. The projectile material should have higher magnetic permeability and low electrical conductivity to avoid the eddy current effects, which resist the trajectory motion of the projectile to have higher initial velocity. The kinetic energy depends on mass and velocity of the projectile.

The velocity of the projectile depends on various factors such as mass, current, and diameter of the solenoid. The diameter ratio between projectile and solenoid plays significant role during the launching. The maximum flux linkage occurs when projectile's diameter comes very close to the core's diameter (Rutgers, 2013).

2.2 Prototype

A prototype was built to analyse the exit velocity of the projectile from solenoid for various conditions as shown in figure 1.

2.2.1 Projectile

The selection of appropriate projectile is a vital factor with length, diameter, mass and shape of the projectile parameters. The bicycle wheel spoke was selected to make projectile, as it contains galvanized steel (Koc, 2010). It has a significant permeability and less weight. Projectiles are made in different lengths and different shapes: Aerodynamic and Cylindrical shapes

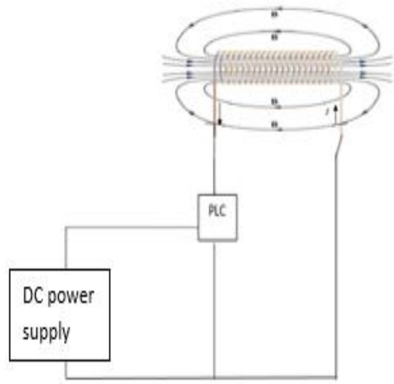


Figure 1: Complete circuit

Table 1: Generally used projectile parameters

Parameter	Value
Length	35 mm
Diameter	1.95 mm
Mass	1.78 g

2.2.2 Solenoid core

Transparent plastic narrow tube was chosen due to the less friction, no eddy current effects, higher stiffness factor. The use of electrically conductive material for core causes eddy current problems, which reduces the effective magnetic field of launching.

2.2.3 Solenoid construction

Solenoid was constructed with the following parameters.

2.2.4 Power source

Coil gun needs high current pulse to accelerate the light projectiles to higher velocities. A high current DC power supply (PeakTech1535) was used to energize the solenoid. Generally, 10A and 20V limit was set on the power supply for testing various criteria except for the current variation.

Table 2: Coil parameters

Parameters	Value
Length	10 cm
Wire Gauge	18SWG
Turns	700
Inner Diameter	9 mm
Outer Diameter	20 mm
Layers	8
Average Resistance	0.6 Ω
Average Inductance	274.4 µH

2.2.5 Control circuit

The coil current flow is controlled using a Programmable Logic Controller (XINJE- XC3- 24RT-E) with a combination of relay, which is used to execute the sequence process. Photo electric sensor (E3F–DS 1034) is fixed near the tail of the solenoid to detect projectile, cuts off the supply using a relay with a delay of two seconds. The delay is calculated by a timer in PLC.

2.2.6 Speed calculation

Exit speed of the projectile is the key factor to be analyzed in speed calculation. A tube was taken and two pairs of Light Dependent Resistors (LDR) and Light Emitting Diodes (LED) were fixed face to face with distance 400 mm apart. The time duration between the detection of the projectile by the two LDRs is calculated using a microcontroller unit. This time was used for speed calculations in various conditions for different lengths and shapes.

2.2.6.1 Microcontroller unit

Arduino Uno, one of the open-source microcontroller board based on the 8bit ATmega328 and 16 MHz ceramic resonator used in this project, to measure the time taken for the projectile to pass a defined length.

3. Results and Discussion

The nose of the projectile consists an impact on aerodynamic drag coefficient. Aerodynamic shaped projectiles can easily fly through the air. Thus, it reduces air friction compared to the cylindrical edged projectile. Furthermore, the speed decreases with linear density.

According to Mirjalili (2005) the larger the projectile more the force is. Further, higher magnetic force can be exerted on projectile when length increase to three quarters of solenoid's length. Supporting the above in our analysis the 35 mm length of the projectile achieved the higher velocity as shown in figure 3. Thus, this value was taken as the reference for other analysis.

Kinetic energy reduces with respect to the length of the projectile. The speed made a huge impact on kinetic energy since it is squared. Length variation gives a small deviation in mass, therefore, the projectile with higher mass has low kinetic energy.

According to equation (2), when current increases, the exit velocity of the projectile will be increased. to study this effect the 35 mm length of projectile specimen was placed to the various current configurations and the results are shown in figure 2.

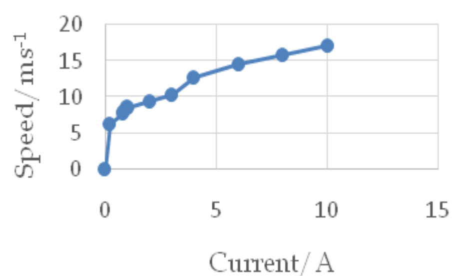


Figure 2: Variation of speed with the current passing through the coil

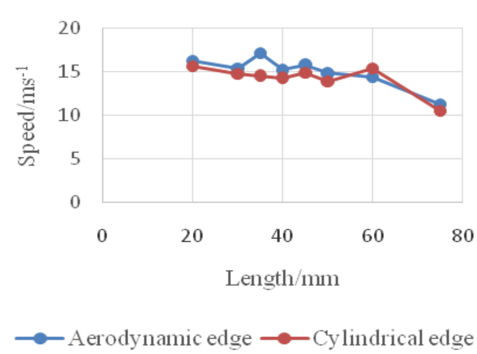


Figure 3: Variation of speed with projectile length

3.1 Domestic application

The minimum voltage and current required for launching the 35 mm length and 1.78 g of projectile with minimum speed, are 3 V and 0.2 A, i.e. 700 turns of solenoid was used to verify practically. In concern about domestic weaving industries, the replacement of electromagnetic launching makes significant change in working progress, as many people are unable to drive the weft insertion system due to the medical issues. Conventional weaving loom has more power consumption with low weft insertion speed but the electromagnetic application makes it more efficient with a significant low power consumption. The higher end shuttle-less weaving looms are much costly and unaffordable for developing nations in terms of financial and power consumption costs.

4. Conclusion

An electromagnetic weft insertion system was successfully developed with very low cost to achieve a speed of 14m/s, which is significantly higher than conventional shuttle weaving looms. The power consumption of the above model is considerably low with a value of 200W. Furthermore, implementation and maintenance of this proposed method is very simple. According to the above research, the following conclusion can be made.

- The total cost of commercial implementation is estimated to be less than $ 200 dollars to achieve the speed of 14 m/s, which is considerably low cost, to obtain this relatively higher speed of weft insertion system. Therefore, replacement of electromagnetic weft insertion system in conventional shuttle weaving loom is economical to increase the production speed in developing countries.Future work targets to further improve the speed of the system by exploring the following ideas.
- The DC power supply can be replaced by connecting two car batteries in parallel, therefore, the weft insertion can be executed by simple energy efficient mechanism.
- The renewable energy source; off-grid solar battery can be replaced for DC power supply, which is more reliable in tropical countries like Sri Lanka and India.
- The projectile speed could be enhanced by cutting off the current flow through the solenoid when the head of the projectile reaches the center of the solenoid while launching.
- Identifying less weighted projectile to decrease the deceleration, during the launching of weft yarn. Polishing projectile to reduce the friction between warp yarns and projectile to reduce the deceleration after the launch.
- Using less density, high permeability and longer projectile to increase the speed, as it would increase the magnetic force.
- The distance between the projectile head and solenoid tail is also an analyzing factor to increase the speed. The maximum flux linkage occurs with specific active distance.

References

Ali M.N. 2001. Analysis of Eddy-Current Losses over Conductive Substrates with Applications to Monolithic Inductors and Transformers: IEEE transactions on microwave theory and techniques, Vol 49 (1); 166-176.

Bresie D.A, and Ingram S.K. 1993. Coil gun technology at the center for electro mechanics, IEEE Transactions on Magnetics. 29; 1.

Hari, P. And Behera, B.K. 1994. Developments in weaving machines: Indian *Journal of fibre & Textile Research.*19; 172-176.

Holzgrafe, J., Lintz,N., Eyre, N. and Patterson, J. 2012. Effect of Projectile Design on Coil Gun Performance.

Koc, E. and Cincik, E. 2010. Analysis of Energy Consumption in Woven Fabric Production: Fibres and Textiles in Europe.18 (79); 14-20.

Mirjalili, S. A. 2005**.** Using Electromagnetic Force in Weft Insertion of a Loom, fibres & textiles in Eastern Europe. 13(51).

Niknejad, A.M. 2001...Analysis of Eddy-Current Losses over Conductive Substrates with Applications to Monolithic Inductors and Transformers: IEEE transactions on microwave theory and techniques.49; 1.

Pandit, S., Kumar, P. And Chakrabarti, D. 2013. Ergonomic Problems Prevalent in Handloom Units of North East India. *International Journal of Scientific and research publication,* 3(1); 2250-3153.

Rutgers,School of Electrical and Electronic Engineering. 2013. Electromagnetic Coil Gun, Final Report. Retrieved from: http://gdclark.com/wpcontent/uploads/2014/08/FinalReport1.pdf.

Renewable Energy: An Attempt towards Biodiesel Production from Cyanobacteria and Micro-Algae Isolated from Fresh Water Bodies of Sri Lanka

M.F. Hossain[1, 2], R.R. Ratnayake[2*], M.V.U.M. Jayasinghe[1], S.A. Kulasooriya[2], K.L.W. Kumara[1]

[1]*Department of Agricultural Biology, Faculty of Agriculture, University of Ruhuna*
[2]*National Institute of Fundamental Studies, Kandy*

Date Received: 22-11-2014 Date Accepted: 29-04-2015

Abstract

The present study was carried out to examine the optimum growth conditions for cyanobacteria isolated from fresh water bodies of Sri Lanka and fatty acid analysis of selected strains towards biodiesel production. Collected samples were cultured in different media (BG-11, GO and ASN-III) recommended for cyanobacteria with different growth parameters (pH, light intensity, shaking). Media for rapid growth were selected in terms of days taken for bluish-green growth to appear in the cultured samples. Growth concentration termed as total pigments was determined by measuring the sum of chlorophyll-*a* and pheophytin-*a* pigment. In the present study, BG11 supported best growth at the optimum pH of 7.5, under 2000 Lux light intensity and at 200 rpm shaking. Addition of original water instead of distilled water during initial sample preparation and, use of vortex mixture with glass beads during isolation, was found to be an effective technique to obtain uni-algal culture. A positive correlation was observed between biomass and total pigments of cyanobacteria. In terms of fatty acid composition, out of three selected strains, only *Spirulina* sp. shows the potential towards biodiesel production.

Keywords: cyanobacteria, micro algae, growth optimization, culture parameters, total pigments, morphology

1. Introduction

Rapid increase of atmospheric carbon dioxide together with depleted supplies of fossil fuel has led to an increased commercial interest in renewable fuels (Halim, Harun, Webley, & Danquah, 2013). As a whole, global petroleum reserves are shrinking at a rapid pace, increasing the demand for alternate fuels (Mutanda et al., 2011). This leads to interesting questions and debate over the choice of new fuels, produced from new raw materials, to complement or replace present petroleum-based fuels (Posten and Schaub, 2009). Several biofuel candidates were proposed to displace fossil fuels in order to eliminate the vulnerability of the energy sector (Korres, Singh, Nizami, and Murphy, 2010). Much of the discussion over biofuel production from plants has focused on higher plants such as corn, sugarcane, soybean, oil-palm and others and these are associated with problems over utilization of arable land, loss of ecosystems and competition with food production (Parmar, Singh, Pandey, Gnansounou, and Madamwar, 2011). Cyanobacteria with an array of light harvesting pigments and superior photosynthetic capabilities can convert up to 10% of the sun's energy into biomass, compared to 5% achieved by eukaryotic algae and 1% recorded by conventional energy crops such as corn or sugarcane (Parmar et al., 2011). The local species can be expected to have a competitive advantage under the existing geographical, climatic and ecological conditions (Duong, Li, Nowak, and Schenk, 2012).

In Sri Lanka, fossil oil is used as the source of energy in many sectors and oil prices directly impact the economy and development of the country. To meet sustainable national development, it is timely to explore the environmental friendly, renewable and low cost alternative fuels.

In view of the above, the present preliminary work was undertaken to select the best conditions to grow cyanobacteria and micro-algae isolated from different fresh water bodies representing dry, intermediate and wet zones of Sri Lanka towards biodiesel production.

[*] *Correspondence: renukar@ifs.ac.lk*
ISSN 2478-0669 Print

2. Methodology

2.1 Sample collection and preparation

Water was collected using a Ruttner sampler from the photic surface layer of the reservoir. The photic zone of the water was determined by Secchi disk dipping into the water from the surface area.

From each sample, 2 L was filtered through a 20 µm mesh size planktonic net. The retentiate was transferred into a screw cap plastic tube and the final volume was made into 25 ml by adding distilled water. Another sample was prepared by adding original water instead of distilled water with the retentiate. Ten milliliters of the planktonic samples were transferred into 50 ml of BG-11 (Stanier, Kunisawa, Mandel, and Cohen-Bazire, 1971), GO (Rippka, Deruelles, Waterbury, Herdman, and Stanier, 1979) and ASNIII (Rippka, Waterbury, and Stanier, 1981) media for culturing.

2.2 Culturing and sub culturing

Samples in the media were cultured in conical flasks and were kept on the shaker (0 rpm, 200 rpm and 300 rpm) in biological growth chamber under fluorescent light (1000 lux, 1500 lux and 2000 lux light intensity) with constant illumination. Four different pH levels (7, 7.5, 8, and 8.5) were selected for the study. Once growth was observed, 100 µl of samples were sub cultured into petri-dishes (Pulz & Gross, 2004). For fatty acid composition analysis, isolated mono culture was cultured in 1 L media for one month and biomass was harvested by centrifugation at 3000 rpm for 10 minutes.

2.3 Isolation of monoculture and morphological identification

Frequent sub culturing was practiced to isolate single colonies from mixed growths of microorganisms. Single colonies were selected using morphological characteristics and monoculture of the sample was put on a glass slide, covered with a cover slip and observed under the Euromex (BioBlue.Lab BB. 1153-PLi) microscope. Identifications were carried out using morphological characteristics as described by Desikachary (Desikachary, 1959). In case of more than one type filamentous cyanobacteria when it was very difficult to isolate them, a vortex mixture was used. One milliliter of the sample along with some pieces of glass beads were poured into a micro-centrifuge tube and it was vortexed. In case of plate culture, algal colonies were picked using a sharp needle and diluted with water in a micro-centrifuge tube prior to vortex.

To solidify the media, it was supplemented with 1.5% (w/v) bacteriological agar. The purity of the culture was confirmed by repeated plating and by regular observation under the microscope according to the method described by (Abou-Shanab, Hwang, Cho, Min, & Jeon, 2011).

2.4 Pigment measurement

Chlorophyll-*a* and Phaeophytin-*a* were determined by the method described by Chorus and Bartram (Chorus and Bartram, 1999). The results were plotted as total pigments by summing up those two pigments.

2.5 Fatty acid analysis

Lipid was extracted and fatty acid composition was determined by the methods of Yaniv and others (Yaniv, Schafferman, Zur, and Shamir, 1996).

2.6 Statistical analysis

Statistical analyses were done using ANOVA in SAS 9.1 statistical analysis software (SAS, 1999) and MINITAB-14.

3. Results and Discussion

3.1 Sampling

Sampling was carried out from six fresh water bodies in three climatic zones of Sri Lanka. The abiotic properties of water samples are shown in Table 1.

Table 1: Abiotic properties of water samples collected

ID	Secchi Depth	Water Temperature	pH	Site Name
S1	87 cm	16.5^{0}C	7.61	Ambewela Tank
S2	55 cm	25^{0}C	7.71	Kandy Lake
S3	65 cm	28.5^{0}C	7.29	Kandalama Tank
S4	61cm	30.3^{0}C	7.03	Kalawewa
S5	48cm	25.15^{0}C	7.95	Kurunegala
S6	58 cm	31^{0}C	8.7	Chandrikawewa

3.2 Culturing

Growth appearance was expressed as days in each media for the cultures to appear bluish green in color. During this study, the time taken for growth appearance in three different media is shown in Table 2.

It was observed that all the samples prepared with original water were growing faster than the samples prepared with distilled water (Table 2). Most likely the original water can favor a robust and opportunistic (fast-growing) environment with superior survival skills. Also, all the samples were fast growing in BG11 medium compared to GO and ASNIII. In BG-11, growth appearance rate was 100% whereas, growth appeared only in three samples in GO and only in two samples in ASNIII media. Some samples had taken less time and others had taken more time for the growth while, BG-11 media was found to be more efficient than the others (Table 2). This result was supported by another study carried out by Rippka and others (Rippka *et al*., 1981). In the present study, heterocyst forming cyanobacteria was found to be selective for growth in GO media. According to Rippka and others (1981), for all aerobic nitrogen fixing cyanobacteria, both isolation and purification are best achieved with medium BG-11 (termed as GO). Fast growing sample was selected to test optimum culture conditions such as pH, light intensity and shaking.

Table 2: Time taken (number of days) to observe bluish green growth in each media

Isolate	Sample with original water			Sample with distilled water		
	BG 11	GO	ASNIII	BG 11	GO	ASNIII
S1	8	10	NG*	14	21	NG
S2	6	15	NG	10	19	NG
S3	10	NG	NG	18	NG	NG
S4	5	8	14	9	13	22
S5	11	NG	NG	16	NG	NG
S6	9	NG	21	15	NG	NG

*NG = No Growth appeared

3.3 Relationship between biomass and total pigments

Chlorophyll-*a* is a widely used and accepted measure of biomass (Chorus and Bartram, 1999). But, chlorophyll immediately starts to degrade to phaeopigments and phaeophytin-a is a degradation product of chlorophyl-*a* (Chorus and Bartram, 1999). Thus, the sum of the both pigments termed as total pigments can be an estimation to calculate the concentration of cyanobacterial growth. Total chlorophyll-*a* and pheophytin-*a* (degraded product of chlorophyll-*a*) were measured as an indirect method to quantify the growth rate of microalgae and cyanobacteria. In the present study, a positive correlation was found between biomass and total pigments in both BG 11 media (Figure 1) and GO media (Figure 2) with all growth parameters (pH, light intensity and shaking) where, with the increase of biomass, an increased value of total pigments were recorded.

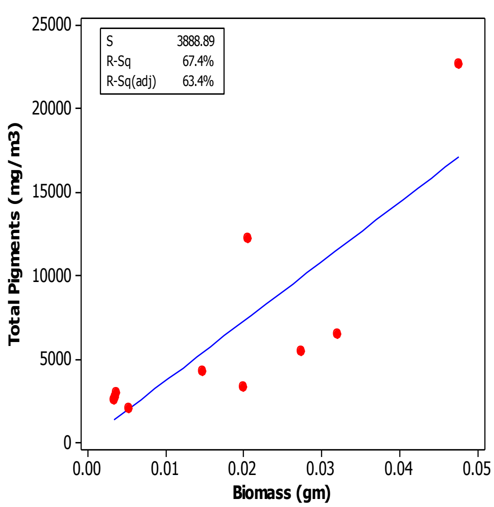


Figure 1: Relationship between biomass and total pigment content in BG 11 media with different growth conditions
(pH, light intensity, shaking)

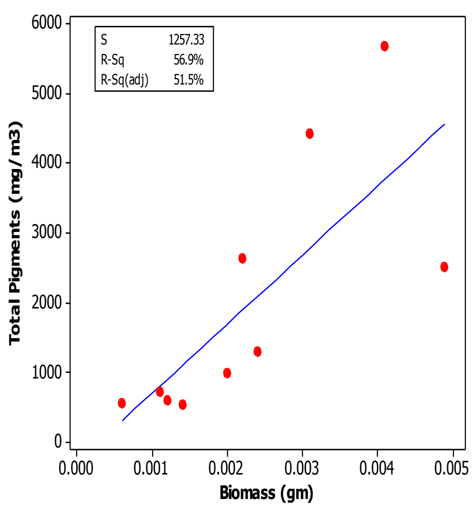


Figure 2: Relationship between biomass and total pigment content in GO media with different growth conditions
(pH, light intensity, shaking)

3.4 Culture conditions: pH, Light intensity and Shaking

Results of the measurement of total pigments was carried out to determine the effective media, optimum pH, optimum light intensity and optimum shaking condition to grow micro algae and cyanobacteria. Highest total pigments were recorded in BG11 medium compared to the other two media and it was significantly different from GO and ASNIII media (Figure 3). Growth recorded in GO and ASN III media were not significantly different from one another.

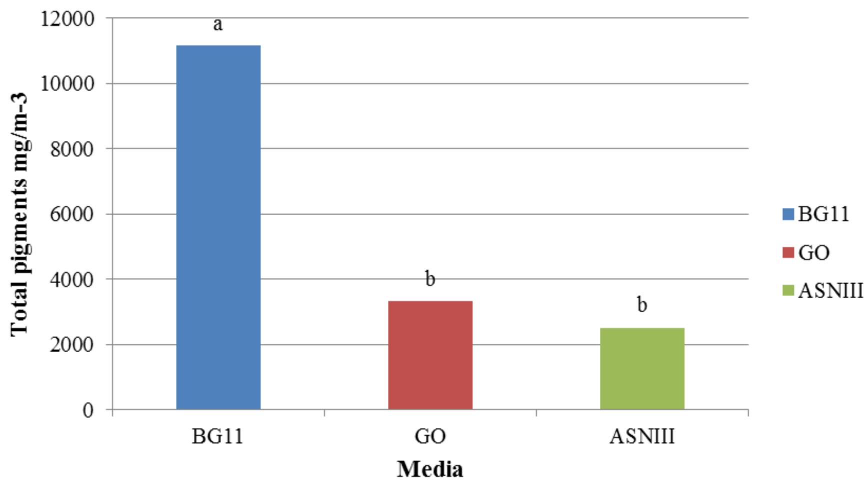


Figure 3: Amount of total pigments in BG11, GO and ASNIII media, Bars with the same letter are not significantly different at 5% probability level.

At the same time, pH 7.5 was found best for growth in BG11 medium (Figure 4). For most strains of cultured microalgae, pH tolerance lies between pH 7 and pH 9, while the optimal is reported to be pH 8.2 to pH 8.7 (Lavens and Sorgeloos, 1996). Although a high growth was recorded in BG11 medium at pH 7.5, at the same pH level, the growth was lower in the other two media (Figure 4).

Light intensity is a factor which appears to exert different effects in the field and in the laboratory (Allison, Hoover, and Morris, 1937). Intermittent illumination (16 hrs light : 8 hrs dark) did not give better yields than continuous illumination and blue-green algae does not appear to require a diurnal alteration of light and dark periods (Fogg et al., 1973).

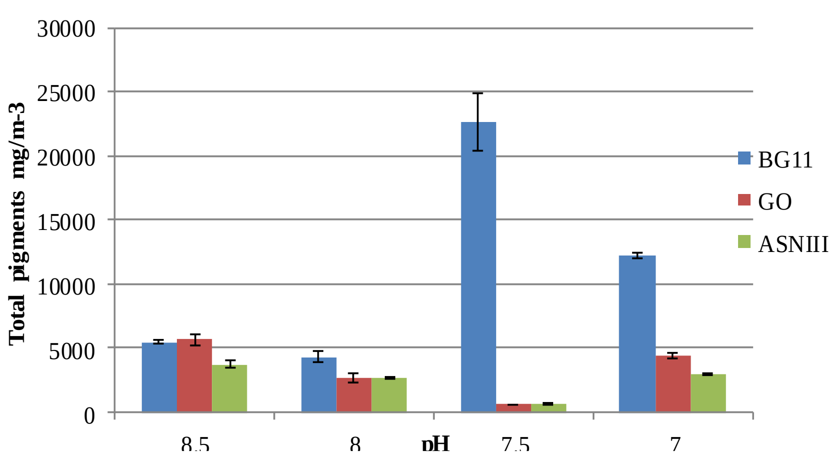


Figure 4: Amount of total pigments in three different media with 4 pH levels; 8.5, 8, 7.5, and 7.

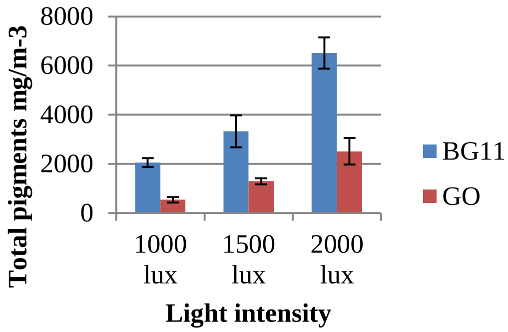


Figure 5: Total pigments of the two media with different light intensity levels.

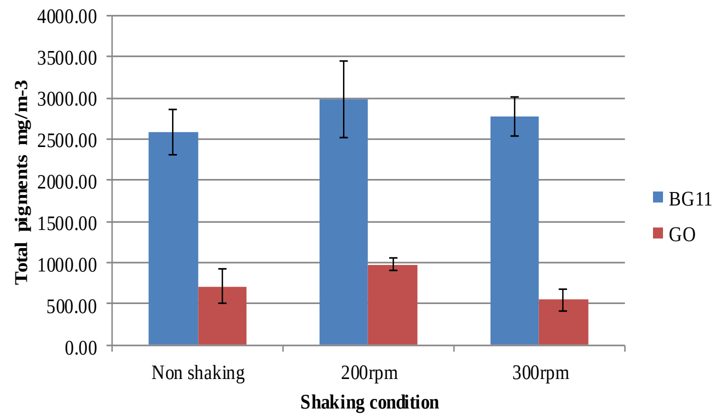


Figure 6: Total pigments of two media with three different shaking conditions.

Highest growth was recorded in 2000 lux light intensity for both BG11 and GO media. Lowest growth was recorded in 1000 lux light intensity (Figure 5). A different study carried out on cyanobacteria and micro algae culturing had used different light intensities. Amongst them, some studies carried out by Stanier et al. (1971), Kodandoor and Rajashekhar (2011), and Rayna Amer (2013) used 2000 lux to enhance the growth.To provide an even aeration to the culture, shaking is important because high growth rates and the good yield depend on an adequate supply of carbon dioxide and continuous removal of oxygen produced in photosynthesis. Highest growth was recorded at 200 rpm (Figure 6) but this shaking condition was not significantly different from the other treatments. In the present study, shaking was found to be effective in preventing sedimentation and clumping of cyanobacteria with the wall of the conical flask.

3.5 Morphological identification of monoculture

Six mono cultures were established by repeated sub culturing in both solid and liquid media which were identified as *Oscillatoria* sp., *Ankistrodesmus* sp., *Chroococcales* sp., *Anabaena* sp., *Arthrospira* sp. and *Spirulina* sp. Isolation procedures using solid media allowed for the selection of microorganisms with color, size and shape. But selection was very difficult in liquid media and was unsuccessful.

3.6 Fatty acid composition

Based on the highest dry biomass production, three strains *Oscillatoria* sp. *Anabaena* sp. and *Spirulina* sp. were selected for fatty acid analysis. Fatty acid was detected only in *Spirulina* sp. which was identified as Lauric acid (9.38%), Stearic acid (6.51%), Behenic acid (6.40%) and Lignoceric acid (8.41%). It was already reported that *Spirulina* contains 6-13% lipids half of which is total fatty acid (Vonshak, 1997). In another study, is has already been reported that cyanobacteria present in fresh water bodies are rich in different fatty acids ranging from C-12 to C-24 including the four which has been identified in the present study (Kodandoor Sharathchandra and Rajashekhar, 2011).

4. Conclusion

The present study revealed that BG11 supports best growth at the optimum pH of 7.5, under 2000 lux light intensity and 200 rpm rate of shaking. Addition of original water instead of distilled water during the initial sample preparation and use of vortex mixture with glass beads during isolation can be an effective technique to obtain a uni-algal culture (monoculture). A positive correlation was also observed between biomass and pigments in different growth conditions during this study. Out of the three species, only *Spirulina* sp. was found to contain fatty acids.

Acknowledgement

The authors would like to thank Mr. N.P. Athukorala, Ms. R.K.C. Karunaratne, Ms. I. Tumpale, Mr. A.K. Pathirana and Ms. R.S.M. Perera (Senior Staff Technical Officer) and Mr. Ekanayake (Research Assistant) for their support during sample collection, preparation, handling and experiments. Authors are also grateful to the EFE & GB nets, UK for providing planktonic nets, and the financial support from the Government of Sri Lanka Presidential Scholarships for Foreign Students-2014 to carry out the PhD degree of the first author.

References

Abou-Shanab, R.A., Hwang, J.H., Cho, Y., Min, B. and Jeon, B.H. 2011. Characterization of microalgal species isolated from fresh water bodies as a potential source for biodiesel production. *Applied Energy, 88*(10): 3300-3306.

Allison, F.E., Hoover, S.R., & Morris, H.J. 1937. Physiological studies with the nitrogen-fixing alga, Nostoc muscorum. *Botanical Gazette*, 433-463.

Chorus, E.I. and Bartram, J. 1999. Toxic cyanobacteria in water: a guide to their public health consequences, monitoring and management.

Desikachary, T. 1959. Cyanophyta. *Indian Council of Agricultural Research*. *New Delhi*.

Duong, V.T., Li, Y., Nowak, E. and Schenk, P.M. 2012. Microalgae isolation and selection for prospective biodiesel production. *Energies*, *5*(6): 1835-1849.

Fogg, G.E., Stewart, W.D.P., Fay, P. and Walsby, A.E. 1973. The Blue-Green Algae. *Academic Press- London and New York*, 1-459.

Halim, R., Harun, R., Webley, P. A., & Danquah, M. K. (2013). Bioprocess engineering aspects of biodiesel and bioethanol production from microalgae *Advanced Biofuels and Bioproducts,* Springer, New York, pp. 601-62.

Kodandoor, S., and Rajashekhar, M. 2011. Fatty acid composition in some fresh water cyanobacteria. *Journal of Algal biomass utilization., 2*(2): 83-97.

Korres, N.E., Singh, A., Nizami, A. S. and Murphy, J.D. 2010. Is grass biomethane a sustainable transport biofuel? *Biofuels, Bioproducts and Biorefining, 4*(3): 310-325.

Lavens, P. and Sorgeloos, P. 1996. *Manual on the production and use of live food for aquaculture*: Food and Agriculture Organization (FAO).

Mutanda, T., Ramesh, D., Karthikeyan, S., Kumari, S., Anandraj, A. and Bux, F. 2011. Bioprospecting for hyper-lipid producing microalgal strains for sustainable biofuel production. *Bioresource technology, 102*(1): 57-70.

Parmar, A., Singh, N.K., Pandey, A., Gnansounou, E. and Madamwar, D. 2011. Cyanobacteria and microalgae: a positive prospect for biofuels. *Bioresource technology*, *102*(22): 10163-10172.

Posten, C., and Schaub, G. 2009. Microalgae and terrestrial biomass as source for fuels—a process view. *Journal of biotechnology, 142*(1): 64-69.

Pulz, O. and Gross, W. 2004. Valuable products from biotechnology of microalgae. *Applied Microbiology and Biotechnology, 65*(6): 635-648.

Ranya A., Rehab, S., Saraa, S., Marwa, A.S., and Shaker, K. 2013. Isolation and Characterization of Cyanobacterial Community Including a Microcystin-Producing Nostoc sp. Strain in the Nile River, Egypt. *Advances in Microbiology, 3*(6A): 38-46. DOI:10.4236/aim.2013.36A005.

Rippka, R., Deruelles, J., Waterbury, J.B., Herdman, M. and Stanier, R.Y. 1979. Generic assignments, strain histories and properties of pure cultures of cyanobacteria. *Journal of General Microbiology, 111*(1): 1-61.

Rippka, R., Waterbury, J. B. and Stanier, R.Y. 1981. Isolation and purification of cyanobacteria: some general principles *The prokaryotes* (pp. 212-220): Springer.

Stanier, R., Kunisawa, R., Mandel, M. and Cohen-Bazire, G. 1971. Purification and properties of unicellular blue-green algae (Order Chroococcales). *Bacteriological Reviews, 35*(2): 171

Vonshak, A. 1997. *Spirulina platensis arthrospira: physiology, cell-biology and biotechnology*: CRC Press.

Yaniv, Z., Schafferman, D., Zur, M. and Shamir, I. 1996. Matthiola incana: Source of omega-3-linolenic acid. *Progress in new crops. ASHS Press, Alexandria, VA*, 368-372.

Suppression of Recombination Channels of Dye-Sensitized Solar Cells Made of SnO_2 Using Core Shell Structure of SiO_2 Extracted From Rice Husk

N.F. Ajward, D.L.N. Jayathilaka, J.C.N. Rajendra, V.P.S. Perera*

Department of Physics, Open University of Sri Lanka, Nawala, Nugegoda.

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Though Dye Sensitized solar Cells (DSSC) are one of the most promising types of solar cells many challenges are to be met to compete with current silicon solar cell technology. Suppression of recombination channels is one of the ways to improve the efficiency of DSSCs. Materials such as Al_2O_3, MgO, and ZrO_2 have been used previously as barrier layers in this regard. SiO_2 is also a good dielectric material which can be extracted from rice husk with high purity. It was evident that deposition of ultra thin layer of SiO_2 around SnO_2 particles increases the current and voltage of DSSCs improving the overall performance. But, dye absorption on the films decreased with the increment of SiO_2% that affected adversely.

Keywords: core shell structure, rice husk, dye-sensitized solar cells

1. Introduction

Dye Sensitized Solar Cells (DSSC) are one of the most promising types of solar cells for next generation of solar cell technology that has power conversion efficiency as high as 12% (Nazeeruddin et al., 2011). Compared with conventional silicon photovoltaics, DSSCs offer the cost savings in the materials and a range of solution deposition methods for device manufacture. However, there are still many challenges to be met before DSCs can truly compete with the current silicon solar cell technology. Device efficiency, stability and lifetimes and scalable methods for device fabrication are the key issues in this field of research. A lot of work has been done to improve efficiency of DSSCs taking different avenues, which includes increasing the surface area of the metal oxide semiconductor, developing new dyes with broad absorption spectra, suppressing the recombination channels and introducing light-scattering materials in the film.

Materials such as Al_2O_3, MgO, and ZrO_2 have been used previously as barrier layers in DSSCs, but there are no records available for the use of SiO_2 for the same purpose (Kay and Grätzel, 2002). But SiO_2 particles have been used to scatter light in TiO_2 films of DSScs.

In this research work we improved the performance of DSSCs by introducing thin barrier layer of SiO_2 surrounding the SnO_2 crystallite to prevent recombination of charge carriers in the diffusion assisted transportation. Here the thin barrier of insulating material enhance the lifetime of germinated charge carriers of DSSC to improve the efficiency.

2. Methodology

Rice Husk (RH) of BG 300 rice variety was collected and initially washed with tap water to remove soils and dirt. It was further washed with distilled water and dried at 120 ˚C. The dried RH was fully burnt to white ash at around 700˚C in a muffle furnace and the Rice Husk Ash (RHA) was collected.

2.1 Extraction of Silica

Aforementioned dried RHA was refluxed with 2M HCl and thoroughly washed with distilled water and dried. 10 g of the sample was stirred in 80 ml of 2.5 N sodium hydroxide solution. It was then boiled in a covered 250 ml Erlenmeyer flask for 3 hours and the solution was filtered using a Whatman No. 41 filter paper. Filtrate was allowed to cool down to room temperature and 5 N H_2SO_4 was added to it until it reaches pH 2. Then NH_4OH was added to the

**Correspondence: vpper@ou.ac.lk*
ISSN 2478-0669 Print

suspension until it reaches pH 8.5 and allowed to be at room temperature for 3.5 hours. The precipitated SiO_2 was separated by filtration and thoroughly washed with distilled water. The silica obtained was oven dried at 120 ^{0}C for 12 hours and allowed to cool down to room temperature.

2.2 Preparation of SnO_2 particles

Tin (IV) chloride was dissolved in distilled water to obtain a 0.5 M solution and ammonia was added stirring the solution to obtain fine particles of SnO_2. The SnO_2 particles were thoroughly washed with distilled water to remove chlorine ions. Then the particles were suspended in diluted ammonium solution for stabilization.

2.3 Preparation of SnO_2 and SiO_2 core shell structures

Tin (IV) Oxide particles were coated with an ultra thin layer of silica by the following method. 0.5g of SnO_2 particles was grinded in an agate mortar with 2 ml of ethanol. Then a measured amount of 0.5M sodium silicate which was prepared by dissolving extracted silica in NaOH was mixed with SnO_2 samples that has been prepared as described above. After that 1 ml of acetic acid was added drop wise to that mixture. Sodium silicates around the SnO_2 particles are expected to turn into SiO_2 in the process of acidification.

2.4 Fabrication of DSSC with SiO_2/SiO_2 composite

The paste as prepared was used to coat films on Conducting Tin Oxide (CTO) glass plates by the doctor blade method that cut into the size of 1.5 x 1 cm^2. Prior to coating the films on the CTO glass, they were thoroughly cleaned by detergent, distilled water and acetone with ultrasonic agitation. CTO plates coated with SnO_2/SiO_2 films were dried on a hot plate and heated up to 120 °C for 5 minutes. Then the films were sintered at 450 °C in a furnace for 30 minutes. When the films cooled down to room temperature they were immersed in Ru-bipyridyl N-719 dye solution (0.5 mM in ethanol) for 12 h. After the dye adsorption, films were rinsed with ethanol and sandwiched with platinum sputtered conducting glass substrates using clips. The capillary space in between the two plates of the cells were filled with electrolyte containing 0.5M potasium iodide, 0.05M iodine in a mixture of acetonitrile and ethylene carbonate 1:4 by volume.

2.5 Characterization techniques

I-V characteristics of the cells were measured under the illumination of 100 $mWcm^{-2}$ simulated light source and computer controlled setup consists of potentiostat/ galvanostat. Elemental analysis of RHA was done using Atomic Absorption Spectroscopy. X-ray diffraction (XRD) patterns and SEM images were also obtained for SnO_2/SiO_2 composite films.

3. Results

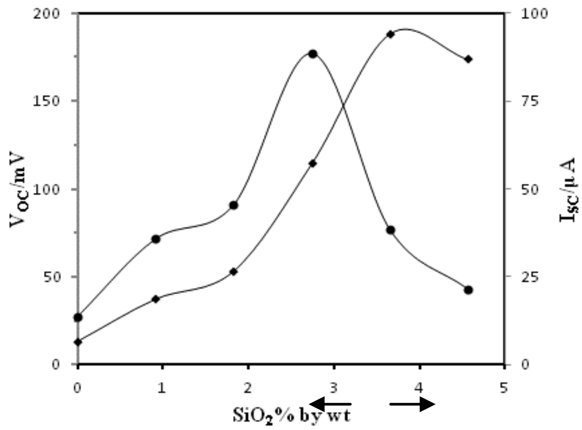
According to the literature reports, particle size of silica extracted from RH is in nano-range with least impurity levels. Elements that are present as impurities in RHA of BG 300 rice variety were analyzed with atomic absorption spectroscopy. Percentages of impurities in RHA after burning and refluxing with HCl are given in table 1.

Table 1: Percentages of impurities in RHA of BG 300 rice variety

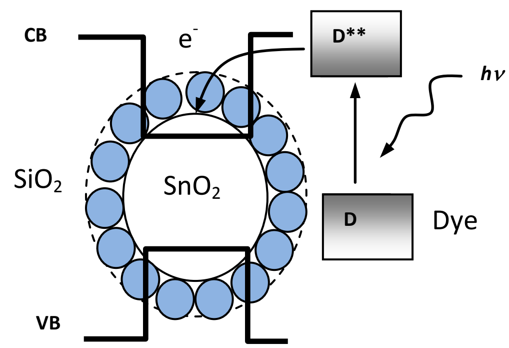
Impurities	% in RHA after burning	% in RHA after reflux with HCl
Calcium	0.926	0.402
Magnesium	0.537	0.198
Manganese	Not detected	Not detected
Ferrous	0.269	0.060

It is inferred from these results that the impurity level of RHA is low and can be reduced further by refluxing with HCl. That is because these impurities present in the RHA as oxides can be removed easily by acid wash.

In this study we have investigated the possibility of using a thin barrier of SiO2 around the SnO_2 particles to impede leakage of electrons undergo recombination processes which is one approach to increase the efficiency of DSSCs. Figure 1(a) shows the measured open-circuit photo-voltage (Voc) and short-circuit photocurrent (Isc) of DSSCs with different SiO_2% by weight in the SnO_2/SiO_2 films



(a)

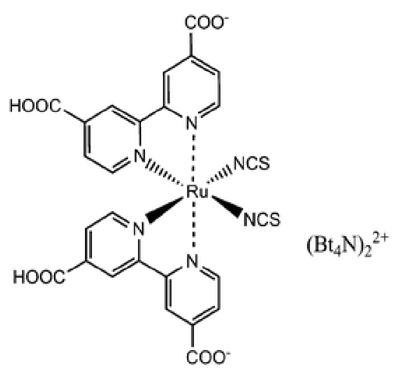


(b)

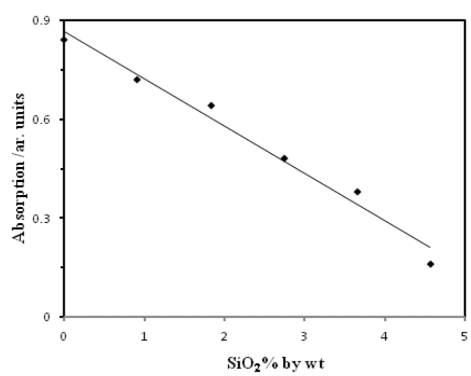
Figure 1: (a) Open-circuit photovoltage (V_{oc}) and short-circuit photocurrent (I_{sc}) of DSSCs with different SiO_2 % in SnO_2 films (b) Suppression of recombination of injected electrons in the conduction band of SnO_2 by SiO_2 shell.

Initial increment of SiO_2 % in the film gradually covers the SnO_2 particles as an ultra thin layer and beyond certain limit of SiO_2 contributes to the growth of the SiO_2 layer around the SnO_2 particles increasing the thickness. This is the reason why both the Isc as well as the Voc increase initially with the increment of SiO_2 % in the SnO_2 films of DSSCs. The increment of Isc and Voc is attributed to the suppression of recombination of injected electrons by the photo excitation of the dye in the conduction band of SnO_2 due to the development of the ultra thin layer of SiO_2 around SnO_2 particles (Figure 1b). The highest photocurrent of DSSCs with the addition of 2.5 % of SiO_2 may have been achieved due to the perfect coverage of SnO_2 particles with ultra thin layer of SiO_2. But Voc continues to increase further up to 4% of SiO_2 in SnO_2 films. It is noticeable that the decrement of Voc afterward is not significant that as the Isc reaching the maximum. Anyway further increment of the thickness of the ultra thin layer of SiO_2 reduces both the Isc and Voc.

The amount of dye adsorbed on the semiconductor film is also a detrimental factor on the performance of DSSCs. We have noticed that the dye absorbed on SnO_2 films decreased with the increment of SiO_2%. To quantitatively analyze it, we have desorbed the dye adsorbed on SnO_2 films with different SiO_2 %. This was done by allowing the films to adsorb the dye for a predetermined period and completely desorbing the dye by immersing the dye adsorbed SnO_2 films in a known volume of 0.5 M KOH solution. The concentration of the dye in the KOH solution was estimated spectroscopically at the wave length of 550 nm. Figure 2 given bellow shows the deviation of dye adsorbed on SnO_2 films for different SiO_2 %.



(a)



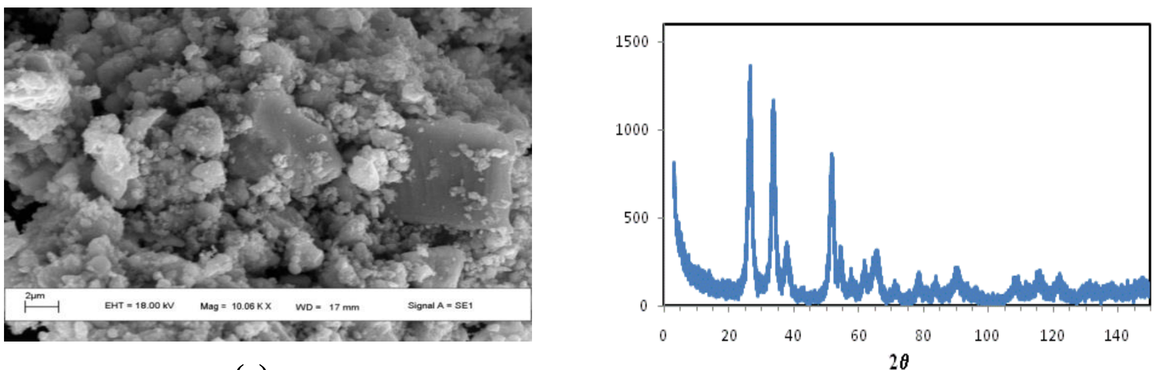
(b)

Figure 2: (a) Variation of dye adsorbed on SnO_2 films for different SiO_2 % and (b) structure of the N-719 dye.

It is evident from the Figure 2 that the dye adsorption on SnO_2 films decrease with the increment of SiO_2 %. This may affect adversely on photocurrent of DSSCs. Although dye aggregations on semiconductor films also result in decreasing photocurrent there should be sufficient amount of dye adsorbed on SnO_2 crystallites for efficient operation of DSSCs. The decrement of Isc at higher SiO_2 percentages is the main consequence of low dye adsorption on SnO_2 films. The adsorption of dye on SnO_2 films decrease with the increment of SiO_2 % because of the acidity of SiO_2 which prevent chelation of N-719 dye on SnO_2 films by the carboxylic groups.

XRD and SEM analysis was also carried out to characterize the SiO_2 ultra thin layer coated on SnO_2 particles. Figure 3 shows the SEM of SnO_2 film with 4.5% of SiO_2. The resolution of the SEM images was not sufficient to identify the SiO_2 thin layer. But it can be seen that the SnO_2 particles are distributed in a wide range of particle sizes which also affect adversely on the performance of DSSCs.

The XRD pattern of the SnO_2 film with 4.5 % of SiO_2 is given in Figure 3(b). No peaks appeared for SiO_2 in the XRD pattern of the SnO_2 films as well. The insertion in the Figure 3(b) is the XRD obtain for SiO_2 powder obtained by acidification of Na_2SiO_3 with acetic acid and sintering at 450 °C for 30 minutes. It is found to be in amorphous form and most probably the SiO_2 around the SnO_2 is also amorphous. Because of the amorphous nature of SiO_2 and low percentage might produce significant peaks for SiO_2 in the XRD pattern.



(a) (b)

Figure 3: (a) SEM image of SnO_2 film with 4.5% of SiO_2 (b) XRD pattern of the SnO_2 film with 4.5 % of SiO_2. Insertion is the XRD obtain only for SiO_2 powder.

4. Conclusion

The silica extracted from rice husk is with low impurity levels suitable for coating ultra thin layers of SiO_2 around SnO_2 to fabricate DSSCs. Deposition of ultra thin layer of SiO_2 on SnO_2 particles improved the performance of DSSCs. The reason for decrement of cell performance with higher percentages of SiO_2 is not only due to the barrier thickness, but also due to the low dye adsorption. It was observed by the SEM images that the particle size of SnO_2 is widely diverse because of particle aggregation. It is recommended to use uniform size of SnO_2 particles for better performance of DSSCs. Some chemical treatment is also required to enhance the adsorption of dye on SiO_2 ultra thin layer deposited on SnO_2 particles.

References

Kay, A. and Grätzel, M. 2002. Dye-Sensitized Core−Shell Nanocrystals: Improved Efficiency of Mesoporous Tin Oxide Electrodes Coated with a Thin Layer of an Insulating Oxide; *Chem. Mater. 14* (7): 2930-2935.

Nazeeruddin, M. K., Baranoff, E. and Gratzel, M. 2011. Dye-sensitized solar cells: A brief overview; Solar Energy 85: 1172-1178.

Feasibility of Biodiesel Production from Waste Cooking Oils in Sri Lanka

L.M.S.D. Perera*

University of Moratuwa

Date Received: 22-11-2014 Date Accepted: 29-04-2015

Abstract

Biodiesel is an environmental friendly and very attractive alternative fuel for Sri Lanka, a country that solely relies on imported petroleum fuel for transportation. However, biodiesel production from edible oils is not practicable due to limitation of agricultural land in Sri Lanka, even though it is considered as the main resource for world biodiesel production. Biodiesel production from non-edible oils is another way of solving this problem. There are three types of non-edible feedstocks that could be used for biodiesel production; oil extracted from non-edible vegetable crops, animal fat/waste cooking oil and microalgae oil. The main constraint associated with the non edible oils is the high amount of Free Fatty Acids (FFA) in the oil and this cause problems during conventional transesterification reaction. Waste Cooking Oil (WCO) is one of the non-edible oils recognized as a potential non edible feedstock worldwide. The availability of WCO in Sri Lanka and the potential biodiesel production is estimated from this study.

Keywords: biodiesel, high FFA, non-edible oils, transesterification, WCO

1. Introduction

Biodiesel is considered as the most promising alternative for petroleum-derived diesel (Dub, M. and Kates, 2003; Atadashi, M.K., Abdul A. and Sulaiman, 2013) which can be used without significant modification to the engines (Kumar, 2007). Compared to petroleum derived diesel it has many merits because biodiesel is nontoxic, biodegradable and has negligible sulfur content, superior flash point and higher combustion efficiency (Atadashi, M.K., Abdul A., and Sulaiman, 2013; Atabani, et al., 2012; Padhi and Singh, 2011).The current primary energy supply in Sri Lanka comprises of biomass, petroleum, coal, major hydro and new renewable energy. Figure 1 shows contribution of various energy sources in Sri Lanka.

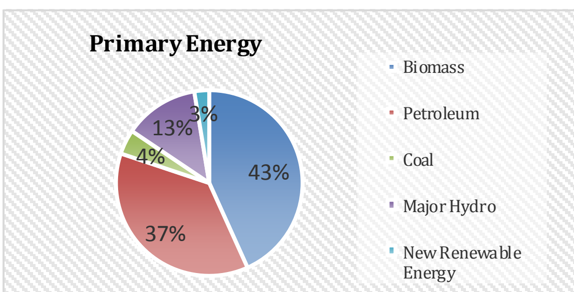


Figure 1: Primary energy distribution of Sri Lanka

Figure 1 shows that the contribution from petroleum for supply of primary energy is very significant and in 2012 and 2013 the total consumption of petroleum products in Sri Lanka were 5219.6 kTOE and 4102.5 kTOE respectively (Sri Lanka Sustainable Energy Authority, 2014). The monetary values of these petroleum imports are extremely high and as such affect the Sri Lankan economy in a large scale. Therefore, introduction of renewable fuel such as biodiesel is really important. However, the existing government policy of not utilizing any food crops for producing biofuels changed the directives towards usage of non-edible feedstocks for the production of biodiesel in Sri Lanka.

* *Correspondence: sujanidarshika@gmail.com*
ISSN 2478-0669 Print

Transport is the most important sector as far as liquid petroleum is concerned as almost all the vehicles in Sri Lanka are powered by either diesel or gasoline. The forecasted diesel consumption in transport sector is estimated from a regression analysis as shown in figure 2.

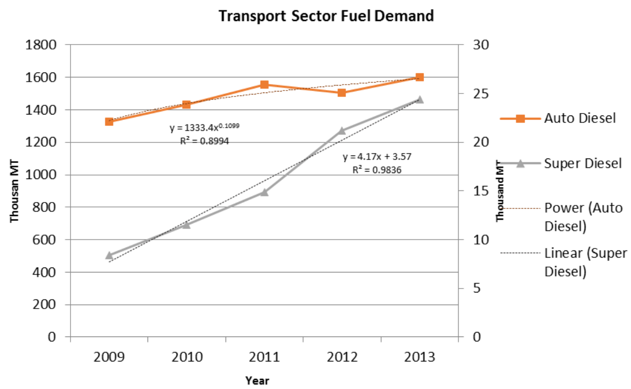


Figure 2: Forecasting of diesel demand for transport sector

According to the analysis biodiesel production of 360,000 MT will be required to substitute 20% of the total diesel requirement of the country by year 2020.

2. Biodiesel production process

Vegetable oils are not suitable for direct use in diesel engines due to its high viscosity. Therefore, different methods such as micro emulsion, pyrolysis and transesterfication are used for the rectification of high viscosity problem. Out of all, transesterification is the most commonly used method for commercial scale biodiesel production (Leung, Wu and Leung, 2010).

2.1 Biodiesel production from non edible oils

In the transesterfication process triglyceride (fat/oil) reacts with an alcohol and forms esters and glycerol in the presence of a catalysts as shown in figure 3 (Atadashi, M.K., Abdul A. and Sulaiman, 2013).

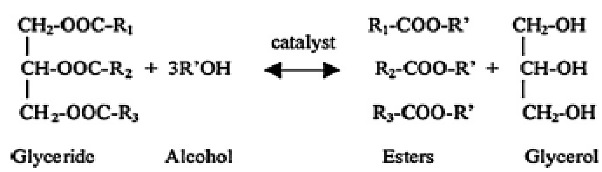


Figure 3: Transesterification reaction of triglycerides

The role of the catalysts is important in this process (Atadashi, M.K., Abdul A. and Sulaiman, 2013) as it improves the surface contact and consequently reaction rates and biodiesel yield. Generally, alkalis, acids, or enzymes are used as catalysts (Ma and Hanna, 1999) and alkaline catalysts are the most commonly used catalysts for the commercial scale biodiesel production (I.M. Atadashi, 2012).

Most of the non-edible oil contains high FFA, which causes difficulties during the trasestrification reaction. The general alkaline catalyszed transesterification is not effective when high FFA is present in the oil because the reaction between FFA and alkali catalysts form soap and inhibit the effectiveness of the separation of glycerol from methyl esters. In addition, it consumes the catalysts and gives only a low yield (Bankovi, Stamenkovi and Veljkovi, 2012; Alptekin, Canakci and Sanli, 2014). FFA level of less than 0.5-3.0% is recommended by various reserchers for alkali catalyszed transesterification (Lotero, Liu, Lopez, Suwannakarn, Bruce and Goodwin, 2005; Demirbas, 2009; Ma and Hanna, 1999; Berchmans and Hirata, 2007; Leung, Wu, and Leung, 2010; Meher, Sagar, and Naik, 2006) Alternatively, acid catalysts can be used to treat FFA as it is less susceptible to the presence of FFA in the oil (Lotero, Liu, Lopez, Suwannakarn, Bruce and Goodwin, 2005). However, acid catalyzed transesterfication is 4000 times slower than base catalyzed transesterfication (Lotero, Liu, Lopez, Suwannakarn, Bruce, and Goodwin, 2005; Wang, Hanna, Zhou, Bhadury, Chen and Song, 2011). Therefore, use of acid catalysts alone is less attractive for industrial purposes (Zhang, Dub, McLean and Kates, 2003).

To over come this problem, most of the researchers suggested a two-step process for feedstocks having FFA contents (Omar, Nordin, Mohamed and Amin, N.A.S., 2009). This process consists of an acid catalyzed FFA esterification reaction which is also called as pretreatment and base catalyzed triglyceride transesterification reaction (Bankovi, Stamenkovi and Veljkovi, 2012). Therefore, this method is suitable for biodiesel production from WCO as well.

3. Potential of biodiesel production from waste cooking oils in Sri Lanka

Waste cooking oil (WCO) is one of the non-edible oils identified as a potential low cost feedstock for biodiesel production in many countries. Conformity of the fuel properties with the accepted standards, most commonly ASTM D 6751 & EN 14214 and the engine performances have also been checked with respect to the biodiesel produced from WCO (Al-Widyan, et al., 2002; Chhetri, et al., 2008).

Therefore, biodiesel production from waste cooking oil is an attractive option for Sri Lanka as well. This is because unlike other non-edible vegetable crops it doesn't require any dedicated cultivation. On the other hand, use of waste oil as a biodiesel feedstock solves the problem of waste oil disposal. Nevertheless, reuse of waste oil as a food or industrial raw material is the most common current practice in Sri Lanka although the waste oil consumption is not recommended due to many health hazards (Hanisah, Kumar and Tajul, 2013).

Cooking oil produces toxic compounds such as peroxides, aldehyde and polymer when it is used for several times (Hanisah, Kumar and Tajul, 2013) and at the same time strange flavors and odors can be produced. These contaminated oils may contain carcinogenic free radicals that severely affect health. Therefore, use of WCO as a biodiesel feedstock solves both environmental and health related problems associated with waste oil.

Table 1: Volume of imported edible oils

Year	Volume in MT							
	Coconut oil	Palm Stearin	Palm Olein	Crude Palm Oil	Palm kernel	Tallow	Soya and Sunflower	Other
2009	802	2,822	26,084	20,750	1,582	4,529	441	12,441
2010	2,080	5,500	53,519	15,299	925	3,155	685	13,179

(Source: Monthly Bulletin, CDA in 2010)

3.1 Types of oil used in Sri Lanka

The most commonly produced edible oil in Sri Lanka is coconut oil. Approximately 97% of the coconut oil production is consumed within the country and rest is exported. Same time, small amount of coconut oil is imported with the other vegetable oils. Palm oil is the other developing trend in Sri Lanka having a production of 12,700 MT and 12,300 MT in year 2009 and 2010 respectively (Coconut Development Authority, 2010). Rest of the country's demand is fulfilled by the importation of various kinds of vegetable oils. According to statistics shown in table 1, palm based oils and coconut oils are the most commonly used oils in Sri Lanka.

It is assumed that 100% of the local palm oil is consumed as crude palm oil and no major oil production is taking place other than coconut oil and palm oil in Sri Lanka. Thus, the consumption pattern of the edible oil in year 2010 can be shown as figure 4.

3.2 Availability of WCO as a feedstock

Oil is used for domestic cooking in almost all the households, restaurants and hotels in Sri Lanka. However, in Sri Lanka, the average monthly waste cooking oil generation per household is very low. Therefore, collection of WCO from households cannot be taken as a viable option due to the low quantity generated and due to cumbersome collecting procedures.

Therefore, one of the best options is to collect it from hotels and restaurants available in Sri Lanka. This is a sustainable source of WCO as the tourism industry is highly promoted in the country and also a rapid growth in this sector is also anticipated. This is confirmed according to the figure 5 as it shows rapid growth in tourist arrival to Sri Lanka during the years 2010 to 2013 and hotels registered under Sri Lanka Tourism Development Authority showed 70% occupancy rate in year 2012 distributed in all the regions except in the Northern region.

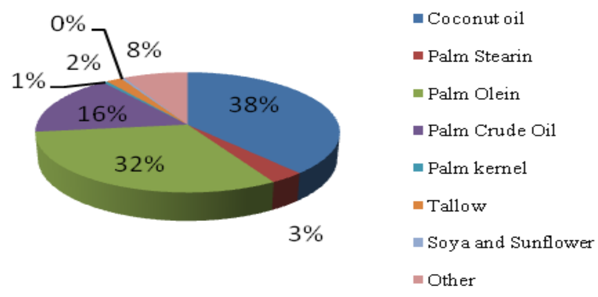


Figure 4: Consumption pattern of edible oils in Sri Lanka

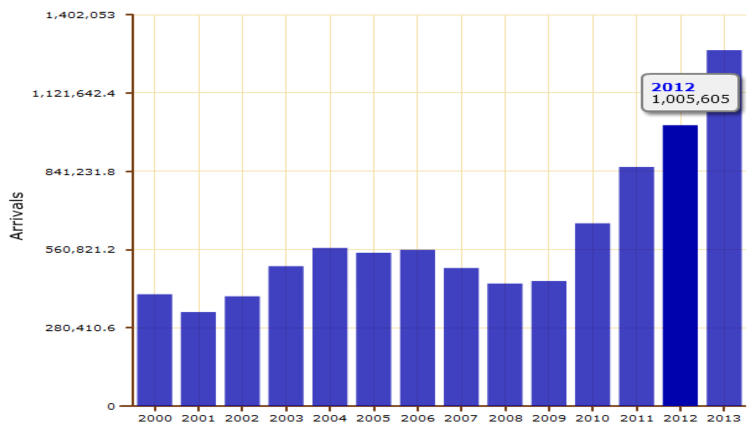


Figure 5: Tourist arrivals to Sri Lanka from 2000-2013

Therefore, country's hotel industry booms due to tourist arrivals and local customers. As occupancy rate of the hotels increases, the WCO generation also increases. Another advantage is that they are located as clusters as indicated by the figure 6 in most attractive places in Sri Lanka. Therefore, collection of waste cooking oil from hotels is easier than collecting from households. Further, WCO from the hotel sector is obtainable throughout the year though some seasonal variations are observed.

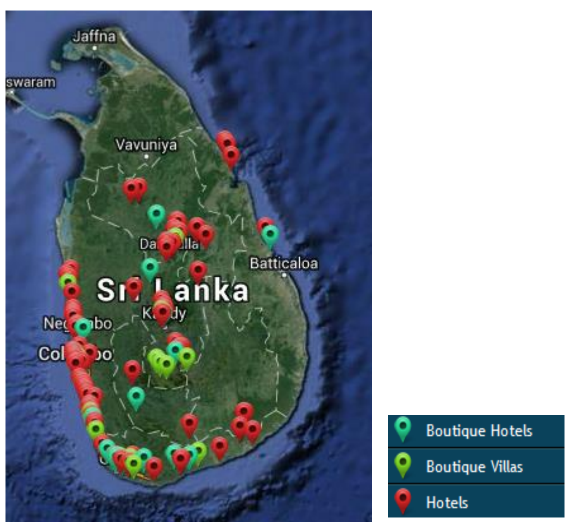


Figure 6: Distribution of different types of hotels/villas in Sri Lanka

The expected WCO generation was calculated based on the number of accomadation establishments and the number of rooms in Sri Lanka.

There are varieties of lodging establishments such as hotels, boutique hotels, boutique villas, guest houses, bungalows etc. However, in this analysis hotels and boutique hotels registered under the Sri Lanka Tourism Development Authority are taken in to consideration as the most viable options because their capacities in terms of rooms are higher. Therefore, generation of WCO per entity is assumed to be greater compared to other small-scale facilities.

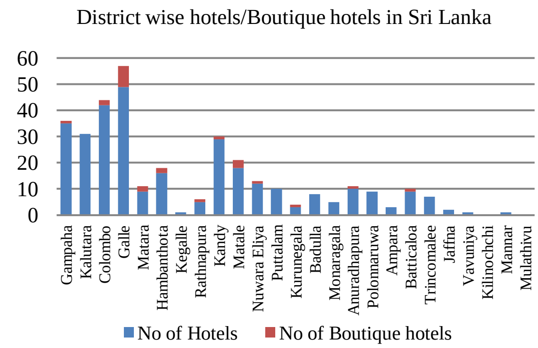


Figure 7: District wise distribution of registered hotels/boutique hotels

Figure 7 shows the district wise distribution of the registered hotels and boutique hotels in Sri Lanka. Most of these establishments are located in Galle, Colombo, Gampaha, Kalutara and Kandy. Average waste oil generation per room is being taken as the most appropriate basis for the estimation of potential waste oil generation from the two categories of hotels. It was calculated based on the actual waste cooking oil generation data collected from different hotels (table 2) in Sri Lanka and the table 3 shows the calculated average waste cooking generation per room based on the data of five hotels.

The density of waste cooking oil is reported as 0.92 g/cm^3 approximately at 15℃ (Sanli, Mustafa and Alptekin, 2011). Therefore, the total waste oil production per annum is 704 MT for 18,537 hotel rooms.

The biodiesel yield achieved from WCO are reported as 97.02% at 5h reaction (Gui, Lee and Bhatia, 2008) and, 94.5% (Chhetri, Watts and Islam, 2008) and 97% (Issariyakul, Kulkarni, Dalai and Bakhshi, 2006) in different studies. Therefore, it is assumed that 95% yield can be achieved from conversion of WCO to biodiesel. Thus, the estimated biodiesel production per annum is 669 MT from WCO collected from the said two establishment categories.

Table 2: Actual waste oil generation of hotels

Hotel No	No of rooms	Waste oil generation											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	120	400	290	390	360	370	350	400	400	320	370	290	480
2	83	230	210	250	250	220	190	200	200	210	240	230	250
3	78	310	260	250	270	260	220	280	290	150	430	310	280
4	55	140	130	200	130	160	130	170	310	250	310	190	290
5	12	20	-	-	20	10	20	10	10	20	20	20	10
6	56	210	120	160	160	140	170	90	130	120	130	100	130

The expected biodiesel production from waste cooking oil generated from said categories is not much significant. However, there are large numbers of restaurants in the country, which generate significant amounts of waste cooking oils collectively depending on the number of sales/customers and the types of the food offered. Another favorable fact is that, the estimation is for the 71% occupancy rate in hotels and there is a provision to increase WCO generation with the increase of occupancy rate.

In contrast, collection of oil from these facilities would be difficult because most of the recognized hotels sell their waste cooking oils for reuse purposes while some are using for their own lamps and boilers with biomass. Waste oils are mainly sold for clay tile manufacturers to use in their furnace and for soap manufacturing and that could reduce the availability of the waste cooking oil as biodiesel feedstock. Therefore, the biggest problem with the biodiesel production from WCO is its unavailability due to other industrial applications.

Table 3: Average waste oil generation per room

Hotel No	Oil consumption / room (kg)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	3	2	3	3	3	3	3	3	3	3	2	4
2	3	3	3	3	3	2	2	2	3	3	3	3
3	4	3	3	3	3	3	4	4	2	6	4	4
4	3	2	4	2	3	2	3	6	5	6	3	5
6	4	2	3	3	3	3	2	2	2	2	2	2
Average	3	3	3	3	3	3	3	3	3	4	3	4

4. Biodiesel production facilities and economies of biodiesel production

District wise biodiesel production from WCO can be estimated based on the district wise distribution of hotels and it is tabulated in table 4. Colombo, Galle, Kalutara, Gampaha and Kandy have the highest potential of biodiesel production from WCO. However, this quantity represents only about 0.14% of the daily diesel consumption of the country. Therefore, setting up of dedicated biodiesel production facilities for WCO is not economical.

There are some advantages associated with WCO biodiesel production because unlike other non-edible crops, no extraction step is being involved in the production process though a physical pretreatment is needed for the removal of impurities in the oil. Collection of oil is also less problematic and less costly due to minor involvement of transportation.

Table 4: District wise estimated biodiesel production

No	District	Estimated biodiesel production (MT)
1	Gampaha	62
2	Kalutara	89
3	Colombo	156
4	Galle	99
5	Matara	13
6	Hambanthota	25
7	Kegalle	0
8	Rathnapura	7
9	Kandy	56
10	Matale	40
11	Nuwara Eliya	22
12	Puttalam	22
13	Kurunegala	2
14	Badulla	7
15	Monaragala	6
16	Anuradhapura	15
17	Polonnaruwa	15
18	Ampara	2
19	Batticaloa	18
20	Trincomalee	11
21	Jaffna	1
22	Vavuniya	1
23	Kilinochchi	-
24	Mannar	0
25	Mulathivu	-
	Total	669

4.1 Economies of biodiesel production from WCO

The expected unit cost of biodiesel is important for the economic viability of the biodiesel production from WCO. The price of the waste oil depends on the supplier and the quality of the oil. Some entities sell their waste oils at an average price of Rs.20-22 per liter and it is found that one entity is selling reused but filtered 20 liter can of oil tin at a price of Rs. 1500. Some hotels sell their waste oil at zero prices due to high impurities in the oil. However, there will be a market price if the biodiesel production commences in the country and it will encourage hotels to sell their waste oil and earn an additional income.
The other raw material prices in the Sri Lankan market are shown the table 5.

Table 5: Price of chemicals

No	Chemical	Price
1	Methanol	Rs. 200-240/ liter
2	KOH	Rs. 275-400 /kg /Rs. 360/liter
3	NaOH	Rs. 80-100/kg
4	H_2SO_4	Rs. 75-220/liter

The listed chemical prices indicate that the unit cost of biodiesel production will be higher than the current price of petroleum diesel and it makes biodiesel production from WCO economically unviable.

However, there will be an economic benefit to the country due to reduction of petroleum product imports. Even though the production of WCO biodiesel is low in terms of quantity, the estimated total saving from imports is about Rs. 48,780,225 per annum.The employment opportunities created through the production of biodiesel is also to be considered.

5. Conclusion and Recommendation

WCO is a proven alternative non-edible feedstock for the biodiesel production. However, the availability of WCO as a feedstock in Sri Lanka is negligible and not economically viable due to high production cost with respect to the present context. Nevertheless, there are some other benefits from WCO biodiesel production such as proper methods of waste oil disposal, reduction of health hazards due to reduction of waste oil reuse, less dependency on imported fuel, saving on foreign exchange, employment opportunities for local communities and reduction of Green House Gases (GHG).

References

Alptekin, E., Canakci, M. and Sanli, H. 2014. Biodiesel production from vegetable oil and waste animal fats in a pilot plant.

Atabani, A., Silitonga, A.S., Ong, H.C., Mahlia, T.M.I., Masjuki, H.H. and Anjum Badruddin, I. 2012. Non-edible vegetable oils :A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renewable and Sustainable Energy Reviews,* 18: 211-245.

Atadashi, I., M.K., A., Abdul Aziz, A., & Sulaiman, N. 2013. The effects of catalysts in biodiesel production: A review. *Renewable and Sustainable Energy Reviews, 19*, 3456– 3470.

Bankovi, I. B., Stamenkovi, O.S. and Veljkovi, V.B. 2012. Biodiesel production from non-edible plant oils. *Renewable and Sustainable Energy Reviews, 16*: 3621-3647.

Berchmans, H.J. and Hirata, S. 2007. Biodiesel production from crude Jatropha curcas L. seed oil with a high content of free fatty acids.

Chhetri, A.B., Watts, K.C. and Islam, M.R. 2008. Waste Cooking Oil as an Alternate Feedstock for Biodiesel Production . *Energies*, 3-18.

Coconut Development Authority. 2010. Monthly bulletin.

Demirbas, A. 2009. Energy Conversion and Management.

Dub, Y.Z., McLean, D. and Kates, M. 2003. Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. *Bioresource Technology*, 229-240.

Gui, M., Lee, K. and Bhatia, S. 2008. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. *Energy*, 1646-1653.

I.M. Atadashi, M. A. 2012. Production of biodiesel using high free fatty acid feedstocks. *Renewable and Sustainable Energy Reviews*, 3275-3285.

Issariyakul, T., Kulkarni, M.G., Dalai, A. K. and Bakhshi, N.N. 2006. Production of biodiesel from waste fryer grease using mixed methanol/ethanol system. *Fuel Processing Technology*, 429-436.

Kumar, N. 2007. Production of biodiesel from high FFA rice bran oil and its utilization in a small capacity diesel engine. *Scientific and Industrial Research*, 399-402.

Leung, D., Wu, X. and Leung, M. 201). A review on biodieselproduction using catalyzed transesterification. *84*(4); 1083-1095.

Lotero, E., Liu, Y., Lopez, D.E., Suwannakarn, K., Bruce, D.A. and Goodwin, J.G. 2005. Synthesis of Biodiesel via Acid Catalysis.

Ma, F. and Hanna, M. 1999. Biodiesel Production : a Review. *70*(1).

Meher, L., Sagar, D. and Naik, S. 2006. Technical aspects of biodiesel production by transesterification - a review. *10*.

Omar, W.W., Nordin, N., Mohamed, M. and Amin, N.A.S. 2009. A two step biodiesel production from waste cooking oil : Optimization of pre treatment step. *Journal of Applied Sciences*, 3098-3103.

Padhi, S.K. and Singh, R.K. 2011. Non-edible oils as the potential source for the production of biodiesel in India: A review. *Journal of Chemical and Pharmaceutical Research*, 39-49.

Sanli, H., M.C. and Alptekin, E. 2011. Characterization of Waste Frying Oils Obtained from Different Facilities. *Bioenergy Technology*.

Sri Lanka Sustainable Energy Authority. 2014. *Sri Lanka Energy Balance 2013*. Sri Lanka Sustainable Energy Authority.

Wang, R., Hanna, M.A., Zhou, W.W., Bhadury, P.S., Chen, Q. and Song, B.A. 2011. Production and selected fuel properties of biodiesel from promising non-edible oils:Euphorbia lathyrisL.,Sapium sebiferumL. andJatropha curcas L. *Bioresource Technology*, 1194-1199.

Zhang, Y., Dub, M., McLean, D. and Kates, M. 2003. Biodiesel production from waste cooking oil: 1. Process design and technological assessment. *Bioresource Technology*.

Power Quality Analysis of Grid Connected Wind Power Plants in Puttalam Area: A Case Study

T.L.B. Attanayaka*, V.G.R.G. Jayawardane, G.B. Alahendra, P.A.G.S. Abeynayake K.A.M.N. Pathiratne, H.M. Wijekoon

Ceylon Electricity Board

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Power Quality is a major aspect of any power system. Therefore, identifying Power Quality issues is important for utilities. Continuous addition of wind power generation to the electrical network influence power quality in a very specific manner. At Present a total installed capacity of 100MW of Wind Power in Puttalam area is connected to the Sri Lankan national grid. A grid connected wind power plant should adhere to the power quality requirements stipulated in The CEB Grid connection requirement for Wind Power Plants – Addendum to the CEB guide for Grid Interconnection of Embedded Generators, December 2000. However there exists, power quality issues such as voltage and current distortions created by harmonics, Voltage Flicker which violates the Grid Code. This study investigates power quality issues related to integrated wind power plants at Puttalam Area.

Keywords: wind power plant, power quality analysis

1. Introduction

During the commissioning stage of any wind power plant (WPP) it should follow the guidelines and regulatory requirements enforced by the state power regulatory body. Although it passes through all test certifications, continuous monitoring of power quality (PQ) from wind power plants is important. The most important point is the point of interconnection that provides a gateway for the wind power plant to the real world. After the commissioning, there is no such practice or guideline for continuous monitoring of power quality at wind connected bus bars. In Sri Lanka, as a nation with over 98% electrification it is very important to observe major power quality issues with regard to larger integration of WPPs. This will ensure quality electricity supply to consumers at all time.

The term power quality is defined as a set of parameters defining the properties of the power supply as delivered to the user at normal operating conditions in terms of continuity of supply and characteristics of voltage and frequency. Connecting wind power plants may create power quality issues which affects the performance of the power system. There are various standards such as IEEE 519 and IEC 61000-3-3 to monitor the power quality. PQ parameters are frequency, magnitude of supply voltage, Flicker, events (dips, swells, and interruptions), transients, unbalance, harmonics, inter-harmonic, and rapid voltage changes. In this study both standards were followed before arriving at a final conclusion. Further IEEE Recommended Practice for Monitoring Electric Power Quality (IEEE 1159) guidelines were followed in data logging, which will be discussed in the latter part of the text in detail.

In year 2010 General Manager (CEB) has appointed a committee to conduct a detailed study and to identify the power quality issues due to integration of wind plants at Puttalam GSS since rapid voltage fluctuations in AVR of the transformer no.1 of the Puttalam GSS were observed. In the above study it was identified that the harmonics were generated by wind plants connected to Puttalam GSS and it was recommended to install additional filters to filter out the harmonics generated by converters of the Wind Farm.

This research is a flash-back of the above study i.e reinvestigating the power quality related issues due to Grid Connected wind power plants in Puttalam area. The wind measurements were taken at 132kV/33kV Puttalam GSS and

* *Correspondence: eetrp1@ceb.lk*
ISSN 2478-0669 Print

220kV/33kV Wind GSS at Norachcholai (which was not in operation at the time of the initial study) during high wind (May-July) and low wind (February-March) periods of the year 2014.

2. Methodology

Initially, a literature review was carried out referring International and Local publications on Power Quality issues related to wind power. Emphasis was given on IEC and IEEE standards on power quality issues and power quality measurements. Standards IEEE Std 1159, IEEE Std 519, IEC 61000-4-7, IEC 61000-4-30 and IEC 61000-3-3 were followed for data collection and analysis.

Fluke 435 Power Quality Analyzer which meets the standards was used for data logging and Fluke Power Log Version 2.9.2 software was used for data retrieving and analysis. Data was collected as per the table 1 at two locations during the two main seasons, high wind and low wind.

Table 1: Summary of data logging

PQ Analyzer connected date	Name of the GSS	Connection Point	Measurement Period	Resolution
14-Mar-2014	Puttalam	1	14-15 Mar	30 sec
		2	14-15 Mar	30 sec
20-Mar-2014	Puttalam	1	20-31 Mar	5 min
		2	20 Mar to 6 April	5 min
22-May-2014	Norachcholai	3	22-24 May	1 min
27-June-2014	Puttalam	1	27-June to 08-July	5 min

- Transformer No. 03 – Seguwantivu and Vidatamunai 20MW wind park
- Transformer No. 01 – Mampuri (Senok) 10MW wind plant
- Wind connected Transformer at Norochcholai (60MW)

Single line diagrams with connection points are shown in Figure 1 (a) and (b). All the measurements were taken at the metering connection point of each transformer. Collected data was analyzed using Power Log software in order to identify the harmonics distortion (check THD limits), and other related power quality issues mentioned above. The *Addendum to the CEB guide for Grid Interconnection of Embedded Generators* explains the following power quality limits that need to be adhered by the wind power plant operators.

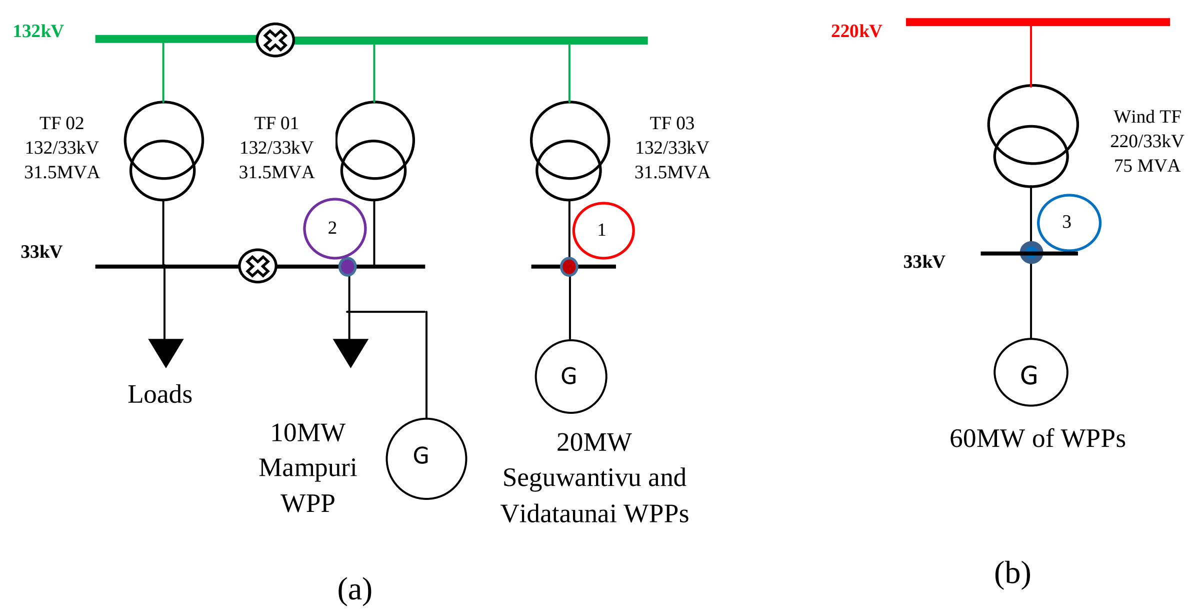


Figure 1: (a) Puttalam Grid Substation Single Line Diagram,
. (b) Norochcholai Wind connected Grid Substation Single Line Diagram

2.1 Harmonics

Relevant emission limits as per IEC 61800-3 are tabulated below.

Table 2: Emission limits as per IEC 61800-3

Harmonic Order	Odd Harmonic Current (% of I rated)	Even Harmonic Current (% of I rated)
n <11	4.0	1.0
11≤n<17	2.0	0.5
17≤n<23	1.5	0.4
23≤n<35	0.6	0.2
35≤n<50	0.3	0.1
THD ≤ 5% (for n=40)		

2.2 Flicker

Flicker emission for continuous and switching operation should be within the limits given in IEC 60868, IEC 61400-21 and IEC 61000-3-7.

2.3 Frequency

The embedded wind plant shall continuously operate without violating following limits.

- Over Frequency: 1.04pu -Continuously
- Under Frequency: 0.94pu –Continuously

3. Results and Discussions

3.1Total harmonic distortion

Harmonic currents and voltages in Seguwantivu-Vidatamunai dedicated feeder were measured in March and June in order to cover the two seasons, low wind and high wind respectively. Total Harmonic Distortion (THD) for current and voltage in the three phases and neutral are depicted in the following figures 2 and 3.

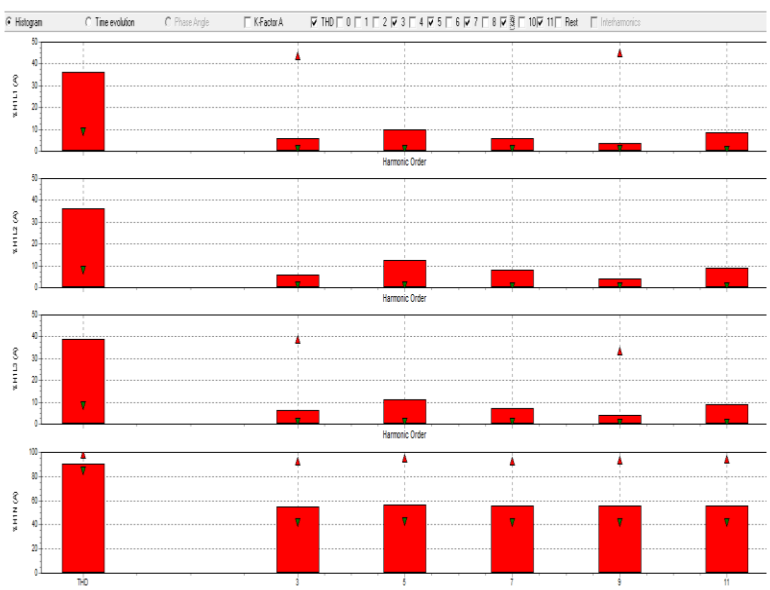


Figure 2: Histogram of Current THD (20/Mar-06/Apr) in Seguwantivu Vidatamunei dedicated feeder

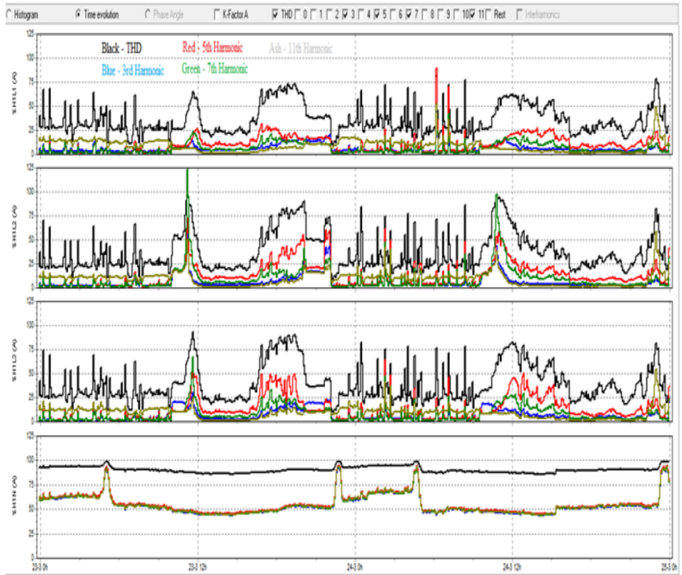


Figure 3: Current THD (March 23-25) in Seguwantivu Vidatamunei dedicated feeder

For low wind, THD levels of current exceed the limits stipulated in the Grid Code. The dominant current harmonic observed is the 5th harmonic followed by 3rd, 11th and 7th respectively (figure 2).

Although voltage THD levels of histogram graph does not exceed the 5% limit (Figure 4), the time series graph (Figure 5) shows that at some instances THD values exceed that limit. Dominant individual voltage harmonic is the 11th harmonic while 3rd, 5th and 7th harmonic components are also present. 3rd harmonic was observed as the major component in the neutral measurement.

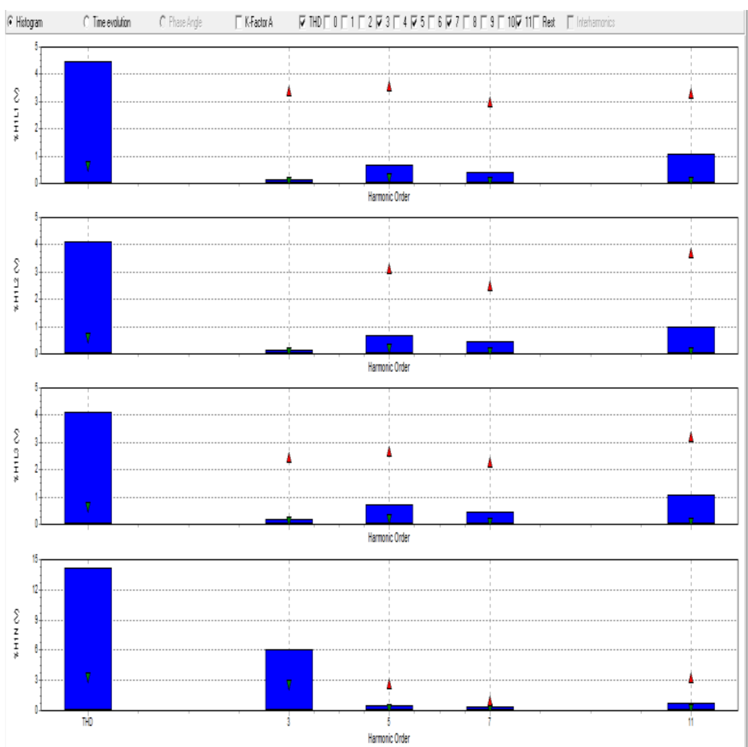


Figure 4: Histogram of Voltage THD (20/Mar-06/Apr) in Seguwantivu -Vidatamunei dedicated feeder

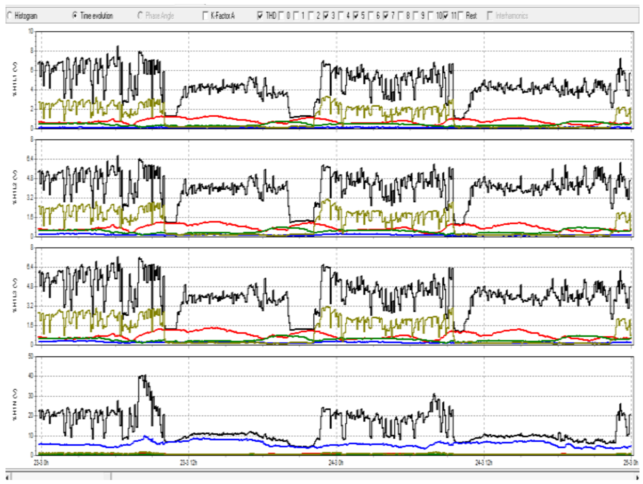


Figure 5: Voltage THD (March 23-25) in Seguwantivu - Vidatamunei dedicated feeder

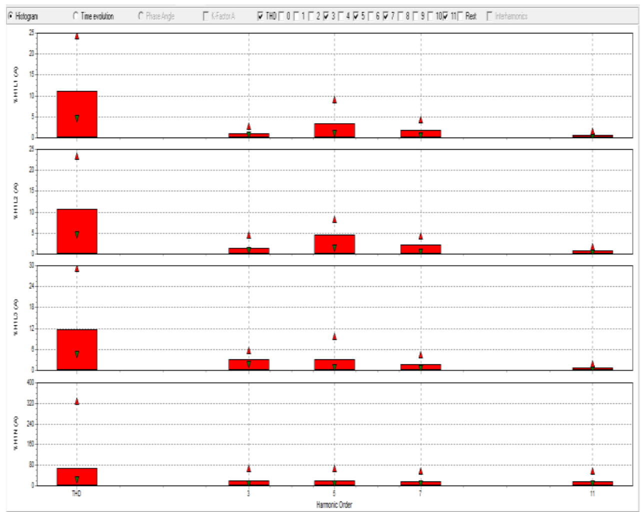


Figure 6: Histogram of Current THD (27/June – 08/Jul) in Seguwantivu Vidatamunei dedicated feeder

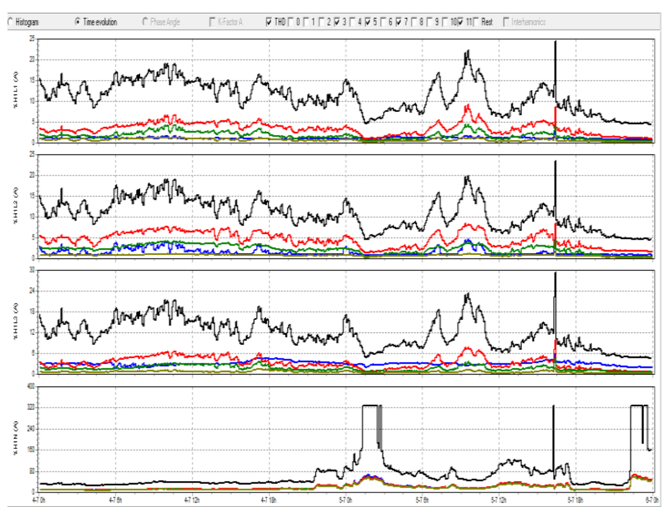


Figure 7: Current THD (July 04 - 06) in Seguwantivu Vidatamunei dedicated feeder

For high wind, THD levels of current exceed the limits stipulated in the Grid Code the dominant harmonic observed is the 5th harmonic followed by 7th, 3rd and 11th respectively.

Voltage THD levels do not exceed 5% level except for neutral. Dominant individual voltage harmonic component is the 5th harmonic for phase voltages and the 3rd harmonic for the neutral. Harmonic currents and voltages at Norochcholai were measured in May. Histogram graphs for current and voltage are shown in the figures 10 and 11 below.

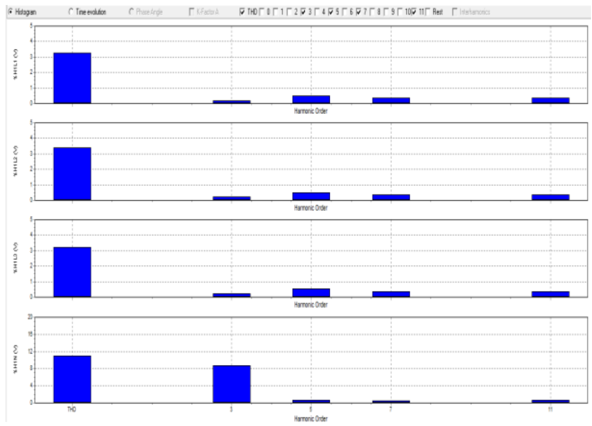


Figure 8: Histogram of voltage THD (27/June – 08/Jul) in Seguwantivu Vidatamunei dedicated feeder

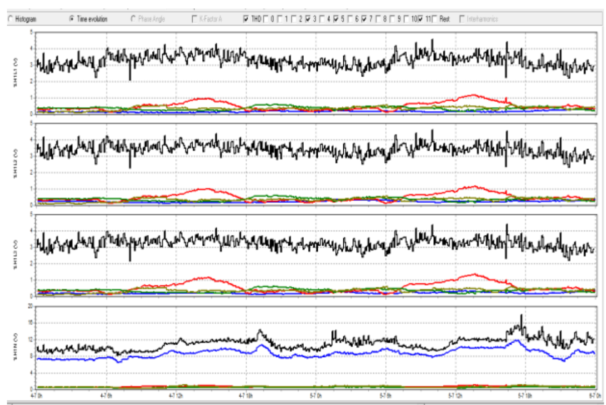


Figure 9: Voltage THD (July 04 - 06) in Seguwantivu Vidatamunei dedicated feeder

Figure 10: Histogram of current THD (May 22-24) in Norochcholai

It is observed that both current and voltage harmonic THD levels of Norochcholai Wind GSS at 33kV level are comparably lower than Puttalam GSS 33kV level.

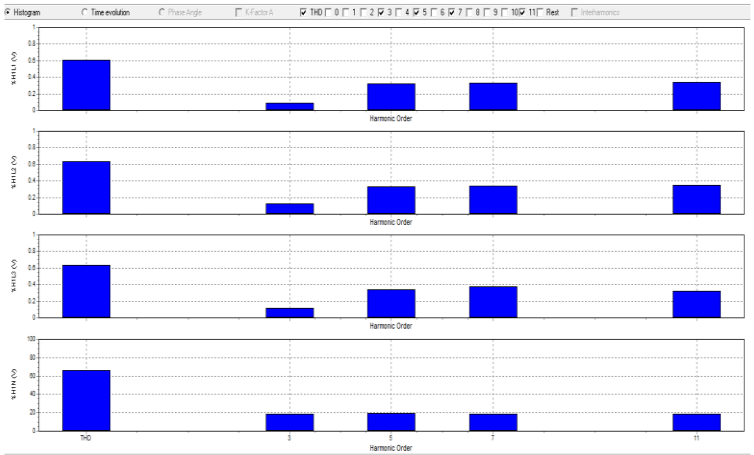


Figure 11: Histogram of voltage THD (May 22-24) in Norochcholai

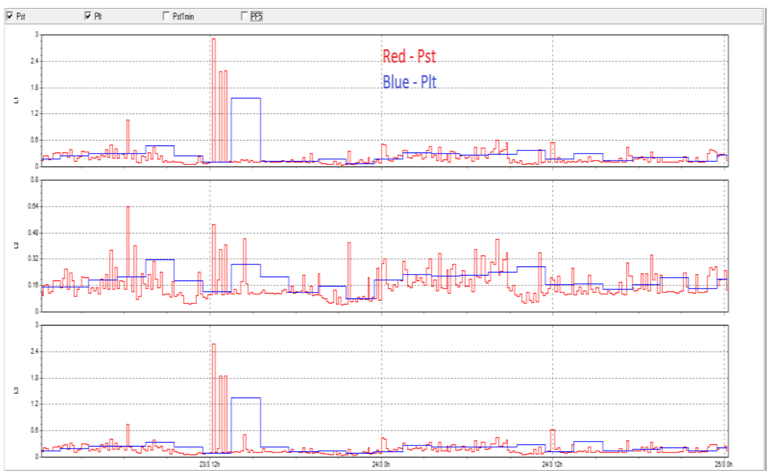


Figure 12: Flicker Index (March 23-25) in Seguwantivu Vidatamunei dedicated feeder

3.2 Flicker

Rapid fluctuations in the voltage of the power supply causes flicker. IEC 61000-2-2 Standard specifies compatibility level for short term flicker (Pst) as 1.0 and Compatibility level for long term flicker (Plt) as 0.8. The flicker calculations in Seguwantivu -Vidatamunei feeder in high wind and low wind seasons are as follows.

It is observed that Pst compatibility levels are violated in few occasions in both high wind and low wind seasons in the Seguwantivu -Vidatamunai feeder. The Pst values range between 0.1-2.4 and Plt values range between 0.1 to 1.6. However, considering the overall time span, the flicker compatibility limits are within acceptable limits.

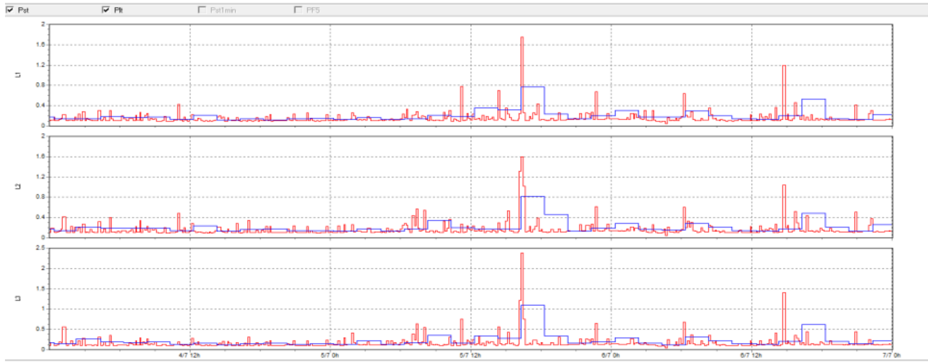


Figure 13: Flicker Index (July 04 - 06) in Seguwantivu Vidatamunei dedicated feeder

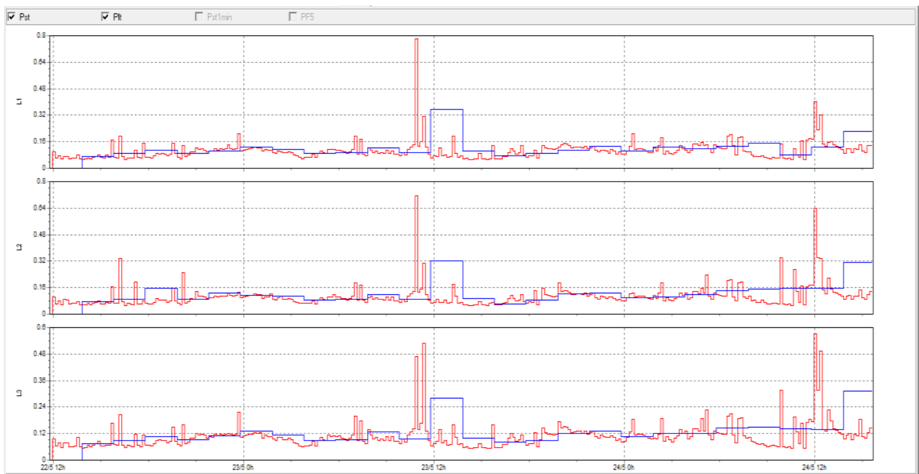


Figure 14: Flicker Index (May 22-24) in Norochcholai

Analyzing the feeder from Norochcholai, the Pst level ranges from 0.1-0.8 and Plt varies between 0.1-0.3. Thus there is no instance where flicker compatibility level violations were recorded.

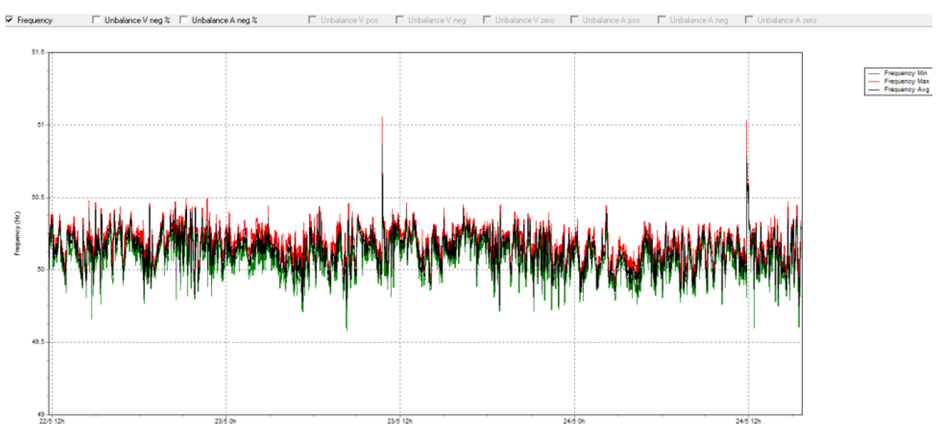


Figure 15: Frequency (May 22-24) in Norochcholai

3.3 Frequency

Analysis of Frequency (Figure 12) plots for any frequency violations revealed no major deviations with respect to the *Addendum to the CEB guide for Grid Interconnection of Embedded Generators*.

4. Conclusion

High THD levels in both voltage and current during low wind season (March) compared to the high wind season (June) was observed in all three phases and neutral of Seguwantivu Vidatamunai dedicated feeder. Further analysis indicates a correlation between THD levels and wind speed variation. THD levels of both voltage and current at Norochcholai GSS are comparably lower than Puttalam GSS. Considering the total measurement period it is safe to conclude that there are no flicker or frequency violations. Continuous monitoring of power quality at wind connected bus bars is highly recommended rather than analyzing at the time of commissioning or during special investigations.

References

Ceylon Electricity Board (CEB). 2000. Grid connection requirement for Wind Power Plants –Addendum to the CEB guide for Grid Interconnection of Embedded Generators.

E. Muljadi, C.P. Butterfield, J. Chacon and H. Romanowitz. 2000. Power Quality Aspects in a Wind Power Plant.

IEC 61000-3-3, Limits - Limitation of voltage changes, voltage fluctuations and flicker.

IEC 61000-4-30, Testing and measurement techniques - Power quality measurement methods.

IEC 61000-4-7, Testing and measurement techniques – General guide on harmonics and inter harmonics measurements and instrumentation, for power supply systems and equipment connected thereto).

IEEE SM 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 1159, IEEE Recommended Practice for Monitoring Electric Power Quality.

Measurement and Analysis of Power Quality at the Puttlam GSS and Point of Common Coupling of Putlam Wind farms, A report submitted to GM (CEB) on recent power quality issues. 2010.

L.U. Yan. 2003. Wind Power Generation - Related Power Quality Issues.

User Manual of Fluke 435 Three Phase Power Quality Analyzer.

Thickness Optimization of P3HT:PC_{60}BM Organic Bulk Heterojunction Solar Cells Based on Optical Performance Using Numerical Modelling

W. Abeygunasekara[1*], L. Samaranayake[1], V. Karunaratne[2], G. Amaratunga[2]

[1]*Department of Electrical and Electronic Engineering, University of Peradeniya, Peradeniya, Sri Lanka*
[2]*Sri Lanka Institute of Nanotechnology, Nanotechnology & Science Park, Mahenwatte, Pitipana, Homagama, Sri Lanka*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Optical modelling is used to investigate the thickness dependent performance of organic solar cells based on a widely used mid performance polymer blend P3HT:PC_{60}BM. The device optimization is carried out for most commonly used device architecture, with widely used material for end electrodes and charge extraction layers. The maximum possible short current density ($J_{sc,max}$) for the given device architecture at each active layer thickness is calculated taking into account the losses at each layer present in the device stack and also the reflections at each interface. It was found that the active layer absorption for devices with reflective back electrode is mainly governed by the optical interference patterns present in the device stack, and peaks and valleys are present in the active layer absorption variation with active layer thickness. Among the absorption peaks detected at various active layer thicknesses, the peak occurring at 75nm is identified as the optimal in terms of device performance with $J_{sc,max}$ of 11.82 mA/cm^2.

Keywords: numerical modeling, thickness optimization, solar cells

1. Introduction

Organic solar cells (OSCs) have emerged as an inexpensive alternative to crystalline inorganic solar cells. The low temperature solution processing techniques (Li, Shrotriya, Huang, et al., 2005), very low energy payback time, cheap and abundant raw materials (Dennler, Scharber, & Brabec, 2009), flexible and light weight designs (Unalan et al., 2008) are some of the features that made the OSCs attractive in the first place. While not suited for large scale power generation due to their low efficiency and limited lifetime and stability, OSCs are gradually making their way into consumer electronics.

OSCs differ fundamentally from traditional Silicon solar cells in many ways. With few hundreds of nanometer device thickness, the optical absorbance of the OSCs are governed mainly by the optical interference patterns present in the device and can vary a great deal with very small thickness changes (Monestier et al., 2007; Sievers, Shrotriya, and Yang, 2006). In addition due to the low charge carrier mobilities of organic semiconductors and consequent difficulty in extraction of generated charge carriers it is critical to keep the device thickness at a minimum possible while maintaining a reasonably sufficient absorption (Li, Shrotriya, Yao and Yang, 2005; Moulé, Bonekamp and Meerholz, 2006). Thus thickness optimization is an important step in device optimization for OSCs. Optical modelling can comprise the initial step of the thickness optimization where the thickness ranges where optical absorption is optimal can be identified. Here an optical model which takes into account the wavelength dependent material properties of the device assembly and also the spectral distribution of the incident irradiance is presented. The model is used here to identify the optimal device thickness of the P3HT:PC_{60}BM devices under the standard illumination condition of AM1.5G.

2. Methodology

The schematic diagram of a typical OSC is given in Figure 1. The device consists of an active layer sandwiched between two end electrodes. Active layer or the absorber is where the photo-generation takes place and the photo-generated charge carriers are collected at the two end electrodes. At each active layer electrode interface there is an optional charge extraction layer to facilitate optimal extraction of photo-generated charge carriers. The whole device is assembled on a transparent substrate.

[*]*Correspondence: lilantha@ee.pdn.ac.lk*
ISSN 2478-0669 Print

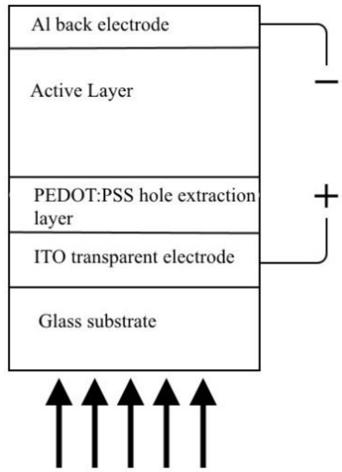


Figure 1: Schematic diagram of an organic solar cell (not to scale) with transparent anode, reflective cathode and a hole extraction layer.

With the device thickness comparable to the wavelength of the incoming light, the traditional ray optics methods are not applicable here, and in order to determine the optical electric field accurately wave optic methods are called for. Here the position dependent optical electric field is determined by direct solving of Maxwell's equation. Each layer in the device stack is characterized by its thickness and wavelength dependent complex refractive index. The equations are implemented and solved numerically using finite element method. (Commercially available finite element software COMSOL has been used for the implementation). The model is solved for the standard solar spectrum of AM1.5G, and absorption at each location of the device stack is calculated by Poynting theorem. The total number of photons absorbed by the active layer and thus the maximum achievable current density at each thickness is calculated.

Here the above described model is used to investigate the thickness performance of OSCs based on the polymer blend poly(3-hexyl thiophene-2,5-diyl)/ [6,6]-phenyl-C61 butyric acid methyl ester (P3HT/PC_{60}BM), which is a widely used polymer blend in donor acceptor polymer based bulk heterojunction OSCs. The devices simulated here consists of glass substrate (1mm), Indium Tin Oxide (ITO) transparent electrode (100nm), Poly (3,4-ethylenedioxythiophene) poly (styrenesulfonate) (PEDOT:PSS) hole extraction layer (50nm), P3HT/PC_{60}BM active layer (variable thickness), and Aluminum reflective back electrode (100nm). Simulations are also done without the back electrode (transparent devices) as a reference to exponential decay model and also to quantify the effects due to optical interference present in the device structure.

3. Results and Discussion

Given in figure 2 is the power absorption at each layer in the device when the active layer thickness is varied from 50nm to 600nm. The active layer absorption of the transparent device increases with the increase of active layer thickness, following the Beer Lambert's law. However, the absorption of the devices with reflective back electrode (opaque devices) is governed by the optical interference pattern present in the device stack and absorption peaks (75nm, 215nm, 365nm, 430nm and 520nm) and valleys (125nm, 275nm) can clearly be seen. The active layer absorption at 75nm amounts to 73% of total incident power and the losses add up to 27%, considering the partial spectrum of 300nm-650nm, which is the effective absorption range for the polymer blend considered here. The active layer absorption for 215nm thickness amounts to 80% with 7% enhancement in absorption, and peaks at 520nm totaling up to 82% with further 2% enhancement.

From Figure 2 it is clear that active layer thicknesses below 75nm is not sufficient for effective optical absorption and with increasing active layer thickness the absorption is also increasing. However, beyond 75nm absorption is mainly governed by the optical interference pattern present in the device stack.

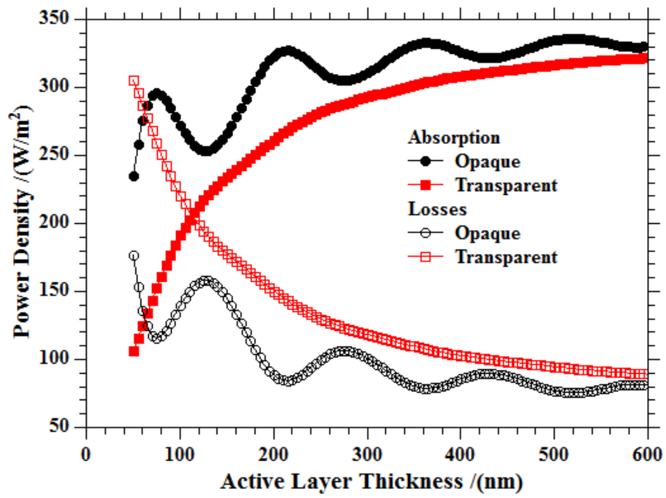


Figure 2: Active layer absorption and total device loss variation with active layer thickness for devices with and without back electrode

The difference between the transparent and opaque devices signifies the importance of the reflective back electrode for this type of devices, where it is necessary to keep the active layer thickness at a minimum possible value in order to extract the photo generated charge carriers and also to minimize the recombination losses. The reflective back electrode effectively doubles the optical thickness of the device by providing a second passing through active layer by reflection, while keeping the extraction thickness of the device unchanged. Considering the first absorption peak of the opaque device occurring at 75nm, following observations can be made. The active layer absorption at 75nm for opaque device is greater than the active layer absorption of transparent device at 140nm, indicating that this absorption peak is a result of combined effects of increasing of optical thickness and also the constructive interference of the optical electric field within the active layer. Comparing with the other absorption peaks occurring at 215nm, 365nm, 430nm and 520nm the 75nm peak is rather sharp indicating high absorption sensitivity to active layer thickness and slight deviation from 75nm would result in a significant loss in absorption. Normally donor-acceptor polymer based bulk heterojunction OSCs are fabricated using low cost solution processing techniques. Most of these techniques do not monitor the thickness of the deposited layer as it is being deposited, but uses pre-determined optimized conditions to achieve the required thicknesses. Thus from practical point of view, to fully take advantage of the 75nm absorption peak, very tight control of fabrication procedure is needed.

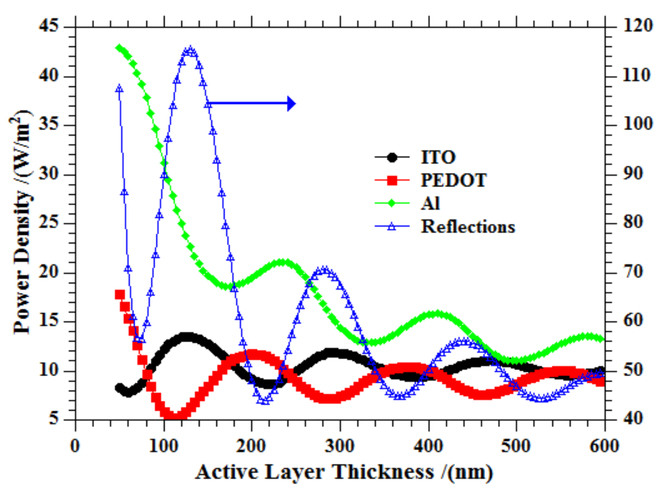


Figure 3: Stray absorption and reflective loss variation with active layer thickness

Given in figure 3 are the device loss variations with active layer thickness. The losses occur due to reflections and stray absorption in layers other than the active layer. The photons absorbed by the active layer result in generation of free charge carriers that can be collected at the end electrodes contributing to the photo generated current of the device.

However, photons absorbed in the other layers dissipate as heat and contributes to the device losses. The losses due to unwanted absorptions fluctuate with the optical interference pattern present in the device stack. Losses at the back electrode are higher initially (for very small active layer thicknesses) and drops down with the increase of thickness, but losses at ITO electrode and PEDOT:PSS hole extraction layer are uniform and do not vary much with active layer thickness. The losses at glass substrate is negligibly small for the wavelength range considered and is not shown. Losses at ITO transparent electrode, PEDOT:PSS layer and Al back electrode cannot be ignored and amounts to about 17% of the total incident power at very small active layer thicknesses (30-75 nm) but gradually falls down to about 8%. The losses due to reflections however vary significantly with the optical interference patterns and falls in the range of 10-25% of incident power. When calculating the loss percentage, from the standard AM1.5G spectrum only the wavelength range that can be absorbed by the active layer is considered.

Given in figure 4 is the $J_{sc,max}$ that can be achieved at each thickness for the device architecture given in Figure 1. For this calculation all the optical losses are taken into account, but extraction losses are not included. The peak current densities corresponding to absorption peaks at 75nm and 215nm thicknesses are 11.82 mA/cm^2 and 13.18 mA/cm^2 respectively. The current density per unit thickness ($J_{sc/nm}$) of active layer is also given in Figure 4. $J_{sc/nm}$ value peaks at 75nm and decreases with the increasing active layer thickness. This indicates that increasing active layer thickness alone is not a very efficient photon harvesting technique. Considering the absorption peaks occurring at 75nm and 215nm, even though the total absorption is higher at 215nm, the $J_{sc/nm}$ value is very much lower than that of 75nm thickness. From 75nm to 215nm the active layer absorption increases only by 7% for tripling the active layer thickness. Thus increasing the active layer thickness to 215nm can only be justified when the recombination losses due to increased thickness can be overcome by the absorption gain. In addition if increasing active layer thickness beyond 75nm in order to achieve higher current density, it has to be increased beyond 175nm. Increasing active layer thickness in the range of 75nm-175nm does not result in any enhancement in the current density.

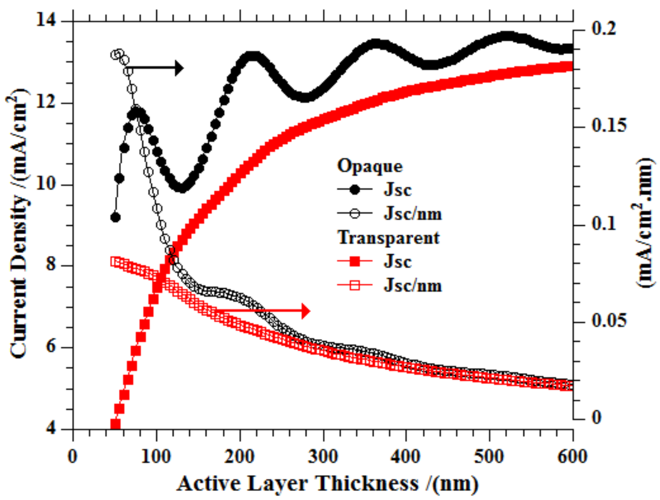


Figure 4: Maximum current density and current density per unit thickness variation with active layer thickness

4. Conclusion

Optical modelling have been used for thickness optimization of OSC based on P3HT:PC$_{60}$BM polymer blend. The active layer power utilization vary between 60% and 82% with total device losses falling in the range of 18% to 40%. The optimal active layer thickness for the device is selected as 75nm with the best power utilization per unit thickness and at this thickness the device utilization of incident power amounts to 73% while the optical losses amounts to 27%. Furthermore at this thickness maximum short circuit current density of 11.82 mA/cm^2 is predicted.

References

Dennler, G., Scharber, M. C. and Brabec, C. J. 2009. Polymer-Fullerene Bulk-Heterojunction Solar Cells. *Advanced Materials*, *21*(13): 1323–1338. http://doi.org/10.1002/adma.200801283.

Li, G., Shrotriya, V., Huang, J., Yao, Y., Moriarty, T., Emery, K., and Yang, Y. 2005. High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends. *Nature Materials*, *4*(11): 864–868. http://doi.org/10.1038/nmat1500.

Li, G., Shrotriya, V., Yao, Y. and Yang, Y. 2005. Investigation of annealing effects and film thickness dependence of polymer solar cells based on poly(3-hexylthiophene). *Journal of Applied Physics*, *98*(4): 043704. http://doi.org/10.1063/1.2008386.

Monestier, F., Pandey, A. K., Simon, J.-J., Torchio, P., Escoubas, L. and Nunzi, J.-M. 2007. Optical modeling of the ultimate efficiency of pentacene: N, N[sup ′]-ditridecylperylene-3, 4, 9, 10-tetracarboxylic diimide–blend solar cells. *Journal of Applied Physics*, *102*(3), 034512. http://doi.org/10.1063/1.2767619.

Moulé, A. J., Bonekamp, J. B. and Meerholz, K. 2006. The effect of active layer thickness and composition on the performance of bulk-heterojunction solar cells. *Journal of Applied Physics*, *100*(9): 094503. http://doi.org/10.1063/1.2360780.

Sievers, D. W., Shrotriya, V. and Yang, Y. 2006. Modeling optical effects and thickness dependent current in polymer bulk-heterojunction solar cells. *Journal of Applied Physics*, *100*(11): 114509. http://doi.org/10.1063/1.2388854.

Potential of Sugarcane as a Source of Green Energy in Sri Lanka

A.P. Keerthipala*, N.V.T.A. Weragoda

Sugarcane Research Institute, Uda Walawe, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

This paper highlights the potential of sugarcane crop and the development of the sugarcane industry to contribute to supply of green energy in Sri Lanka. It elaborates the sugarcane as an energy crop, i.e., a crop that is capable of providing energy for the people; dietary energy, and the energy needs for domestic and commercial purposes. In addition to sugar, sugarcane industry has a high potential for generating electricity and producing fuel alcohol by using its by-products; cane tops/trash, bagasse and molasses and fuel alcohol directly from cane juice. This contribution could be enhanced further by introducing energy cane. Sri Lanka is endowed with a favourable environment for sugarcane cultivation in the dry and intermediate zones, and plans are underway to expand sugarcane cultivation in Uva, Eastern, North Central and Northern provinces to achieve 40% self-sufficiency in sugar by the year 2020 and 100% by the year 2030. The development of sugarcane industry in an integrated manner makes the achievability of this target a possibility and it can make a significant contribution to food and energy security, foreign exchange saving, income and employment generation, development of rural entrepreneurship, clean development, etc. To contribute more to energy sector, some research on the development of energy cane, production of fuel alcohol from molasses and bagasse is required. In addition, pricing of sugarcane and alcohol and excise duties on fuel alcohol are some areas requiring policy measures.

Keywords: energy security, food security, green energy, sugarcane

1. Introduction

The total energy requirement of the country in 2013 was 11,125 ktoe (kilo tonnes of oil equivalent) (Ministry of Power and Energy, 2015), and it has been estimated that the demand for energy will increase to about 18,000 ktoe by the year 2030 at an annual growth rate of 3% (Ministry of Power and Energy, 2006). According to the Ministry of Power and Energy (2015), nearly 56% of the energy requirement comes from biomass and hydro, and the balance is from fossil fuels. With the increase in standard of living, percapita energy consumption also increases. It was estimated that the correlation coefficient between per capita GNP and the per capita demands for electricity and fossil fuels are 0.95 and 0.98 respectively (authors' estimates are based on information provided in Appendix Tables 1 and 2). This has posed a significant threat to economy in terms of draining foreign exchange and pollution of the environment by emission of green-house gasses such as carbondioxide, carbonmonoxide, sulphurdioxide, etc. which could contribute to global warming (Jayathilake, 2008). In the year 2013, the country has imported fossil fuels worth US$ 4.3 billion which is nearly 24% of the total import bill (Central Bank of Sri Lanka, 2013). The fossil fuels imported are mainly used for electricity generation and transportation. Thus, importation of fossil fuel makes a significant impact on the national balance of payments. On the other hand, emission of green-house gasses during combustion of fossil fuels makes a significant threat to the environment. Dependence on fossil fuel for energy also makes a threat to energy security since fossil fuel prices are highly fluctuating as shown in Appendix Table 2. Energy security of a country is an important criterion of economic development since energy supply and GDP (Gross Domestic Product) growth are closely interlinked. For example, the correlation coefficient between the growth rate of GDP and the supply of electricity and fuels is 0.45 (Authors' estimates based in information shown in Appendix Table 1). Furthermore, since it has been forecasted that the world fossil fuel resources will be depleted in near future; oil reserves in 54 years, natural gas in 64 years and coal in 155 years (Nair, 2014), dependence more on fossil fuels for electricity generation and transportation will have a direct impact on the energy security of the country. Thus, supply of energy by fossil fuel makes a threat to economic development in terms of adverse impacts on national balance of payment, energy security and the environment which could cause climate change impacts, etc.

Correspondence: apkeerthipala@yahoo.com
ISSN 2478-0669 Print

Thus, a necessity has arisen to resort to renewable sources of energy as a solution to the above-mentioned economic and environmental issues of the country. This paper intends to highlight the potential of sugarcane crop and the development of the sugarcane industry in Sri Lanka to contribute to energy sector by providing a renewable source of energy to contribute to national greener economic development by income and employment generation, providing food and energy security, and protecting the environment for the present as well as future generations.

2. Methods

This paper is based secondary information in published sources and the findings of the research conducted by the Sugarcane Research Institute, Sri Lanka, on the subject.

3. Results and Discussion

3.1 Sugarcane as an energy crop

Sugarcane, being a C4 plant, synthesises solar energy into green biomass more efficiently, and thus, it has an outstanding ability to produce biomass for green energy production (Herrera, 1999; Almazan, et al., 1998). Sugarcane can fix 2-3% of solar radiation and transform into biomass (Almazan, et al., 1998). Also, sugarcane is a plant with high net energy ratio (Nair, 2014). The ratio of energy value of bio mass and the energy consumed in cultivation is about 20:1 (Harrera, 1999). The harvestable biomass produced by sugarcane is more than double that of any other crop which could be used as a feed stock for bio-fuel production (Nair, 2014). In the dry and intermediate zones of Sri Lanka, there exists favourable climatic and soil conditions for growing sugarcane and with the available high-yielding varieties and under good management, sugarcane yield could be increased up to about 70-80 t/ha under rain-fed and 100-120 t/ha under irrigation. An average yield of 90 t/ha could be expected by cultivating these varieties (Keerthipala, 2013).

In sugarcane industry, the main by-products generated during sugar manufacturing process are bio-energy sources (Chandrasena, 2008). When the sugarcane crop is harvested, the cane tops and trash left behind on the cane field could be used for generation of electricity. On average, the residue remained on the field is about 9-10% of the total biomass produced by the crop (Dharmawardene, 2004). After milling, the fibrous residue remained, bagasse, is about 30% of the cane weight. This is used as a source of energy for the sugar factory. The energy value of bagasse is 0.187 fuel oil equivalents at 50% moisture (Paturau, 1989). Under efficient conditions, each tonne of bagasse can produce 130 kWh of electricity (Bhardwaj, 2013). Development of energy cane (type I energy cane (contains< 20% fibre and > 15% brix) and type II energy cane (>20% fibre and <15% brix), allows an increasein electricity production from biomass. Sugarcane could be grown in marginal lands at the minimal biotic and abiotic stresses (Nair, 2014). The energy values of sugarcane and energy cane, according to Leal (2007), are shown in Table 1.

Table1: Energy values of sugarcane and energy cane

	Sugarcane	Energy cane
Productivity (t/ha)	70	100
Fibre (% cane)	13.5	26.0
Trash (% cane)	14.0	25.0
Pol (% cane)	14.5	12.0
Total fibre (t/ha/year)	19.3	51.0
Primary energy (GJ/ha/year) (MJ/t cane)	520	1100
	7400	11200

(Source: Leal, 2007)

Molasses, the liquid separated after centrifuging sugar crystals from massecuite is about 4.5% of the cane crushed. This liquid contains, among other things, about 55% fermentable sugars (Chandrasena *et al*., 2006). This can be fermented into ethyl alcohol and the alcohol that could be obtained is nearly 300 l/t. Alternatively, cane juice also can be directly fermented, and it is possible to produce 70-90 l/ of alcohol from one tonne of cane (Thomson, 1979)., Bagasse can also be fermented to produce second generation alcohol and each tonne of bagasse can generate about 250 l of alcohol (Nair, 2014).

3.2 Potential of sugar development in supplying renewable energy in Sri Lanka

It has been envisaged that about 800,000 tonnes of sugar should be produced to achieve self-sufficiency in sugar by the year 2030 (Keerthipala, 2013). This requires cultivation of sugarcane on 125,000 ha of lands in Moneragala, Badulla, Ampara, Trincomalee, Anuradhapura, Vaunia, Kilinochchi and Puttalam and expanding the processing capacity to 40,000 TCD (Tonnes of Cane per Day). This makes possible production of 8 million tonnes of sugarcane and 800,000 tonnes of sugar which is sufficient to meet the domestic requirement by the year 2030.This results in 0.8 million cane tops/trash (10% of cane), 2.4 million tonnes of bagasse (30%) and 360,000 tonnes of molasses (4.5%) as by-products.

As mentioned in the previous section, bagasse and cane tops and trash can be used for generation of electricity. The excess electricity that could be generated for the national grid is nearly 800 million kWh per year. It is envisaged that the availability of electricity for the national grid could be raised by utilising solar energy during day time for running the sugar mill.

The by-product, molasses, could be fermented into ethyl alcohol, and nearly 108 million litres of anhydrous alcohol could be produced. The alcohol could be used as a fuel for motor vehicles. The production of ethyl alcohol could be further increased by fermenting sugarcane juice directly into ethyl alcohol as practised in Brazil, depending on the relative prices of sugar and alcohol. As mentioned in the previous section, introduction of sugarcane with high fibre content (energy cane) and production of 2^{nd} generation alcohol by fermenting bagasse, in addition to use it for electricity, will also make possible the generation of more electricity and production of more fuel alcohol from sugarcane.

The following benefits could be obtained by sugarcane industry development not only by supplying an essential food, sweetener (sugar, jaggery, syrup, etc.), but also by providing energy (electricity and ethyl alcohol):

- Saving nearly 665 million US dollars annually from the importation of sugar, alcohol and petroleum.
- Generation of 425,000 direct employment opportunities and 400,000 indirect employments.
- Contribution of nearly 105,000 million rupees to GDP (1.5%).
- Generation of income from carbon trading and contribution to clean development.
- Upliftment of the socio-economic status of the under-developed rural dry zone areas.

Generation of income from carbon trading is a new important area in renewable energy production by biomass since it makes possible reduction of carbon dioxide emission to the environment as required for clean development under the Kyoto Protocol (Jayasinghe, 2008; Batagoda, 2008).

3.3 Research and development needs for increasing contribution of sugar industry to energy sector in Sri Lanka

The Sugarcane Research Institute has already initiated some research in respect of breeding of sugarcane varieties with high fibre content without much reducing the sugar content and development of more efficient yeast strains for fermentation of molasses and cane juice.

Development of technology on the following areas is required to enhance the contribution of sugarcane to renewable energy development:

- Breeding of sugarcane varieties for having both high sugar and high fibre contents: The Sugarcane Research Institute will continue breeding of sugarcane varieties for both high sugar and fibre, and hence, it will be in a position to introduce energy cane for producing higher amounts of both sugar and electricity from one tonne of cane.

- Production of energy cane with short duration: Initial arrangements are being made to breed sugarcane with sweet sorghum to reduce the crop age of energy cane. This will make possible producing higher amount of biomass in a shorter duration.

- Improvement of sugarcane molasses fermentation for ethyl alcohol production: Development of efficient yeast strains has been initiated by isolation of yeasts from natural environments, testing them for desirable features and production of improved yeasts by protoplast fusion.

- Fermentation of sugarcane juice directly to alcohol: Depending on the price of sugar, cane juice could be directly fermented to fuel alcohol and the efficiency of this process should be improved.

- Production of second generation alcohol from sugarcane bagasse: Methods will be developed to produce alcohol from cane trash and bagasse by microbial processes.

3.4 Policy measures

In addition to the implementation of the policy measures proposed in the draft Sri Lanka sugar sector development policy (Ministry of Sugar Industry Development, 2013) and the sugarcane industry development plan (Keerthipala, 2013) to develop the sugarcane industry, the following measures have to be implemented to increase the contribution of the sugarcane industry to energy sector in Sri Lanka:

- Pricing of sugarcane based on the commercial value of cane in terms of the value of sugar, and energy from by-products, particularly bagasse and molasses.

- Pricing of fuel alcohol and removing excise duties to make fuel alcohol affordable.
- Pricing of electricity to encourage electricity generation from renewable sources.
- Policies for blending fuel alcohol with motor fuel.

4. Conclusion

Sugarcane is an energy plant for humans and the nation. Tapping its potential, not only as a source of sweetener, but also as a source of renewable energy, will protect the environment benefiting the present as well as future generations. Development of the sugarcane industry has the potential to make a significant contribution to power sector in Sri Lanka by providing a minimum of 800 million kWh of electricity and 108 million litres of alcohol as motor fuel annually in addition to supplying 800,000 tonnes of sugar to meet the domestic consumption requirements. This can be further increased by introducing energy cane with necessary policy measures. Thus, development of sugarcane industry in an integrated manner to produce sugar, electricity and fuel alcohol could make a significant contribution to sustainable economic development of the country by income generation from sugar, electricity and fuel alcohol and carbon trading, saving foreign exchange by reducing sugar and fuel imports, ensuring local food and energy security, generating direct and indirect employment in production and service activities, etc.

References

Almazan, O., Gonzalez, L. and Galvez, L. 1998. The Sugarcane, Its By-products and Co-Products. Maurice Paturau Memorial Lecture, Food and Agricultural Research Council 1998, Mauritius.

Batagoda, B.M.S. 2008. Carbon Trading: A New International Business Opportunity in Sri Lanka. Review, 34(9): 41-7.

Bhardwaj, A. 2013. Integrated Sugar Industry in India, A presentation.

Chandrasena, G., Keerthipala, A.P. and Walker, G.M. 2006. Isolation and Characterisation of Sri Lankan Yeast Germplasm and its Evaluation for Alcohol Production, Journal of the Institute of Brewing, Vol. 112 No, 04.

Chandrasena, G. 2008. Sugarcane as a Source of Biofuel. Economic Review, 34(9): 29-32.

Central Bank of Sri Lanka, (2013). Annual Report.

Dharmawardene, M.W.N. 2004. By-Products of Sri Lankan Sugarcane Industry. Revised ed. Sugarcane Research Institute, pp 99.

Herrera, M.C. 1999. Cane, Sugar and the Environment. Proceedings of the FAO-Cuba Sugar Conference, 7-9 December 1999, Cuba.

Jayasinghe, P. 2008. Sustainably Grown Fuel Wood (Dendro) as a Biomass Energy Source in Sri Lanka. Economic Review, 34(9): 23-28.

Jayathilake, A. 2008. Climate Change due to Global Warming: A Global Challenge in Sri Lanka Perspective, Economic Review, 34(3 and 4): 9-14.

Keerthipala, A.P. 2013. Development of the Sugar Industry of Sri Lanka: Actions Needed. A Report submitted to the Ministry of Sugar Industry Development, Sugarcane Research Institute, Uda Walawe.

Keerthipala, A.P. 2013. Achieving Self-sufficiency of 40% in Sugar in Sri Lanka by the Year 2020.Sugarcane Research Institute, Uda Walawe.

Leal, M.R.L.V. 2007. The Potential of Sugarcane as an Energy Source. Proceedings of the International Society of Sugarcane Technologists, August 2007, Durban, South Africa, 26: 23-33.

Ministry of Sugar Industry Development. 2013. Sri Lanka Sugar Sector Development Policy (Draft). Sugarcane Research Institute, Uda Walawe.

Ministry of Power and Energy. 2015. Sri Lanka Energy Sector Development Plan for a Knowledge-based Economy 2015-2015. Ministry of Power and Energy, Sri Lanka, pp 37.

Nair, N.V. 2014. Bioenergy-Potential of Sugarcane and Related Grasses. Proceedings of the Symposium of Bioenergy for Sustainable Development-Role of Sugar Crops, 23-25 June 2014, Coimbatore, India, 1-5.

Thomson, G.D. 1979. Ethanol from Sugarcane. Proceedings of the South African Sugar Technologists' Association, June 1999, 1-5.

Cultivation of Microalgae; *Chaetoceros calcitrans* for Biodiesel Production as Affected by Different Nitrate Concentrations and Salinity Levels

A.M. Gammanpila[1*], C.P. Rupasinghe[2], S. Subasinghe[2]

[1]*Faculty of Graduate studies, University of Ruhuna, Sri Lanka.*
[2]*Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya, Sri Lanka.*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Microalgae are considered as a promising biological material for the production of biodiesel. The key to economic algal biomass production for biodiesel is optimization of the growth conditions. The aim of the present work was to study the effect of nitrate concentration and salinity level on growth and lipid production of marine diatom, *Chaetoceros calcitrans* cultured in an outdoor culture system, in view of its possible utilization as novel raw materials for biodiesel production. Guillard and Ryther`s modified F/2 media was used as the culture media with different sodium nitrate concentrations such as, 0.0375 g/L, 0.075 g/L and 0.15 g/L. In the second experiment, *Chaetoceros calcitrans* was cultured in medias of different salinity levels; 35 ppt, 30 ppt and 25 ppt. At the end of the 15 days growth period, cells were harvested by flocculation and dry weight and the percentage lipid content were estimated. Average dry matter yield and the % lipid contents were observed as 0.5 g/L with 6.5 % lipid, 0.6 g/L with 6.2 % lipid and 0.7 g/L with 6.0 % lipid in 0.0375 g/L, 0.075 g/L and 0.15 g/L nitrate concentrations respectively. A significantly lower average dry matter yield and significantly higher % lipid content were observed in the treatment with lowest nitrate concentration ($p > 0.05$). Further, no significant effects on measured parameters were observed when *C. calcitrans* was cultured in medias of different salinity levels, which reveals its ability to grow in a range of salinity (25 ppt to 35 ppt). Therefore, it is clear that *C. calcitrans* can be cultivated at a low nitrate concentration (0.0375 g/L) and wide range of salinity levels (25 ppt to 35 ppt) to produce biodiesel.

Keywords: Chaetoceros calcitrans, nitrate, salinity level, dry weight, lipid yield

1. Introduction

Fuel production from biomass is gaining more significance these days due to problems with global warming, pollutant emissions and increase in cost of petroleum fuels. Further, it is understood that the present petroleum reserves are to be depleted in less than 50 years at the present rate of consumption (Huang et al., 2010). Therefore, in recent years biodiesel has received considerable attention as a biodegradable and renewable source of energy.

Biodiesel is a group of esters produced by a transesterification reaction between fatty acids and an alcohol in presence of a catalyst (Chisti, 2007). One of the biggest challenges in biodiesel production is the availability of feed-stock. Thus far, biodiesel is produced from different crops such as jatropha oil, palm oil, soybean oil, canola oil, rice bran, sunflower oil, coconut oil, corn oil, fish oil, cotton seed oil etc (Padmanabhan and Stanley, 2012). Biodiesel production from edible oil has negative environmental impact because it requires much available, arable land (Surendhiran and Vijay, 2012).

Production of biodiesel from microalgae is a newly emerging field because of their high oil content and rapid biomass production. They are one of the fastest growing photosynthesizing organisms which can complete an entire growing cycle every few days (McGinnis et al., 1997; Sakthivel et al., 2011). Further, microalgae are capable of synthesizing more oil per acre than the terrestrial plants and they are able to use a wide variety of water sources, such as; fresh water, marine water, brackish water and waste water (Sharma et al., 2012). Therefore, microalgae have a strong potential to produce biofuels without competing with production of food, fodder and other products derived from crops for food production.Some of the species of microalgae already possess high oil concentration and they can be

[*]*Correspondence:*
ISSN 2478-0669 Print

manipulated to produce more oil. According to previous studies the lipid content in some microalgae could be increased by changing the nutrient concentration, temperature, CO_2 aeration fixation, salinity and light intensity (Gu et al., 2012).

Chaetoceros calcitrans is a microscopic unicellular marine algae having cell walls impregnated with silica that is extensively used in the aqua culture industry (Padmanabhan and Stanley, 2012). The main objective of the present study was to investigate the growth and lipid content of this algae species under different concentrations of nitrate ($NaNO_3$) in the growth medium and different salinity levels with the aim to obtain optimum levels for biodiesel production.

2. Methodology

The pure *Chaetoceros calcitrans* cultures were grown in an outdoor culture system under protected house for 15 days growth period. The medium used for cultivation was Guillard and Ryther's modified F/2 media (Guillard, 1975). The original nitrogen source concentration in the Guillard and Ryther's modified F/2 media was 0.075 gL^{-1} of $NaNO_3$. The experiment was performed with three treatments, such as; half concentration of original, original concentration and double of the original nitrate concentration.

For determination of optimum salinity level, *Chaetoceros calcitrans* was cultured in 35 ppt, 30 ppt and 25 ppt salinity levels in Guillard and Ryther's modified F/2 media (Guillard, 1975). The cultures were aerated with mechanical aerators. All the glassware and media were sterilized prior to inoculation. All the experiments were carried out in triplicates.

Oil extraction: The cells were harvested at the stationary phase by chemical flocculation. The cells were washed three times with distilled water and dried in an oven for 6 hours at 105 °C for dry weight estimation. The lipid content of the dried algae samples were then determined using Soxlet apparatus.

The statistical analysis was done by using Minitab 14 version. One-way Analysis of Variance (one-way ANOVA) was performed at 95 % level of probability in order to test the significance of differences of lipid content and growth performances under different treatments. When the test reported $p \leq 0.05$, a Turkey post-hoc test was performed for pair wise comparisons.

3. Results and Discussion

The economic utilization of microalgae as a renewable energy source, necessitates the development of culture conditions for growing these organisms in large scale (Bindhu, 2013). In the present study, effect of nitrate concentration and salinity level of the culture medium on growth and lipid content of *Cheatoceros calcitrans* under outdoor culture conditions was studied to determine the best condition to maximize the lipid yield for biodiesel production.

Results revealed that, dry biomass weight in the cultures with different $NaNO_3$ concentrations were significantly different ($p \leq 0.05$). As shown in Figure 01, cultures with highest nitrate concentration (0.15 g/L) reported significantly higher dry biomass of 0.7 g/L. The growth of *C. calcitrans* was greatly reduced but did not completely cease in nitrogen-deprived cultures. This agrees with previous observations on *Chaetoceros* species (McGinnis et al., 1997).

Furthermore, one way ANOVA test clearly illustrated that nitrogen deprivation stimulated lipid storage in *C. calcitrans*. A significantly high lipid accumulation of 6.5 % was recorded when the cultures were grown in half of the original nitrate concentration (0.0375 g/L) (Figure 02). However, final oil yield, which is the multiplication of dry weight by percentage oil content, was not significantly different between treatments (Figure 03).

According to McGinnis et al. (1997), when sufficient nutrients are available, proteins are synthesized; however, when nutrients are limited, cell division is suppressed, and a greater amount of carbon is available for lipid storage. Montoyaa et al. (2010) reported a gradual decrease in the growth rate accompanied by almost a double of the lipid content (from 7.88 to 15.86%) when nitrogen concentration in the medium decrease by 75%, with respect to the optimal values for growth. Not only *Chaetoceros* sp, in many other microalgae, lipid storage has been induced by the depletion or removal of nitrogen from the culture media (Dayananda et al., 2006; Feng et al., 2012; Montoyaa et al., 2010). Although other nutrient deficiencies, such as silicon and phosphorus, were able to induce this shift, nitrogen depletion appeared to be more effective for most species (McGinnis et al., 1997).

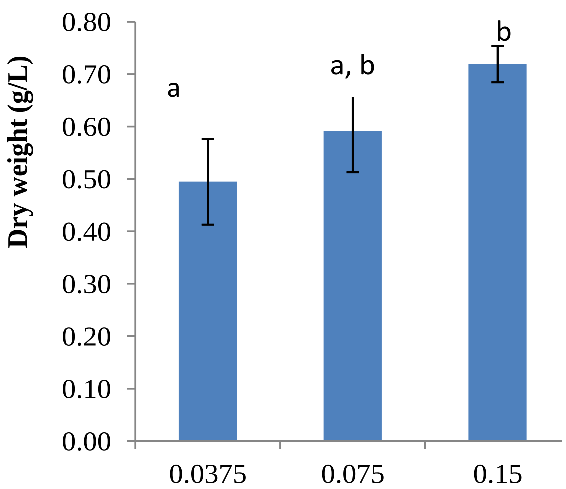


Figure 1: Dry weight of *C. calcitrans* under different nitrate concentrations

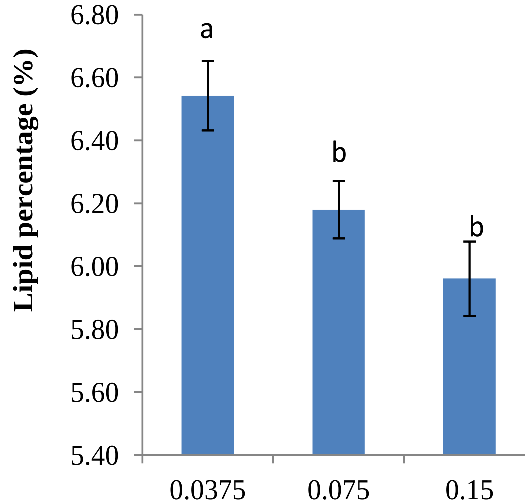


Figure 2: Percentage lipid content of *C. calcitrans* under different nitrate concentrations

*Different letters above the columns indicate values are significantly different ($p < 0.05$)

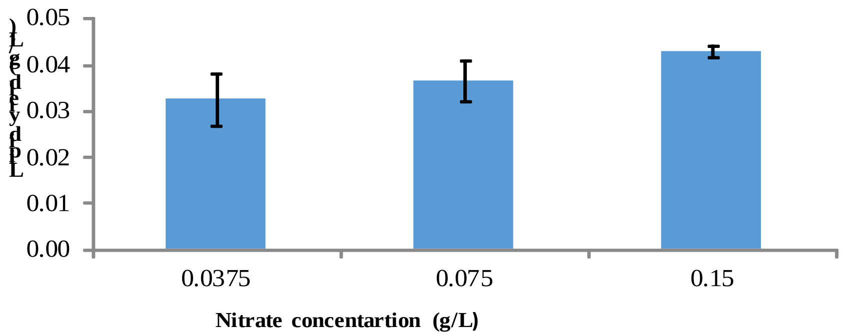


Figure 3: Lipid yield (g/L) of *C. calcitrans* under different nitrate concentrations

Algae differ in their adaptability to salinity and based on their tolerance extent, they are grouped as halophilic (salt requiring for optimum growth) and halotolerant (having response mechanism that permits their existence in saline medium). The effects of salinity on dry weight and lipid content of *C. calcitrans* are shown in Figure 04 and 05. According to ANOVA test, salinity has no significant effect ($P \leq 0.05$) on *C. calcitrans* growth and lipid content. At 25 ppt, 30 ppt and 35 ppt salinity levels, average dry weights and the % lipid contents were 0.64 g/L, 0.68 g/L, 0.66 g/ L and 6.3 %, 6.0 %, 5.7 % respectively. A similar salinity tolerance has been reported previously for *Nannochloropsis* sp by Hu and Gao (2006). Many freshwater species are also reported to withstand higher salinities (Ruangsomboon, 2014). Similarly, many marine forms can survive at lower salinity, but for their optimum growth they express specific requirements for additional salts (Rai and Rajashekhar, 2014). Rao et al. (2007) showed reduced growth in marine algae, *Botryococcus braunii* at higher salinities due to decrease in photosynthetic rate.

According to the present results, harvestable lipid yield from *C. calcitrans* cultured at 35 ppt salinity level with 0.075 g/L $NaNO_3$ in the Guillard and Ryther`s F/2 media was 120 g per $1m^2$ of tank with 25 cm depth per year with one month harvesting cycle under local climatic conditions. That gives 1200 kg of lipid per hectare per year.

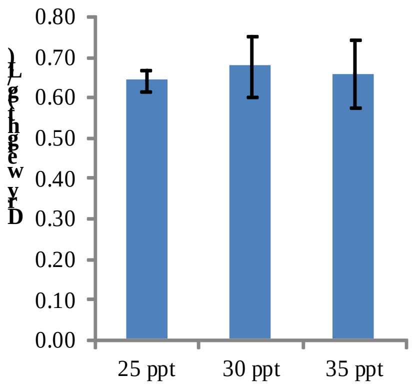


Figure 4: Dry weight (g/L) of *C. calcitrans* under different salinity levels

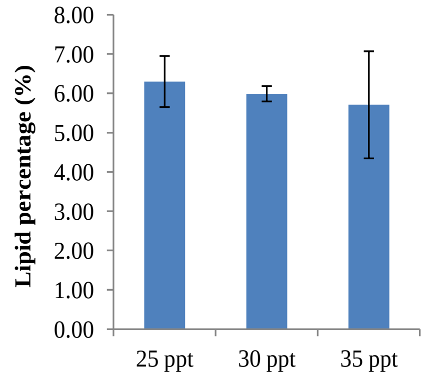


Figure 5: Percentage lipid content of *C. calcitrans* under different salinity levels

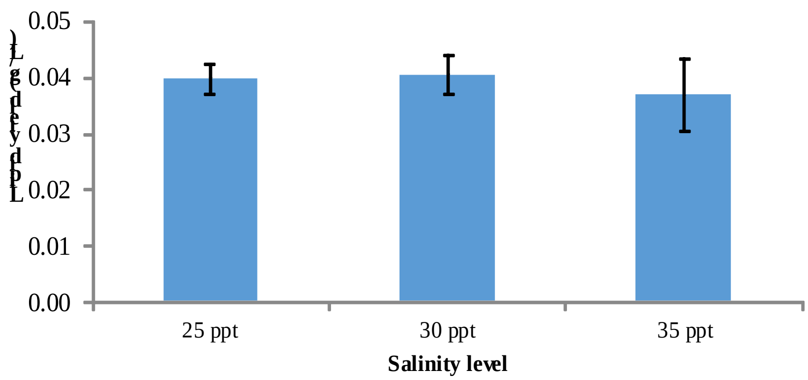


Figure 6: Lipid yield (g/L) of *C. calcitrans* under different salinity levels

4. Conclusion

C. calcitrans exhibited higher lipid content in nitrate deficient medium and tolerated a wide range of salinity. These characteristics indicate that this species might be a suitable candidate for future exploitation as an alternative renewable fuel source.

Acknowledgement

The financial assistance for this research work was provided by National Research Council Grant No. 11-195.

References

Bindhu, K.B. 2013. Optimum Nutritional Requirement for the growth of *Chaetoceros calcitrans*. *Research journal of marine sciences*, 1 (3): 1-9.

Chisti, Y. 2007. Biodiesel from microalgae. *Biotechnology advances* 25: 294-306.

Dayananda, C., Sarada, R., Shamala, T.R. and Ravishankar, G.A. 2006. Influence of Nitrogen sources on growth, hydrocarbon and fatty acid production by *Botryococcus braunii*. *Asian journal of plant sciences*, 5: 799-804.

Feng, P., Deng, Z., Fan, L. and Hu, Z. 2012. Lipid accumulation and growth characteristics of *Chlorella zofingiensis* under different nitrate and phosphate concentrations. *Journal of bioscience and bioengineering*, 114 (4): 405-410.

Gu, N., Lin, Q., Li, G., Tan, Y., Huang, L. and Lin, J. 2012. Effect of salinity on growth, biochemical composition, and lipid productivity of *Nannochloropsis oculata* CS 179. *Engineering in life sciences* 12 (5): 1-7.

Guillard, R.R.L. 1975. Culture of phytoplankton for feeding marine invertebrates. Plenum Press, New York, New York.

Hu, H. and Gao, K. 2006. Response of growth and fatty acid compositions of *Nannochloropsis* sp. to environmental factors under elevated CO_2 concentration. *Biotechnology letters*, 28: 987-992.

Huang, G., Chen, F., Wei, D., Zhang, X. and Chen, G. 2010. Biodiesel production by microalgal biotechnology. *Applied energy*, 87: 38-46.

McGinnis, K.M., Dempster, T.A. and Sommerfeld, M.R. 1997. Characterization of the growth and lipid content of the diatom *Chaetoceros muelleri*. *Journal of applied phycology*, 9: 19-24.

Montoyaa, E.Y.O., Carvalho, J.C.M. and Converti, A. 2010. Effect of temperature and nitrogen concentration on the growth and lipid content of *Nannochloropsis oculata* for biodiesel production. *Simosio Brasil Japao*.

Padmanabhan, A.M.R. and Stanley, A. 2012. Microalgae as an Oil Producer for Biofuel Applications. *Research journal of recent sciences*, 1 (3): 57-62.

Rai, S.V. and Rajashekhar, M. 2014. Effect of pH, salinity and temperature on the growth of six species of marine phytoplankton. *Journal of algal biomass utilization*, 5 (4): 55-59.

Rao, A.R., Dayananda, C., Sarada, R., Shamala, T.R. and Ravishankar, G.A. 2007. EVect of salinity on growth of green alga *Botryococcus braunii* and its constituents. *Bioresource technology*, 98: 560-564.

Ruangsomboon, S. 2014. Effect of Media and Salinity on Lipid Content of Cyanobacterium *Hapalosiphon* sp. *Chiang Mai journal of sciences*, 41(2): 307-315.

Sakthivel, R., Elumalai, S. and Mohommad, M. 2011. Microalgae lipid research, past, present: A critical review for biodiesel production, in the future. *Journal of experimental sciences*, 2 (10): 29-49.

Sharma, K.K., Schuhmann, H. and Schenk, P.M. 2012. High lipid induction in microalgae for biodiesel production. *Energies*, 5: 1532-1553.

Surendhiran, D. and Vijay, M. 2012. Microalgal biodiesel - A comprehensive review on the potential and alternative biofuel. *Research journal of chemical sciences*, 2 (11): 71-82.

Grid Integration of Large Scale Fixed Speed Wind Farm Considering Static Voltage Stability

N.W.A. Lidula[1*], N. Mithulananthan[2]

[1] *Department of Electrical Engineering, University of Moratuwa, Sri Lanka*
[2] *School of Information Technology and Electrical Engineering, The University of Queensland, Australia*

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

This paper addresses the influence of integrating a large-scale wind farm on static voltage stability of a power system based on the factors such as, wind speed, wind farm interconnection bus, interconnection cable length and wind farm size. Using the continuation power flow method effects of each factor were analyzed and an index is proposed to locate a large scale fixed speed wind farm in a power system.

Keywords: continuation power flow, static voltage stability, wind farms, wind farm placement index

1. Introduction

The total installed capacity of wind power, around the world, at the end of year 2013 was 318 GW where 35 GW was added during 2013. It is expected that large scale electricity production from wind power will continue to be increased in the coming years (Ackermann, 2005)

A wind farm can cause local as well as system wide impacts on power systems. Local impacts occur due to each turbine or farm and are largely independent of the overall wind power penetration level in the system. Wind power locally has an impact on branch flows and node voltages, protection schemes, fault currents, and switchgear ratings, harmonic distortion and voltage flicker. System-wide impacts are the impacts that affect the behaviour of the system as a whole. They are strongly related to the wind power penetration level and the terminal characteristics of wind turbine or wind farm. Higher penetration levels of wind power could affect power system dynamics and stability, reactive power and voltage control, frequency control and load following/ dispatch of conventional units (Slootweg and Kling, 2003).

2. Methodology

In this paper, an index to identify the optimum location for wind farm placement is proposed considering static voltage stability of power systems. Possible wind farm sites are considered to be identified earlier and can be ranked using the proposed index. A comprehensive analysis of different factors such as wind speed, wind farm interconnection bus, interconnection cable length and wind farm size that have an influence on the static voltage stability was carried out as foundation to form the proposed index.

2.1 Wind turbine technologies and modeling

Wind turbines can be designed to operate either at fixed speed or variable speed. There are four basic wind turbine technologies currently in use, namely, fixed speed, limited variable speed, doubly fed induction generator (DFIG) and variable speed with full-scale frequency converter (Sahin , 2004). According to the market share, by year 2009, it has been found that use of DFIG was 65 % while use of fixed speed turbine was only 5 % but still has some interest because they are simple, robust, and reliable. Cost of the electrical parts is also low (Arántegui et al. 2013). Major problem is that squirrel cage induction generators (SCIGs) absorb reactive power from the system. Therefore, full load power factor is relatively low and is compensated by connecting capacitors in parallel to the generator (Sahin 2004). This paper concentrates on these fixed speed wind farms, considering its inability to produce its own excitation current.For a wind rotor of cross sectional area A, if density of air is ρ and wind speed is υ, the power P in the wind stream available for the rotor can be expressed as (Ackermann, 2005).

[*] *Correspondence: lidula@elect.mrt.ac.lk*
ISSN 2478-0669 Print

$$P = \frac{1}{2}\rho A v^3 \qquad 1$$

PQ characteristic of the fixed speed wind turbine is approximately a parabola with zero-slope at no-load operation. This can be represented by equation 2, where, Q_{NL} is the induction generator no-load reactive power absorption and "a" is a coefficient, which depends on the turbine design (Vladislav and Hans, 2002)

$$Q = Q_{NL} + aP^2 \qquad 2$$

"Middelgrunden" wind farm in Denmark was selected in this work and the PQ characteristic curve of the turbines in the farm is given by equation 3, which was derived by manufacturer's data.

$$Q = -0.0778P^2 - 470 \qquad 3$$

For static voltage stability, terminal characteristics, especially active and reactive power exchanges are important. Thus, wind farm is represented as a negative PQ load in the simulation, i.e. active power output of the wind farm was considered negative and reactive power absorption of the wind farm is considered positive.

2.2 The phenomenon of static voltage stability

There should be adequate reactive power locally available for the power system to avoid voltage instability. The phenomenon of static voltage stability can be illustrated as a plot of the power transferred versus the voltage at receiving end, which is most commonly known as "PV curve" or "nose curve". The power systems are operated in the upper part of the curve where it is "stable". Power system becomes voltage unstable at the nose point or critical point. Before reaching the critical point, a large voltage drop due to heavy reactive power losses can be observed in the PV curve. Continuation power flow method is employed to trace the PV curve in this study considering the fact that, it not only gives the nose point of the PV curve, but also provides sensitivity factors such as voltage tangent vectors, which is useful in the analysis.

2.3 Formulating the wind farm placement index

Wind speed, wind farm interconnection bus and wind farm interconnection cable length could be considered as some major factors that would affect the static voltage stability of a power system.

2.3.1 Wind speed

Wind power production is proportional to cubic power of the wind speed. This would result in low power outputs at low wind speeds and comparatively very high outputs at higher wind speeds. PQ-characteristic can be represented by (substituting 1 in 3).

$$Q = -0.0778k^2v^6 - 470 \qquad 4$$

Reactive power absorption of the wind farm is nearly proportional to the sixth power of wind speed, where k (= 0.5ρA) is a constant. This would result in very high reactive power absorption at high wind speeds and low power factor at low wind speeds.

2.3.2 Wind farm interconnection bus-bar

In (Saha, 2004) , it is concluded that connecting the wind farm at higher voltage levels reduces the risk of static voltage instability. Since fixed speed wind turbines absorb reactive power, the interconnection bus should not be a "weak" bus. The tangent vectors (TV) of the bus-bars near collapse point can be used in determining the relative weakness of system bus-bars. Also, if the selected bus-bar shares power with many other loads connected to a single node of a major grid, it is weaker in the power transfer capability.

2.3.3 Wind farm interconnection cable length

Inductive reactance increases with cable length. Thus, reactive power losses increase with the increase in line length, which would demand more reactive power from power system.

2.3.4 The wind farm placement index

First, high wind potential areas should be selected where a large wind farm could be built. If the selected bus-bars are j = 1, 2…, n; several rankings are introduced according to the three major factors discussed above. For each factor, the bus-bar having the *lowest ranking value* is defined to be the most preferred in that particular factor.

2.3.4.1 R_{wj} - Wind speed rank of bus j

The general wind resource classification, which is shown in the Table 1, is used in formulating the "wind speed rank". It has classified the wind resources from poor to excellent considering the active power outputs.

However, reactive power absorption increases with increasing wind speed (w), which weakens the power system. Therefore, following procedure is proposed in wind speed ranking (R_{wj}), which selects wind speeds in-between 6ms^{-1} and 9ms^{-1} as the most preferred wind speed range.

If $9 > w_j > 6$ Then $R_{wj} = 1$ (*preferred range*)
Else If $w_j \leq 6$ Then $R_{wj} = 2$
Else If $w_j \geq 9$ Then $R_{wj} = 3$

Table 1: Wind resource classification

Wind Speed at 65m (ms^{-1})	Power Density at 65m (Wm^{-2})	Suitability for Large Wind Turbines
< 6	< 250	Poor
6.0 – 7.0	250 – 400	Fair
7.0 – 8.0	400 – 600	Good
8.0 – 9.0	600 – 850	Very Good
> 9.0	> 850	Excellent

2.3.4.2 R_{Vj} - Voltage rank of bus j

R_{Vj} index is formulated by ranking the bus-bars according to their voltage level. Generator buses and buses having SVC are given the highest priority assigning a zero for R_{Vj} since synchronous generators and SVCs regulate the bus voltage. The procedure could be formulated as follows:

If j = generator bus or having SVC , Then $R_{Vj} = 0$
Else Rank bus-bars from higher voltage level to lower *(Higher the voltage level more preferred the bus)*

2.3.4.3 $R_{TV\,j}$ - Voltage tangent vector rank of bus j

R_{TVj} is formulated considering the inverse voltage tangent vectors (TV) of the bus-bars near the collapse point. i.e.:

Find $1/TV$
Rank bus-bars from higher value to lower (*Lower the tangent vector more preferred the bus*)

2.3.4.4 R_{lj} - Interconnection cable length rank of bus j

Inverse of the required cable/line lengths to interconnect the wind farm to the bus-bar j is considered in formulating R_{lj}.

Find 1/ (Cable length)
Rank bus-bars from higher value to lower (*shorter the cable length more preferred the bus*)

2.3.4.5 i_{grid} – Index of grid connection of bus j

i_{grid} is formulated considering the fact, whether the bus j is within the major power system grid or in a separate small mesh of load busses connecting to a single node of the major grid. The method of evaluation is as follows:

If j = node of the major power system grid
Then $i_{grid} = 0$
Else i_{grid} = number of busses in the small mesh of load buses getting connected to the single node of the major grid *(smaller the no. of busses in the group more preferred the bus)*

2.3.4.6 I_{wpj} - Wind farm placement index of bus j

The overall "Wind Farm Placement Index" (I_{wpj}) is formulated using all the above discussed indices. Equation (5) explains the final index.

$$I_{wpj} = R_{wj} + C_v R_{Vj} + \frac{1}{C_{TV}} R_{TVj} + \frac{1}{C_l} R_{lj} + i_{grid}$$

Where; I	=	wind farm placement index of bus j
R_{wj}	=	wind speed rank of bus j
R_{Vj}	=	voltage rank of bus j
R_{TVj}	=	voltage Tangent Vector rank of bus j
R_{lj}	=	interconnection cable length rank of bus j
i_{grid}	=	index of Grid connection of bus j
C_V	=	1.5
C_{TV}	=	0.375n where, n = number of bus-bars of concern

If $\forall j \quad 1 \leq L_j \leq 10$ km,

where, L_j = Interconnection cable length to bus j

Then $C_l = 2$

Else $C_l = 1$

The coefficients C_V, C_{TV} and C_l were introduced to include a weight to different factors considering their level of effect on static voltage stability of a power system. The values of the coefficients are found by analyzing the simulation results.

2.4 Test system and analytical tools

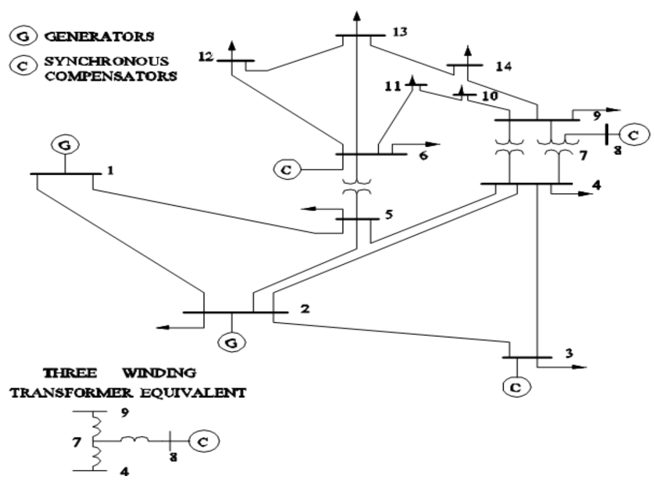


Figure 1: IEEE 14-bus system

The IEEE 14 bus test system shown in Fig. 1 was used in this study and the wind farm was modeled based on the “Middelgrunden” wind farm in Denmark considering the availability of online data. The Middelgrunden wind farm has 20 fixed speed wind turbines, each at 2 MW and the average wind speed is around 7~ 8 ms^{-1}.

Per unit power outputs and the power factor of wind farm at different wind speeds is plotted in Figure 2. Figure shows that the power factor is low at low wind speeds and increases up to a maximum of 0.85 at 9.5ms^{-1} wind speed and stays constant thereafter. Power factor correction capacitor compensation is not considered here. Reactive power consumption of the wind farm stays nearly constant around 0.2 pu up to about 8 ms^{-1} wind speed and it increases to 0.4 pu around 12 ms^{-1} which becomes more than 0.5 pu at 14 ms^{-1}.

Continuous power flow analysis was performed using the UWPFLOW software. UWPFLOW is a research tool that is designed to determine maximum loadability margins in power systems associated with bifurcations. Maximum loadability of the IEEE 14 bus system is 0.704 pu. Table 2 illustrates tangent vectors of the bus-bars near collapse point, rated voltage level and bus type of the IEEE 14-bus system. The weakest bus of the IEEE 14-bus system is identified as bus 14, which has the highest tangent vector (Mithulananthan, 1997). Buses 2, 4, 6 and 14 were selected as the candidate locations for wind farm to study its effect.

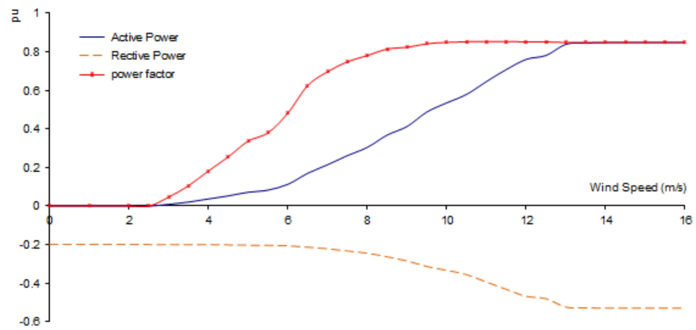


Figure 2: Per unit (pu) output vs. wind speed

Table 2: IEEE-14 bus system – bus details

Bus No.	Voltage (kV)	Bus Type	Normalized Tangent Vector near Collapse (TV)
2	69.0	Generator	0.003968
4	69.0	Load	0.008019
6	13.8	Load + Synchronous Compensator	0.012139
14	13.8	Load	0.014546

3. Results and Discussion

3.1 Influence of wind speed

PV curves of the system, when the wind farm is connected at the weakest bus (Bus 14) are shown in Figure 3. It shows that the system maximum loadability changes with the changing wind speed and system becomes even weaker with the introduction of the wind farm at the weakest Bus. At 3 ms^{-1} wind speed, loadability has reduced by 8.9% from that without the wind farm. According to Figure 2, there is a lower power factor at low wind speeds giving low loadability levels. Loadability then increases with the increasing wind speeds and at 7 ms^{-1} wind speed, loadability reduction is only 3.6%. However, loadability again starts to decrease and there is 59% reduction at 14ms^{-1} wind speed compared to the loadability without integrating the windfarm. When compared with Figure 2, for wind speeds above 8 ms^{-1}, there is a higher reactive power absorption by the wind farm. Thus, with the reduced reactive power reserve in the system at high wind speeds, power system is more prone to voltage collapse within very low loading margin.

It shows that the wind speed has significant effect on static voltage stability of a power system. Also it could be highlighted that wind speed in between 6 ms^{-1} and 9 ms^{-1} has the minimum effect on voltage stability, while wind speeds higher than 9 ms^{-1} affect the system the most. Thus, it would be more preferable to go for a site with an average wind speed in between 6 ms^{-1} and 9 ms^{-1} to build up a large scale wind farm. However, introducing a wind farm at the weakest Bus of a system further weakens the power system.

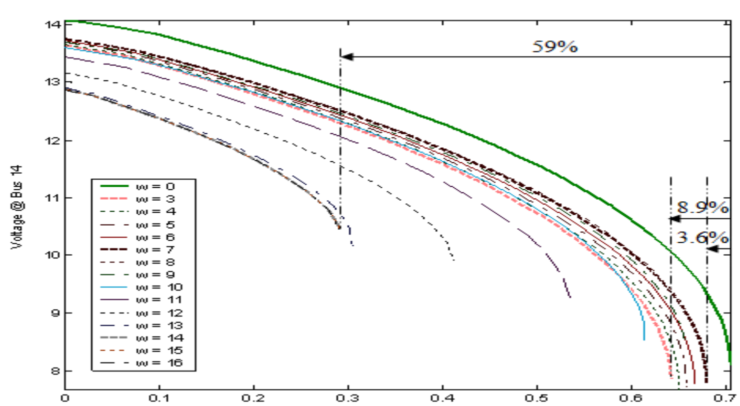


Figure 3: PV curves with changing wind speed when wind farm at bus 14

3.2 Influence of wind farm interconnection bus

Figure 4 illustrates the power system loadability with changing wind speeds when the wind farm is connected to the buses 2, 4, 6 and 14 respectively. Variation of maximum loadability of a power system with varying wind speeds is higher when wind farm is connected to a weaker bus and insignificant if a generator bus. The variation is comparatively low if wind farm is connected to a bus having a higher voltage level. Similar results were observed (which is shown in Figure 5), when the voltage profiles of bus 14, the weakest bus with changing wind speed was analysed.

Variation of maximum loadability of a power system with varying wind speeds is much higher when the wind farm is connected to a weaker Bus and much less if it is connected to a generator Bus. The variation is comparatively low if wind farm is connected to a higher voltage level Bus. Also when Bus 6 and Bus 14 are compared, it is clear that loadability can be improved by reactive power compensation. As a whole it reveals that the grid connection position of the wind farm and the wind speed in the wind farm have a considerable effect on static voltage stability of a power system.

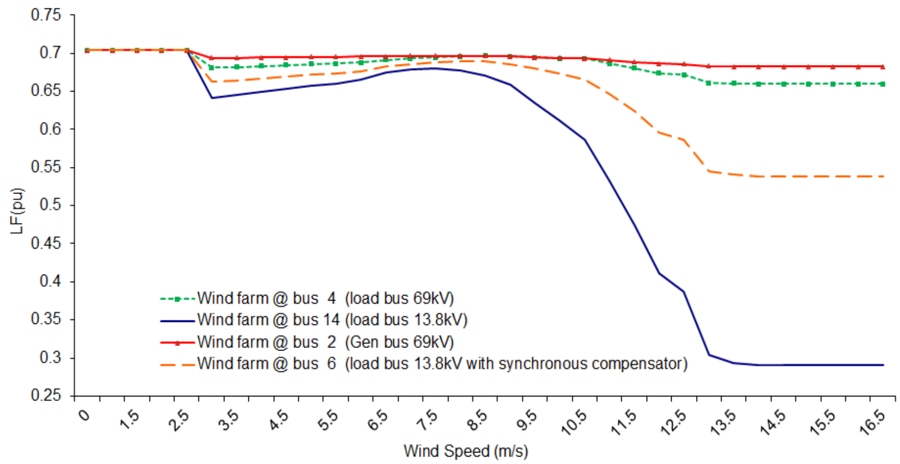


Figure 4: Power system loadability with changing wind speed

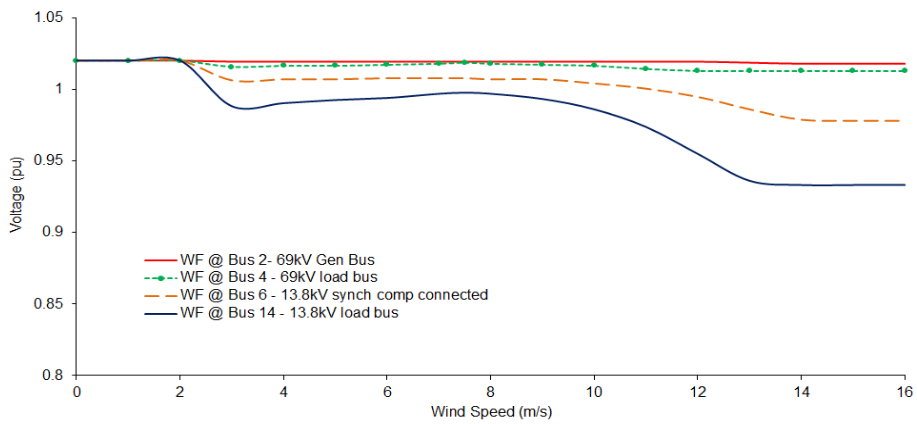


Figure 5: Variation of bus 14 base voltage with changing wind speed

3.3 Influence of wind farm capacity

Power system maximum loadability change with changing wind farm capacity is shown in Figure 6. The results were obtained for the four cases: wind farm at the weakest and the strongest bus at two different wind speeds. For the IEEE-14 bus system, regardless of the wind farm location, change of loadability is insignificant up to 10 wind turbines where the total wind farm capacity is 20 MW (3.9 % of the load). Thereafter, system loadability decreases with the increasing number of wind turbines. Also, higher wind speeds give a better loadability up to a certain level of wind capacity, which depends on where the wind farm is connected. If same wind speed 5.5 ms^{-1} is considered, power system loadability has reduced by nearly 92%, if a wind farm having 75 wind turbines (30 % of load) is connected to bus 14. But, if the wind farm is connected at bus 2, reduction in system loadability is only 9% even after the number of wind turbines is increased to 100 (38.6 % of load).

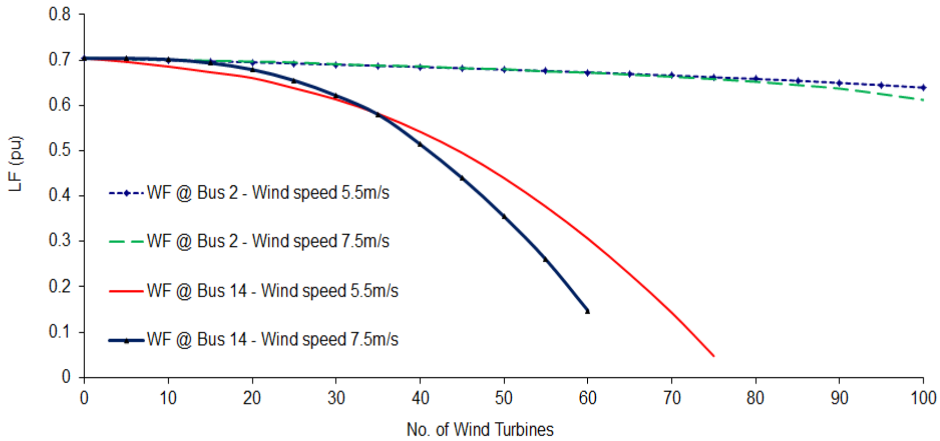


Figure 6: Change of power system loadability with increasing wind penetration

3.4 Influence of wind farm interconnection cable length

Figure 7 illustrates the relationship between the cable length and the loadability of the power system when the wind farm is connected to Bus 14, the weakest bus of the IEEE 14 bus system. Static voltage stability of the power system weakens with the increasing cable length. With the increasing cable length the system collapses in a higher voltage and also the maximum load factor of the power system reduces. According to the results for a 20 km cable length there is about 9% reduction in the maximum load factor of the system and for 50 km length cable there is around 40% reduction in the system loadability compared to a 1 km length interconnection cable.

Thus, it could be concluded that the wind farm interconnection cable length has an adverse effect on the static voltage stability of the power system. Higher the cable length more would be the effect on system loadability and this should be considered in placing a wind farm.

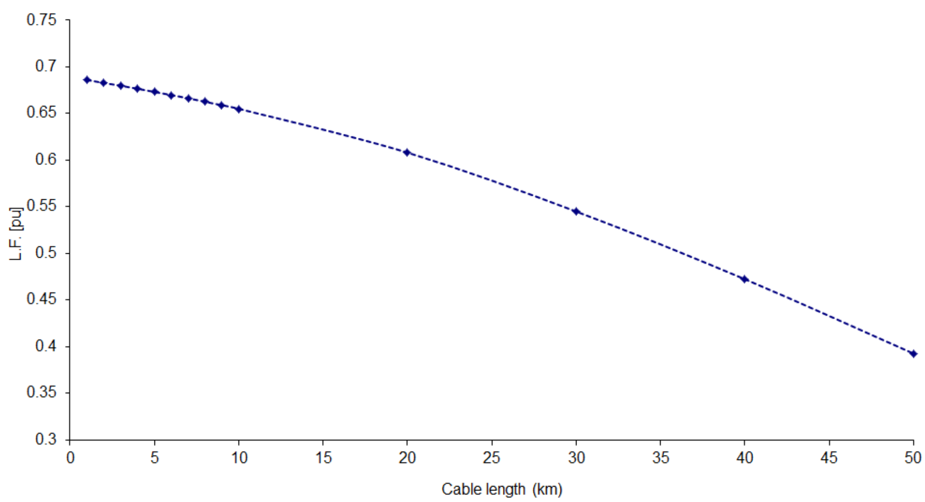


Figure 7: Variation of system loadability with changing wind farm interconnection cable length

3.5 Influence of reactive power compensation

Figure 8 illustrates the effect on maximum loadability of the power system when reactive power compensation is introduced at the wind farm interconnection point. Results are shown when the wind farm is connected to bus 14, the weakest bus of the IEEE 14 bus system. The optimal size of the shunt compensation was determined by computing the maximum amount of reactive power placed at the optimal location that gives the maximum value of loadability (Claudio and Alvarado, 1999). In selecting the capacitor size, it is necessary to compromise between the loadability and the node voltage. Reactive power compensation, either with shunt capacitance or SVC, improves the maximum loadability of a power system.

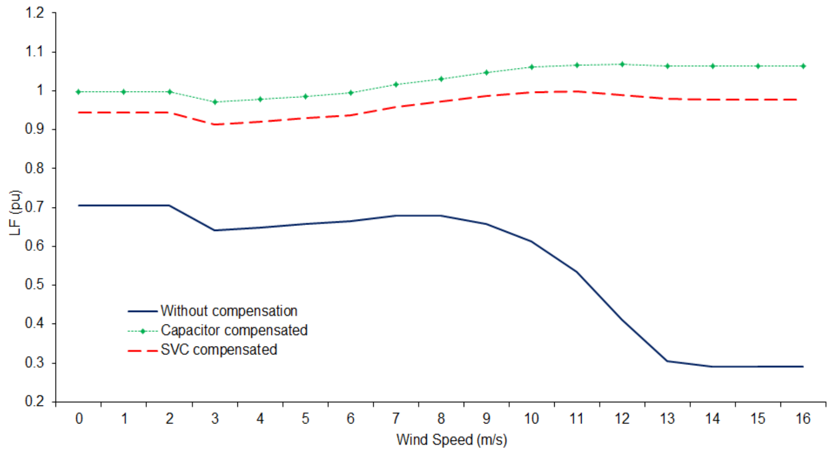


Figure 8: Variation of loadability with changing wind speed for Capacitor and SVC compensations

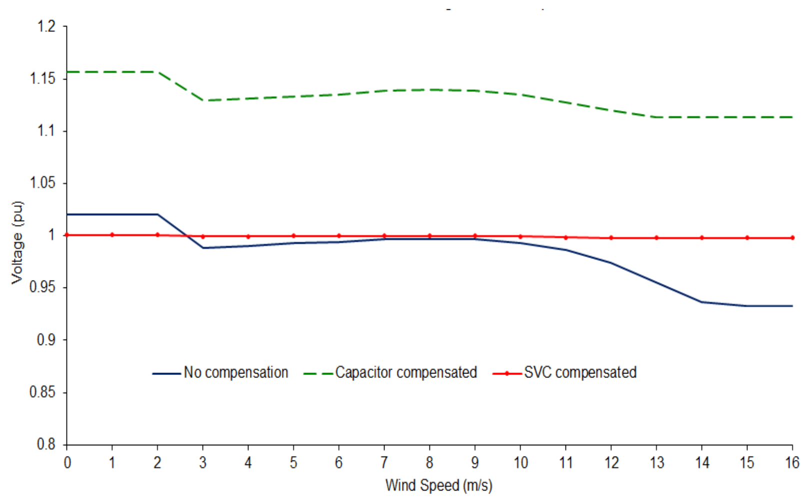


Figure 9: Voltage at bus 14 with changing wind speeds for capacitor and SVC compensations

Figure 9 illustrates the voltage variation of bus 14, the weakest bus with varying wind speed. Adding a shunt capacitor has boosted the voltage and there is no voltage regulation. But, with SVC compensation node voltage has maintained at and around 1 pu, without any considerable variation with the changing wind speed.

Considering both Figures 8 and 9, it can be concluded that connecting an SVC at the wind farm interconnection point is the most suitable option to improve the static voltage stability of a power system having a wind farm. It not only increases the loadability of the power system but also regulates the voltage at desired level without any variation with the changing wind speed.

3.6 Application of wind farm placement index

The proposed wind farm placement index was applied to the IEEE 14 bus. Buses 2, 4, 6 and 14 were selected with hypothetical wind potential of 5.5, 8, 6 and 7.5ms^{-1} respectively. Wind farm is assumed to be connected to the corresponding bus using 3, 5, 2 and 3km long cables. Table 3 summarizes the system conditions and Table 4 summarizes the calculation of the wind farm placement index.

The coefficients were found as: C_V =1.5; C_{TV} =0.375×4 =1.5; since $\forall j \;\; 1 \leq$ Lj $\leq$10 km, C_{lj}= 2. According to Table 4, bus 2 has the lowest index, which could be considered as the best position to place a large wind farm. Considering the increasing value of I_{WPj}, second and third preferences go to buses 4 and 6, respectively while bus 14 is at the least preference. The results are verified by doing the continuation power flow analysis for the four cases where wind farm is connected at buses 2, 4, 6 and 14, respectively. Figure 10 illustrates the results obtained, which is exactly in agreement with the results given in Table 4.

Table 3: Conditions of selected buses of IEEE-14 bus system

Bus No.	Wind speed (ms^{-1})	Voltage (kV)	Tangent Vector (TV)	1/TV	Cable length (km)	1/Cable length
2	5.5	69.0 (Gen.)	0.00397	252.0161	3	0.333
4	8.0	69.0 (Load)	0.00802	124.7038	5	0.200
6	6.0	13.8 (Load)	0.01214	82.37911	2	0.500
14	7.5	13.8 (Load)	0.01455	68.74742	3	0.333

Table 4: Calculation of wind farm placement index for IEEE-14 Bus System

Bus No	R_{wj}	$C_V R_{Vj}$	R_{TVj}/C_{TV}	R_{lj}/C_l	$i_{grid,j}$	I_{WPj}	Rank
2	2	0	0.67	1.0	0	3.67	1
4	1	1.5	1.33	1.5	0	5.33	2
6	2	3.0	2.00	0.5	0	7.50	3
14	1	3.0	2.67	1.0	0	7.67	4

4. Conclusion

The paper proposes an index to place a large-scale conventional wind farm in power systems. This index is entirely based on the static voltage stability of power systems.

For a static voltage stability study, it is possible to find the total wind farm output by scaling up a single wind turbine output, if the wind turbines are situated in a line. If power systems have lack of reactive power, system loadability reduces at low wind speeds, and then increases with the increasing wind speed up to about 8 ms^{-1}, which starts to fall considerably thereafter. If the system is capable of providing reactive power or if it is provided with SVC, system loadability increases with the increasing wind speed. If the bus voltage is higher, system maximum loadability and node voltage change with changing wind speed is significantly low. If the interconnection bus is a generator bus, effect on static voltage stability is insignificant. The importance of the relative strength depends on the number of buses of concern. Relative strength of the bus-bars can be determined from the voltage tangent vectors of the buses. It is preferred if the selected bus is within the major power grid. Shorter the wind farm interconnection cable length less the effect on static voltage stability and more preferred would be the site.

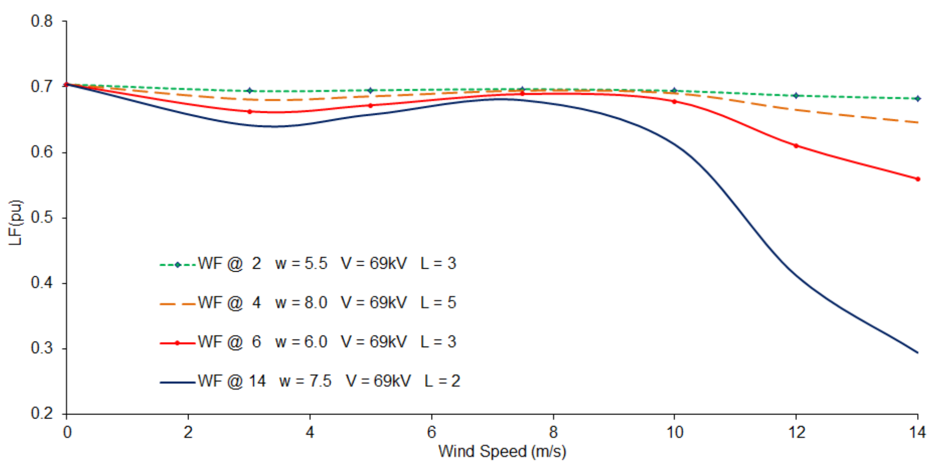


Figure 10: System loadability variation with changing wind speed – IEEE-14 bus system

Application of the proposed "Wind Farm Placement Index" in IEEE 14 bus test system showed that the proposed index exactly picks up the most suitable bus to place a wind farm by ranking the buses in the preferred order. Connecting an SVC at the wind farm interconnection point is the desirable option to improve static voltage stability compared to shunt capacitor. Unlike shunt capacitor, SVC regulates the node voltage while increasing the system loadability.

References

Arántegui, R.L., Corsatea, T. and Suomalainen, K. 2013. Technology, market and economic aspects of wind energy in Europe, 2012 JRC wind status report, Luxembourg: Publications Office of the European Union.

Guptha, R.K., Alaywan, Z.A., Stuart, R.B. and Reece, T.A. 1990. Steady State Voltage Instability Operations Perspective, IEEE Transactions on Power Systems, Vol.5 (4): 1345-1354.

Slootweg, J.G. and Kling, W.L. 2004. Is the Answer Blowing in the Wind?, IEE Power and Energy Magazine: 26-33.

Ackermann , T. 2005. Wind Power in Power Systems, England, John Wiley and Sons, Ltd: 7-23.

Claudio, A. and Alvarado, A.F. 1999. Program Description, UWPFLOW Continuation and Direct Methods to Locate Fold Bifurcations in AC/DC/FACTS Power Systems.

Claudio, A., Cañizares, Z. and Faur, T. 1999. Analysis of SVC and TCSC Controllers in Voltage Collapse, IEEE Transactions on Power Systems, Vol.14 (1): 158-165.

Electric Systems Consulting-ABB Inc. 2004. Integration of Wind Energy into the Alberta Electric System – Stages 2 and 3: Planning and Interconnection Criteria, Prepared for Alberta Electric System Operator, Report Number:10803 -2 .R01.4.

Eriksen, P.B., Ackermann, T., Abildgaard, H., Paul, W.W. and García J.M.R. 2005. System Operation with High Wind Penetration, IEEE power and energy magazine.

Kundur, P. 1993. Voltage Stability, Power System Stability and Control, McGraw-Hill, Inc: 959-1024.

Lundberg, S. 2000. Electrical limiting factors for wind energy installations, Institutionen för elteknik, Examensarbete 50E, Göteborg, Sweden.

Middelgrunden Wind Turbine Cooperative. 2001. [http://www.middelgrunden.dk/MG_UK/project_info/ production.htm#powe]

Mithulananthan, N. 1997. Voltage Stability Study of the Sri Lankan Power System Grid.

Saha, T.K. and Ha, L.T. 2004. Investigation of Power Losses and Voltage Stability Limits for Large Wind Farm Connections to a Subtransmission Network, IEEE.

Sahin, A.D. 2004. Progress and recent trends in wind energy, Progress in Energy and Combustion Science 30: 501-543.

Sami, R. 2001. Online Voltage Stability Assessment of Power System – An Approach of Black Box Modelling, Tampere University of Technology Publications.

The Global Wind Energy Council. Global Wind Report Annual Market Update 2013. [http://www.gwec.net/wp-ontent/uploads/2014/04/GWEC-Global-Wind-Report_9-April-2014.pdf]

Vladislav A. and Hans K. 2002. An aggregate model of a grid-connected, large scale, offshore wind farm for power stability investigations – importance of windmill mechanical system, Electrical Power and Energy Systems 24: 709-717.

Vladislav, A., Hans, K., Arne, H.N., JØrgen, K.P. and Niels, K.P. 2003. Modelling and Transient Stability of Large Wind Farms, Electrical Power and Energy Systems 25: 123-144.

Yome, A.S., Mithulananthan, N. and Lee, Y. 2005. Effect of Realistic Load Direction in Static Voltage Stability Study, IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific, Dalian, China.

Feasibility of Solar PV Integration in to the Grid Connected Telecom Base Stations

A.S. Rodrigo* and K. Wijesinghe

Department of Electrical Engineering, University of Moratuwa, Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Integrated Solar PV in scalable on to the grid connected and standalone power generation system has drawn increased attention these days due to its sustainability and greener generation. This has become a good option to reduce the utility power consumption of telecom Radio Base Stations. The techno economic feasibility of Solar PV integration methodologies in to On-Grid telecom based stations, basically in to the DC bus by rectifier systems comprising of inbuilt DC to DC converting Solar PV charger controllers or in to the A/C bus through grid tie inverter system facilitated with "Net metering" are discussed in this paper. It was found that it is feasible to integrate Solar PV in to on grid sites with different tariff structures.

Keywords: renewable, solar photovoltaic, economic feasibility, net-metering, telecom, base station

1. Introduction

Price of electricity is increasing worldwide with depletion of non-renewable sources in global context, even true in local. Therefore, there is a global trend of moving towards sustainability and green energy generation. There is a trend of combining diesel power with renewables like solar and wind to reduce the fuel cost (Solangi, 2011).

There are large numbers of telecom Radio Base Stations (RBSes) in Sri Lanka, which are on grid and off-grid, operated by different telecom operators. Most of these sites are located at unpopulated hill tops, where national power grid is not available or not reliable. Therefore, most of telecom operators in Sri Lanka rely on standby diesel power generation. Thus, the major operating cost of these sites is the fuel cost for diesel power generation. Due to the global trend of moving towards sustainability and green energy generation and to reduce their fuel cost, Sri Lankan telecommunication companies are also now focusing on renewable energy generation for their base stations. Some of the Off-Grid renewable energy generation systems have been proved to be economically viable and are able to provide a green light to focus more on Hybrid energy system for future deployments. However, for On-Grid sites, less effort has been taken for renewable energy integration.

Therefore, the major objectives of this study were to clearly identify whether it is technically and economically feasible to integrate Solar PV in to the On-Grid Telecommunication Radio Bases Stations and to benchmark feasible telecom RBSes with their Power-loading patterns, space availability and different tariff structures.

1.1 Alternative energy systems for telecommunication radio base stations

There are several non- conventional energy generating methods, which can be used to power up telecommunication base stations. However, the selection of an alternative energy system for a particular site has to be carried out through careful study of the pros and cons of individual energy generating techniques. The most popular alternative energy generating technologies for telecommunication base stations are as follows (Boyle and Godfrey, 2004)

1.1.1 Solar photovoltaic (PV) energy

Being a country closer to the equator, the possibility of using the solar photovoltaic energy is high in Sri Lanka, as the number of daylight hours are high compared to countries away from the equator and the seasonal variation is almost negligible.

* *Correspodence: asanka@elect.mrt.ac.lk*
ISSN 2478-0669 Print

1.1.2 Wind energy

Wind energy distribution from point to point may differ depending on the altitude, geographical variations, landscaping of the area and obstacles in the wind flow path. Therefore, it is not predictable unless onsite observations are made.

1.1.3 Fuel cell

Hydrogen fuel cell technology is used in telecommunication base stations as an alternative power generating method, but the application is mainly used as a backup power source. Therefore, it cannot be termed as a retrofitter for diesel generator of a site, which is operating full time on generator.

1.1.4 Pico hydro

Installing pico hydro plants for telecommunication base stations are not widely used and the initial investment for setting up a pico hydro plant is very high. In most cases, telecommunication base stations are located at high altitudes such as near the top most area of hills where water resource issues for operating pico hydro plants may arise.

1.1.5 Bio fuel

The application of bio fuel to telecommunications must be treated as a case-by-case prospect rather than a universal alternative. The primary consideration will be local access to a regional supply of bio fuel. The impact of biodiesel production upon regional agriculture should also be evaluated.

In Sri Lankan context, most of the Telecom RBSes are constructed as green field, self-support or guy mast towers, Roof Top sites with towers -ormono pole structures, indoor base stations etc. In urban areas, most of the telecom base stations are Roof Tops sites with grid connected outdoor models. Since majority of RBSes sites have surfaces facing the sun and simple structural requirements, and since there is the necessity for roof like shelters for most common RBSes available i.e. Outdoor RBSes models for operational convenience, integrating Solar PV in to On-Grid Base Stations can be deployed in mass scale than any other technologies discussed.

1.2 Solar PV Integration Methodologies in to On-Grid Telecom RBSes.

Basically there are two options available.

1.2.1 Option 1

Solar PV integration in to rectifier systems are comprising of inbuilt DC to DC converting Solar PV charger controllers with Maximum Power Point Tracking (MPPT) plus A/C to DC converting rectifier modules.

In here, a rectifier system comprising of A/C to DC converting rectifier modules and DC to DC converting Solar PV Charger Controllers with MPPT by introducing a sub rack to conventional rectifier systems to hold Solar PV Charger Controllers exist. This setup does not need a separate hardware for integrate Solar PV (PLCs) and there is no need of fast charging deep cyclic Valve Regulated Lead Acid (VRLA) Batteries. A typical arrangement of Solar PV integration in to Hybrid Controller, DC to DC converting Solar PV charger controllers with MPPT plus A/C to DC converting rectifier modules is shown in Figure 1.

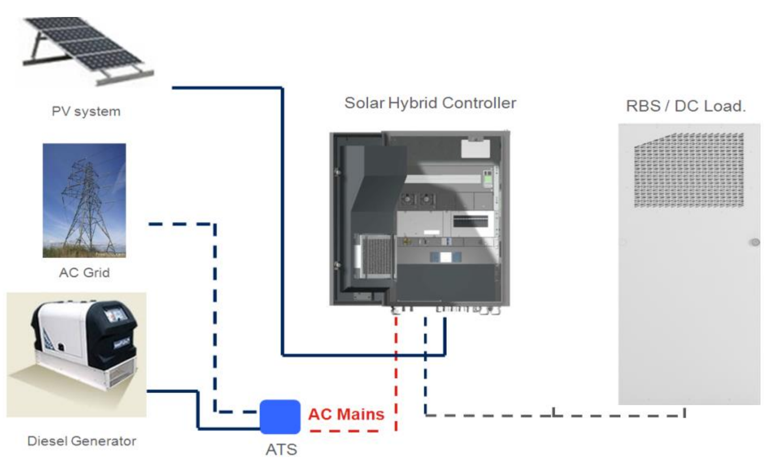


Figure 1: Solar PV integration in to hybrid controller

1.2.2 Option 2

Solar PV integration through grid tie inverter system facilitated with “Net metering”.

In here, the net metering is an electricity policy for consumers who own renewable energy facilities such as wind, Solar PV etc and allows them to use generation whenever possible, instead of just when generated. Under net metering, the system owner receives retail credit for at least a portion of the electricity they generate. A typical arrangement of Solar PV integrated grid tie inverter system applicable for “Net metering” is shown in Figure 2.

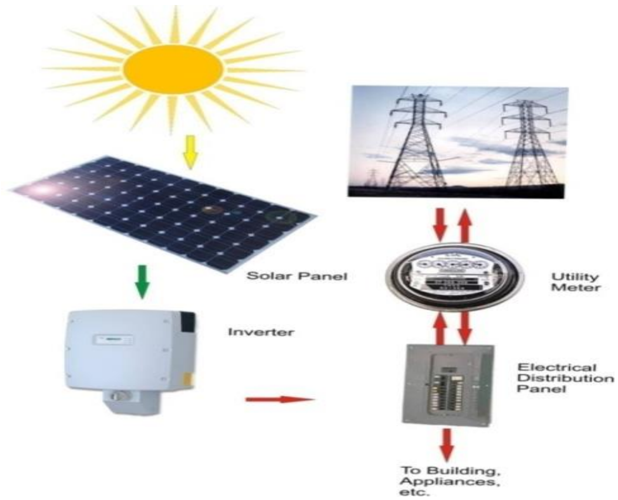


Figure 2: Solar PV integrated grid tie inverter system applicable for “Net metering”

This system has advantages of high efficient use of the system, long life span, the investment cost is somewhat lower, the use of the electricity will not be restricted by the system itself and the weather condition influence. However, the major disadvantage of this system is that the return of the electricity powered by solar will be restricted by the local public electricity net (Ex: Availability of healthy grid Voltage & Frequency, applicable tariff rate etc).

2. Methodology

2.1 Feasibility of solar PV integration to telecom RBSes: case study

This study focused on Radio Base Stations deployed for Access Network Coverage. Almost around 2414 numbers belong to one particular telecom operator scattered island wide among 9 operational regions. Out of them, the sites having sun facing nearby surfaces with sufficient spacing are extracted and categorized according to their power loadings and respective tariff classes. Then the best Solar PV sizing and integration methodology for each category was identified and financial paybacks were evaluated for the combinations of their power loading and respective tariff classes. Out of the 2414 sites there are 2272 sites which are possible for solar PV integration, since availability of Sun facing nearby surfaces are categorized according to their power loading levels. Site categorization according to the regional deployments is shown in Table 1.

Table 1: Site categorization according to the regional deployments

	Region	Site count	No space for solar PV*	Possible for solar PV by space	Site count under different power loadings		
					0 <Low<2 kW	2kW<Medium<4kW	4kW<High
1	Western Central	510	52	458	138	286	34
2	Western North	306	10	296	48	226	22
3	Western South	274	9	265	117	136	12
4	North Western	273	12	261	65	178	18
5	Southern	251	6	245	52	169	24
6	Central	238	11	227	63	143	21
7	North Central	236	8	228	72	133	23
8	Eastern	202	13	189	58	103	28
9	Northern	124	21	103	38	46	19
	Sub Total	2414	142	2272			

* No space on Cabin RT / Sun facing nearby Surface

2.2 Applicable tariffs

Three different tariffs are applicable for telecom RBSes in Sri Lanka. The first one is the domestic tariff rate (applicable to households). This is in block wise to offer subsidies and it would become an average unit cost of 58 Rs/kWh for consumptions around 2000 units per month, since on the average 2 kW constant loads are available in most telecom RBSes. Second type is the category of General Purpose (GP1), where a unit cost would be around 27 Rs/kWh after including 25% of fuel surcharge applicable at present. Third category is the special rates offered by the site owners, which is 50 Rs/ kWh in average. The tariff rates applicable to selected telecom service stations are summarized in Table 2.

Table 2: Site categorization according to the applicable tariff categories

	Region	PV integration possible site count	Site count under different tariff rates		
			D1	GP 1	Special (site owners)
1	Western Central	458	32	414	12
2	Western North	296	17	279	0
3	Western South	265	15	248	2
4	North Western	261	16	245	0
5	Southern	245	14	231	0
6	Central	227	12	215	0
7	North Central	228	18	210	0
8	Eastern	189	11	178	0
9	Northern	103	1	99	3
	Sub Total	2272	136	2119	17

3. Results and Discussion

The HOMER software is used as a design tool for simulating to integrate energy sources for telecom power setup. It includes equipment configuration, capacities, capital cost, replacement cost, operation and maintenance cost, characteristic curves and lifetime, hourly load profiles, renewable energy resource data with monthly average, rates of energy, emissions, cost and characteristics of fuel and project economics.

Following assumptions were made during the analysis;

- The life span of equipment, for batteries assumed to be minimum life of 5 years, each of rectifier modules for 15years, and for each of Solar PV panel lives up to 25 years of linear power output with a de-rating factor of 80%.
- Tariff rates are considered 27 Rs/kWh for GP1 and 58 Rs/kWh applicable for D1 since the energy consumption for most of the sites are having an average constant load of 2kW.
- Cost of Solar PV panels is taken as 1$/1W , 1.5 kW Solar PV DC to DC converting Solar PV Charger Controller module with MPPT is taken as 750 $ with same replacement costs with 15 years of life span.
- Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m^2/day) is same for all cases as derived from NASA Surface meteorology and for Colombo City with Latitude 6.54 and Longitude 79.50 was taken as 4.3 kWh/m^2/day.
- Panel Area of a 250W Solar PV with an average module with efficiency of 15.1% is 1.6 m^2.
- Price of 1 kW Solar PV Panels is USD 1000 and Price of 1.5 kW Solar PV DC to DC charger controller with MPPT is USD 750.

Following different cases were analysed;

3.1 Option 1

Solar PV integration in to rectifier systems are comprising of inbuilt DC to DC converting Solar PV Charger Controllers with MPPT plus A/C to DC converting rectifier modules.

- Case 1: Size of 1kW Solar PV integration in to Rectifier System.
- Case 2: Size of 2 kW Solar PV integration in to Rectifier System.
- Case 3: Size of 3 kW Solar PV integration in to Rectifier System.

3.1 Option 2

Solar PV integration through grid tie inverter system facilitated with “Net metering”.

- Case 1: Size of 1 kW Solar PV integration in to Grid tie inverter for Net Metering.
- Case 2: Size of 2 kW Solar PV integration in to Grid tie inverter for Net Metering.

- Case 2: Size of 3 kW Solar PV integration in to Grid tie inverter for Net Metering.

The Economic Analysis of Solar PV integrations on to Rectifier Systems with different capacities of Solar PV array sizing against respective tariff categories are derived and tabulated in Table 3.

Table 3: Economic analysis of solar PV integrations on to rectifier system for different tariff categories

	Solar PV integration on to a Rectifier System					
Tariff Category	D1 (58 Rs/kWh)			GP1 (27 Rs/kWh)		
Solar PV Capacity	1 kW	2 kW	3 kW	1 kW	2 kW	3 kW
Panel Area required for Solar PV Installation with average module efficiency 15.1% (m^2)	6.40	12.80	19.2	6.4	12.8	19.2
Energy output - Daily (kWh/day)	4.16	8.32	12.48	4.16	8.32	12.48
Energy output - Monthly (kWh/month)	124.80	249.60	374.4	127.8	249.6	374.4
Required nos of 1.5 kW DC/DC Solar PV charger controllers with 96.5% efficiency	1.00	2.00	2.00	1.00	2.00	2.00
Energy on to the DC bus - Monthly (kWh/month)	120.00	240.00	360.00	120.00	240.00	360.00
Energy on to the DC bus - Yearly (kWh/year)	1,440.00	2,880.00	4,320.00	1,440.00	2,880.00	4,320.00
Annual Saving (LKR/year)	83,520.00	167,040.00	250,560.00	38,880.00	77,760.00	116,640.00
Total Investment (USD)	1,750.00	3,500.00	4,500.00	1,750.00	3,500.00	4,500.00
Total Investment (LKR)	227,500.00	455,000.00	585,000.00	227,500.00	455,000.00	585,000.00
Simple Pay Back in years.	2.72	2.72	2.33	5.85	5.85	5.01
NPV in LKR (r=10% p.a.)	598,405.85	598,405.85	598,405.85	178,684.55	373,872.81	696,573.09
IRR (%)	29.00	29.00	34.00	16.00	16.00	19.00

Case 3: Size of 3 kW Solar PV integration in to Grid tie inverter for Net Metering. Similarly, Economic analysis for option 2 was done and tabulated in Table 4.

4. Discussion and Conclusion

It can be seen that, systems having Solar PV energy DC output directly integrated on to the DC bus, have lesser paybacks than integrating it in to A/C bus through Grid tie inverter for Net Metering for both D1 and GP-1 tariff rates. It can also be seen that, higher the renewable energy fraction gives lesser the payback time, and installation for D1 tariff paybacks almost half of the time earlier corresponds to the GP-1 tariff rate.

For systems having Solar PV energy directly integrated on to the DC bus have positive NPVs under rate of depreciation 10% p.a. for all 1,2 and 3 kW installations under both D1 and GP-1, but better for tariff rate D1. Further, higher the renewable energy fraction gives higher NPV values with high IRRs. For systems having Solar PV energy integrating in to A/C bus through Grid tie inverter for Net Metering have similar results but lesser than corresponding Solar PV installations comes under D1 tariff rate.

For systems having Solar PV energy integrating in to A/C bus through Grid tie inverter for Net Metering comes under tariff rate GP-1, still have positive NPVs, and acceptable IRRs under rate of depreciation 10% p.a., is the lowest among all comparisons. Both types of Solar PV integration methods come under tariff rate D1, have high IRRs, almost twice that of the same capacity of Solar PV installations falling under the tariff category of GP-1. Also this rate is much higher than the present loan interest rates, as well as depreciation rates, implying much more robust good projects for D1 tariff category. (Due to Project IRR > Present Loan Interest > Inflation rate).
From financial point of view too, it can be seen that Solar PV energy integration directly on to the DC bus is much more financially beneficial than integrating it in to A/C bus through Grid tie inverter for Net Metering for telecom applications.

Table 4: Economic analysis of solar PV integration in to grid tie inverters for net metering with different tariff categories

Solar PV integration in to Grid tie inverter for Net Metering						
Tariff Category	D1 (58 Rs/kWh)			GP1 (27 Rs/kWh)		
Solar PV Installed Capacity	1 kW	2 kW	3 kW	1 kW	2 kW	3 kW
Panel Area required for Solar PV Installation with average module efficiency 15.1% (m2)	6.4	12.8	19.2	6.4	12.8	19.2
Energy output - Daily (kWh/day)	4.16	8.32	12.48	4.16	8.32	12.48
Energy output - Monthly (kWh/month)	124.8	249.6	374.4	127.8	249.6	374.4
Capacity of required DC to A/C Grid Tie Inverter with 97% inversion efficiency (kW)	1	2	3	1	2	3
Energy on to the AC bus - Monthly (kWh/month)	120	240	360	120	240	360
Energy on to the AC bus - Yearly (kWh/year)	1440	2880	4320	1440	2880	4320
Annual Saving (LKR/year)	83,520.00	167,040.00	250,560.00	388,80.00	77,760.00	116,640.00
Price of respective capacity of Solar PV DC to A/C Grid Tie Inverter with MPPT	1200	1600	1900	1200	1600	1900
Total Investment (USD)	2200	3600	4900	2200	3600	4900
Total Investment (LKR)	286,000.00	468,000.00	637,000.00	286,000.00	468,000.00	637,000.00
Simple Pay Back in years	3.42	2.8	2.54	7.36	6.02	5.46
NPV in LKR (r=10% p.a.)	521,898.64	1,196,313.81	1,887,730.58	102,177.34	356,871.21	628,566.68
IRR (%)	23	28	31	13	16	18

It can be recommended to go for Solar PV integration on to DC bus rather than integrating for A/C bus for Net Metering. Furthermore, it is identified that the higher capacity Solar PV systems will pay back much faster than lower capacity Solar PV installations. Because cost of appropriate converter or inverter systems don’t linearly increase against its capacity, rather according to reduced rate.

References

Boyle, A. and Godfrey. G. 2004. Renewable energy. OXFORD university press.

Ferenc L.T., Rogner, H.H. 2006. Oil and nuclear power: Past, present, and future, Energy Economics, Vol 28: January 2006, Pages 1-25.

Hybrid Optimization Modeling Software for micro grid and distributed generation power system design and renewable energy integration.

Lund, H. and Mathiesen, B.V. 2009. "Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050." Energy 34: 524-531.

National Aeronautics and Space Administration. 2013. A renewable energy resource web site developed by NASA” about Surface meteorology and solar energy resource. [https://eosweb.larc.nasa.gov]

Omer, A.M. 2007. Energy, environment and sustainable development, Renewable and Sustainable Energy Reviews, Vol 12 (9): 2265-2300.

Solangi, K.H., Islam, M.R., Saidur, R., Rahim, N.A. and Fayaz, H. 2011. A review on global solar energy policy, Renewable and Sustainable Energy Reviews, Vol5 (4): 2149-2163.

Turner, K. and John A. 1999. A realizable renewable energy future. Utility Commission Sri Lanka. 2013“A Retail Tariff Proposal for 2013 Ceylon Electricity Board March” published by Public[http://www.pucsl.gov.lk/english/ wpcontent/ uploads/2013/03/Electricity-Tariff-2013-Proposal-by-CEB-Main-tables. Pdf www.homerenergy. com]

Energy Creation through Sustainable Waste Solution - Geocycle Sri Lanka

M.W.R. Malalasooriya*, W.M.S. Chulakumara, E.M.S.M. Edirisooriya, N.A. Hemali, C. Herath, A.M.A.N. Arampath

Geocycle Sri Lanka

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Hunger and global requirement for energy is a growing interest for reasons of energy security, diversity, and sustainability – as well as for greenhouse gas emission and mitigation. In recent years, the world has enacted regulations – and adopted aggressive goals to encourage increased usage of bio fuels and other alternative resources. This paper summarizes how Holcim (Lanka) has successfully adopted the use of alternative fuels and thereby reducing on fossil based virgin fuels.

In Sri Lanka also the energy consumption is increasing at alarming rate and demand for power has been running ahead of supply. It is also now widely recognized that fossil fuels (i.e., coal, petroleum and natural gas) and other conventional resources, presently being used for generation of electrical energy, may not be either sufficient or suitable to keep pace with ever increasing demand of energy. Also generation of power by coal based steam power plants or nuclear power plants causes pollution, which is likely to be more acute in future due to large generating capacities. The recent energy crisis has forced industries to develop new and alternative methods of energy generation.

Keyword: waste to energy

1. Introduction

1.1 Introduction of Holcim & Geocycle

Holcim Ltd, incorporated in Switzerland is leading supplier of cement and aggregate products across the world with its presence in over 70 countries worldwide.

1.2 Sustainability initiatives of Holcim

Cement manufacturing is a highly energy intensive industry and the key sustainability initiatives in the cement industry is centredon reducing the environmental impacts of operations mainly. This involves

- Maximize use of alternative fuels and raw materials (AFR)
- Optimize use of mineral components by optimizing the clinker composition in the cement and replacing the reduced clinker with mineral components.

1.3 Setting up of Geocycle business units / companies

Use of AFR was developed further as a strategy in line with the principles of sustainability, combining with the economic goals by Holcim

- To reduce the environmental impacts by promoting energy and material recovery
- To use AFR as a source of value creation

To achieve the above two strategies, use of AFR was brought under a different identity and formed as a business unit enabling it to operate as a player in the waste management industry and was named Geocycle. “Geocycle” is one such implemented at Holcim (Lanka) as part of its global initiative to be less dependent on fossil fuels and moving on to alternative sources of energy. “Geocycle” at Holcim Lanka was established in the year 2003 as a key initiative to drive sustainable development goals in Sri Lanka. Geocycle is a business unit of Holcim Lanka which is specialized in providing waste management solutions for industries in Sri Lanka with “Peace of mind”.

On one hand, Geocycle provides industrial hazardous waste generators an environmentally friendly disposal solution and a responsible final destination. Since its inception there are over 300 customers representing both local and

* *Correspondence: randeewa.malalasooriya@lafargeholcim.com*
ISSN 2478-0669 Print

multinational have partnered with Geocycle making it the most preferred waste management solution provider in Sri Lanka.

On the other hand, Geocycle provides alternative fuel resources to cement manufacturing by directly reducing the usage of non-renewable energy (imported coal) and as a result, reducing the Carbon foot print and GHG (Green House Gases) emissions. At the beginning of year 2015 Holcim (Lanka) has replaced 34% of coal usage by alternative fuels and thrives on achieving 100% within next few years.

2. Energy demand and sources

It is estimated that world energy consumption will grow by 56 % between 2010 and 2040. Total world energy use rises from 524 quadrillion British thermal units (Btu) in 2010 to 630 quadrillion Btu in 2020 and to 820 quadrillion Btu in 2040 (Figure 1). Much of the growth in energy consumption occurs in countries outside the Organization for Economic Cooperation and Development (OECD), known as non-OECD, where demand is driven by strong, long-term economic growth. Energy use in non-OECD countries increases by 90 %; in OECD countries, the increase is 17 %.

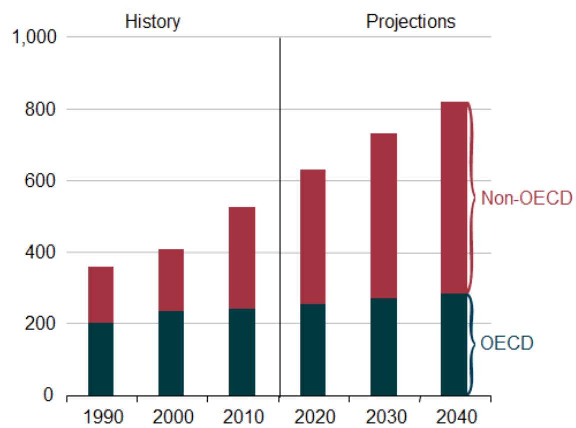


Figure 1: World energy consumption, 1990-2040 (quadrillion Btu)
(Source: http://www.eia.gov/forecasts/archive/ieo13/)

The world's real gross domestic product (GDP, expressed in purchasing power parity terms) rises by an average of 3.6 % per year from 2010 to 2040. The fastest rates of growth are projected for the emerging, non-OECD regions, where combined GDP increases by 4.7 % per year. In the OECD regions, GDP grows at a much slower rate of 2.1 % per year over the projection, owing to more mature economies and slow or declining population growth trends. The strong growth in non-OECD GDP drives the fast-paced growth in future energy consumption projected for these nations.

By 2040, the world's energy supply mix will be divided into four almost-equal parts: oil, gas, coal and low-carbon sources. Resources are not a constraint over this period, but each of these four pillars faces a distinct set of challenges. Policy choices and market developments that bring the share of fossil fuels in primary energy demand down to just under three-quarters in 2040 are not enough to stem the rise in energy-related carbon dioxide (CO_2) emissions, which grow by one-fifth.

In the long term, the *IEO2013* Reference case projects increased world consumption of marketed energy from all fuel sources through 2040 (Figure 2). Fossil fuels are expected to continue supplying much of the energy used worldwide. Although liquid fuels-mostly petroleum-based-remain the largest source of energy, the liquids share of world marketed energy consumption falls from 34 % in 2010 to 28 % in 2040, as projected high world oil prices lead many energy users to switch away from liquid fuels when feasible. The fastest growing sources of world energy in the Reference case are renewable and nuclear power. In the Reference case, the renewable share of total energy use rises from 11 % in 2010 to 15 % in 2040, and the nuclear share grows from 5 % to 7 %.

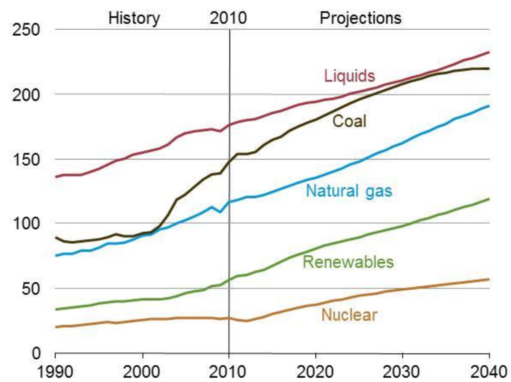


Figure 2: World energy consumption by fuel type (quadrillion Btu)

2.1 Global primary energy consumption in industry sector

Globally total energy produced is used by following 4 sectors

- Residential
- Commercial
- Transportation
- Industrial

Industrial sector is the largest consumer of total and primary energy and it accounts about 30 % of total global primary energy usage. Cement, iron and steel, chemicals, pulp and paper and aluminum industries take the lead in consumption of energy in world wide. Figure 1.1 shows the industrial final energy use in 2005 and majority is taken by chemical and petrochemical industry. Coal is the main primary energy source in cement industry and it is basically used for making of clinker inside the kiln.

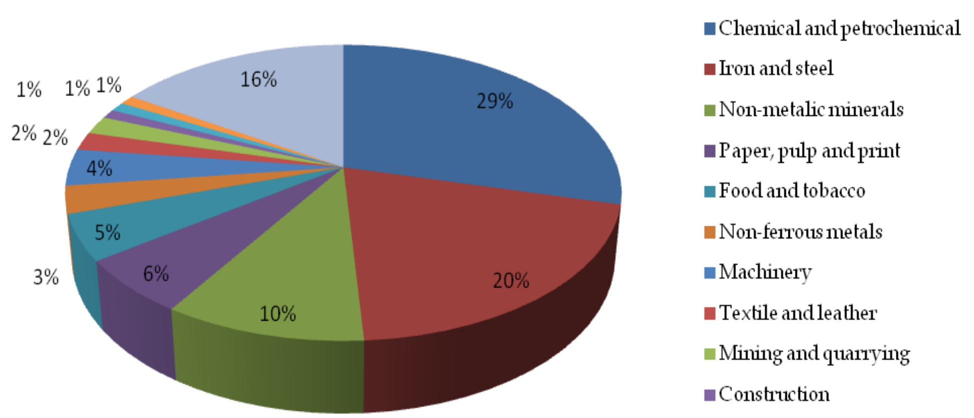


Figure 3: Share of final energy use in 2005
(Source: Energy end-use: Industry)

2.2 Substitution of coal in cement industry

In clinker formation process, limestone should be heated up to 1450 ^{0}C temperatures and this thermal energy is obtained by firing of coal or petroleum coke after pulverizing. Since coal is a fossil fuel with rapid depleting rate, other alternative fuels such as solid waste are used to replace coal. Clinker is the main component of the cement and is a mineral of Ca, Si, Al and Fe. Solid wastes which are having these elements and organic fraction can be used to replace coal in calculated ratios which does not change the clinker chemistry and meantime the calorific value of waste is converted to thermal energy and it will be used for this heating process and finally some amount of coal is being saved and waste is also completely destructed in environmental friendly manner.

3. Geocycle business in Sri Lanka towards waste to energy

Sri Lanka is one of 25 Biodiversity Hotspots in the world: having highest biodiversity density in the Asia with GDP per capita 3,385$. It also has 28 Industrial zones and 13 Export processing zones governed by Board of Investment.

Holcim Lanka is the nation's one and only fully integrated cement manufacturer owing to the novel technologies present in Holcim Group of companies, catering for one third of the nation's cement demand.
Holcim and Geocycle global in thought; Geocycle, the global brand for waste management in the Holcim group, plays a significant role towards meeting Holcim's sustainable development objectives. Geocycle represents around the globe for more than 35 countries in all five continents, allowing exchange of technology, expertise and exposure.

3.1 Waste and energy problem in Sri Lanka

In the present day context, the envisaged development will further increase huge volumes of waste much beyond the capacity and capability of the industries. Out of the many pressing needs of waste management, sustainable disposal is a must. This is a crucial move in the context that environmental responsible waste disposal is yet to be established because free dumping and irresponsible waste disposal has become the most preferred method of disposing wastes all over the country.

3.2 Paradigm shift of waste management in Sri Lanka

Nevertheless Geocycle could achieve its prime objective of environmental responsible Hazardous mat disposal together with the blessings of key state authorities, international organizations and environmental responsible industrial partners. Geocycle further extended its capacity for providing additional services to the customers such as collection and transportation, branded product disposal, analytical services, total services solutions and consultancy services.
Continuous solution provides on critical national issues; Geocycle has recently proved the capacity to professionally manage the national level crisis situations to dispose residues from chemical accidents that has occurred in the country. Disposal of chemical where house burnt, DCD contaminated milk powder disposal, disposal of empty cytoxic containers, Disposal of burnt Trichloroisocyanuric Acid containers were some of the key success cases and there were many cases in onsite chemical waste management across the country.

Compliance and beyond; The greatest achievement for Geocycle is to obtain the first ever Environmental Protection License (EPL) to co-process hazardous waste in Sri Lanka, from the Provincial Environmental Authority of North Western Province. This is not an accomplishment of one single business unit, but also an achievement of entire country. Also it has obtained EPL for hazardous waste collection, transportation, storing and pre-processing from Central Environmental Authority.

3.3 Pre processing

The technique of preprocessing is used to convert the waste materials into physically and chemically compatible fuel to feed to the cement kiln as an alternative fuel. Normally waste materials are generated in different types and they should be subjected to some preprocessing operations such as size reduction, drying, mixing and etc.

In Geocycle Sri Lanka, there is a dedicated preprocessing platform in Katunayake Export Processing zone to treat about 70 % of the total waste receiving through Geocycle business. Rests of the preprocessing activities are done in the premises of Puttalam cement plant and finally a mixture of a fuel (Alternative fuel) is being processed for cement kiln.

3.4 Co- processing

Co processing is the burning process of alternative fuels inside the cement kiln at extreme temperatures.

Figure 4 shows how co processing works and gives thermal energy for cement manufacturing process. In normal incineration of waste, additional fuels should be supplied and total energy is also wasted with some solid residues. But when it comes to co processing, the energy to heat wastes is taken from coal and thermal energy is given to the process by reducing the amount of coal to be used.

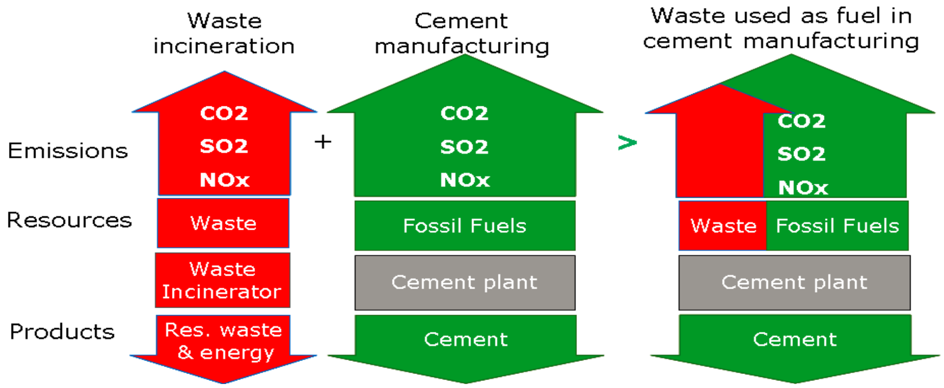


Figure 4: Waste co processing

3.5 Energy supply through waste materials

Goecycle's whole operations give two main value additions to the business as well as to the nation.

- Sustainable waste management solution to the Sri Lankan industry
- Replacement of the fossil fuel usage in cement Kiln

The ratio of energy taken from alternative fuels to total thermal energy supply to cement kiln is called Thermal Substitution Rate (TSR) and Geocycle Sri Lanka achieves 30% of TSR by replacing maximum amount of coal.

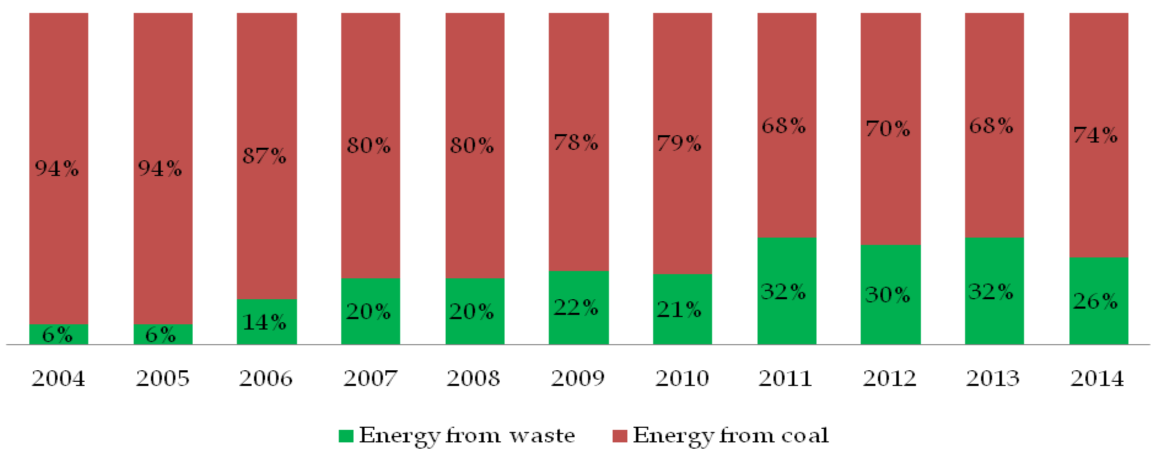


Figure 5: Replacement of coal with waste

Figure 5 shows the drastic change of energy derived from waste in the last 11 years. Now Geocyle Sri Lanka is expanding the business more towards hazardous waste from agricultural waste. In 2004, it was started with more of agricultural waste and nowadays it is dominated by hazardous category by being approved as the hazardous waste disposer in Sri Lanka.

4. Sustainability

Since the beginning of Geocycle, the ability to use biomass (Rice husks, saw dust) has dramatically increased. Of course with this increased demand, supply chain is also benefited. Additional quantities of alternative energy sources need to arrive at gates daily and the income for the dependent supplying community has also increased as a direct result.

Furthermore there had been hundreds of direct and indirect employment opportunities been created. Livelihoods of supporting communities have being vastly improved thanks to the newly developed alternative fuel supply chain. Resources supplying areas are known to be the most remote and non-accessible areas in Sri Lanka and with the new business opportunities arriving local infrastructure too has shown improvements.

4.1 Environmental sustainability

Cement manufacturing is a highly energy intensive industry. The key sustainability initiatives in the cement industry are centred on reducing the environmental impacts.

This involves

- Maximize use of alternative fuels and raw materials (AFR)
- Optimize use of mineral components by optimizing the clinker composition in the cement and replacing the reduced clinker with mineral components

4.2 Setting up of Geocycle business unit

Use of AFR was developed further as a strategy in line with the principles of sustainability, combining with the economic goals by Holcim Lanka.

- To reduce the environmental impacts by promoting energy and material recovery
- To use AFR as a source of value creation

To achieve the above strategies, use of AFR was brought under a different identity and formed as a business unit enabling it to operate as a player in the waste management industry and was named Geocycle. Furthermore Entire manufacturing process at Holcim Lanka is certified under ISO 14001, assuring that we respect all environmental boundaries and bound to protect environment and all its components. Holcim Lanka is the only Sri Lankan organisation to acquire 7 types of EPLs (Environment Protection Licences) fulfilling 374 environmental specific requirements.

Holcim Lanka is also the only entity to receive green cement certification and eco label type in Sri Lanka and is certified as the first and only cement manufacturer of its kind in Sri Lanka by the Green Building Council of Sri Lanka (GBSL) in 2014.

Among some of the projects carried out during 2013,

- Eliminating dust emissions from operations by installing a Bag Filter system for cooler bypass stacks at PCW (Puttalam Cement Works)
- Implementing systems to measure and monitor effects of our operation on the community and the environment
- implementing an internationally recognized Environmental Management System (EMS) within our plants
- State of the art hazardous waste pre-processing facility and co-processing
- Innovation of solar drying facility to dry industrial sludges
- Tree planting and other community greening project
- Biodiversity projects for tree planting and rehabilitation at quarry
- Animal rescue program

4.3 Economic sustainability

Geocycle has achieved Economic sustainability through increased profitability of Holcim via the reduction of fuel costs. This reduction is measured using GAV, which measures absolute value added to the Holcim by two means.

4.3.1 Substituting the use of coal

From 2003 to 2014, the energy derived from waste increased from 0% to 30%. This substitution of energy has favourably contributed to the Gross Added Value of Geocycle in two ways

- Reduction of the volume of coal which has a relatively higher energy cost per unit of energy relative to waste
- Shielding the company from the sharp rise in the price of coal, which recorded a CAGR of 8% since 2003

5. Conclusion

It is clear that demand for energy is ever increasing by the day due to rapid population increase and resource required as a result. But it must be the prime concern of industries to come up with innovative and alternative means of self-catering of its energy requirements. As the leading cement manufacturer in SriLanka and as a responsible organisation Holcim (Lanka) / Geocycle has proven its capability with the ideal solution. Holcim (Lanka) solution has not only provided them with an answer to the energy crisis but also has covered many over laying aspects of sustainable development. Benefits are at large for all stakeholders and entire product lifecycle and supply chain has positively benefitted as a result.

Greater use of renewable energy is seen as a key component of any move to combat climate change, and is being aggressively promoted as such by Holcim, Geocycle and by other group companies. Yet there is little economic analysis of renewable energy.

This paper surveyed on what the present status is and adds to it. The conclusion is that the main renewables face a major problem because of their intermittency and that this has not been adequately factored into discussions of their potential other industries and how Holcim (Lanka) has successfully overcome the energy crisis. Without new technologies and innovations that can overcome this burning issue it would only add to the issue of energy crisis which too has successfully adopted by Holcim Geocycle in Sri Lanka.

Abbreviations

- GHG: Green House Gases.
- OECD: Organization for Economic Cooperation and Development.
- GDP: Gross Domestic Product.
- DCD: Dicyandiamide.
- EPL: Environmental Protection License.
- TSR: Thermal Substitution Rate.
- AFR: Alternative fuels and raw materials.
- GBSL: Green Building Council of Sri Lanka
- EMS: Environmental Management System
- PCW: Puttlam Cement Works
- GAV : Gross Added value

References

Mayuri Wijayasundara, Sajith Edirisooriya, Tharinda Jayawardena, Sudarshan Senaratne . (June, 2011). Creating values through sustainability – A global practice adopted in local context. CIMA Case Study Awards 2011 in Sri Lanka.

Eberhard Jochem. Energy End-Use:. Chapter 08, 518-526, Industry. Retrived 17th June, 2015 from http://www.iiasa.ac.at/

International Energy outlook, US Energy information Administration June 25 2013 from www.eia.gov /forecast.

Study on Large Scale Wind Power Integration to Power System

L. Ding*, L. Haiwei, H. Mingliang, H. Chunhong

China Power Engineering Consulting Group, Beijing, China

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Jiuquan is the first wind power farm with more than 10GW capacity that was ever planned in China. It is important to consider how to effectively and safely transfer the wind power to the load center. As the wind energy is inherently not continuous, peak regulation should be considered. In this paper, the design phase is thoroughly discussed, particularly in terms of peak capacity, reactive power compensation, voltage control, stability etc.. The paper also shows the overall wind power integration and transmission scheme.

Keywords: wind power, transmission planning, peak regulation, reactive power compensation

1. Introduction

China has huge wind power resources and it is believed that it has around 700-1,200GW (Li, J.F. Ed., 2013) capacity. This could play a significant role in the country's future energy supply. The richest wind energy resources are distributed along the south-eastern coasts and in the north (north-east, north and north-west). A few inland spots are also abundant with wind resources. Besides, China has rich off-shore wind resources.

According to the report by China National Energy Administration in 2014, the national wind power industry is maintaining a strong growth. In the year of 2014, newly installed wind power capacity breaks the historical record and reaches 19.81 GW. As of 2014, the total installed capacity reaches 96.37 GW, accounting for 7% of the total power generation capacity and 27% of the global wind power installed capacity. In 2014, the wind electricity generation is 153.4 billion kWh, accounting for 2.78 percent of the nation's total electricity generation. (China National Energy Administration, 2015) Both the annual and accumulated installed capacity ranks 1st in the world.

Jiuquan wind power base is China's first planned wind power farm with over 10GW capacity (China National Development and Reform Commission, 2007). The wind power assembling and transmission systems are designed by the China Power Engineer Consulting group Corporation (CPECC). The construction is planned in two phases. In the first phase, 5GW capacity has been installed and is already put into operation, producing power to the load center of north-west grid through a 750kV power line. The second phase with 8GW planned capacity is now under construction. After completion, the project will generate a total capacity of 13GW, and one±800kV DC line will be connected to transfer the power to southern grid which is not a synchronized grid with north-west power grid. Large-scale wind power delivery demands higher requirements for power system planning and dispatch, the overall planning scheme is demonstrated and the main technical problems encountered in power system planning and designing are studied in this paper.

2. Plan of wind power in Jiuquan

Gansu is one of the provinces that has the richest wind resources in China. Exploitable wind resource amount in Gansu is over 20 GW. This reserve of wind resources ranks 5th in the country. In the province, wind energy reserve declines from northwest to southeast. The region with the richest wind resources is located in the Hexi corridor occupying 23% acreage of the whole province. The available wind energy reserve is over 500kWh/m^2. The annual average effective wind energy density is over 100W/m2. The annual available time of wind energy is over 4500 hours.

Hexi corridor is a narrow valley between two mountains. Anxi area and Yumen area are both located at the

* *Correspondence:*
ISSN 2478-0669 Print

narrowest part of the corridor and thus have the strongest wind. According to historic data, in Yumen area the average wind energy density at 10 meters above the ground is 307 W/m^2, at 30 meter is 426 W/m^2, and at 40 meters is 447W/m^2. Available time for 10 meters height is 6980 hours, for 30 meters is 7593 hours, and 7076 hours for 40 meters height. According to data measured by anemometer tower in Anxi, the annual average wind speed is 7.6 m/s; the annual available time of wind speed between 3.0～21 m/s and between 4.0 ～25 m/s is 7530 hours and 6781 hours respectively; and the annual average wind energy density is 558 W/m^2.

In Anxi, Yumen and Mazongshan places of Hexi corridor, the annual average wind speed is over 3.0 m/s. The variation is small over the year and it also keeps a small annual change. According to the monthly average wind speed in several years, the difference between the maximum and minimum values is only 1.0～1.5 m/s. The variation coefficient of the annual average wind speed is between 0.02～0.025. In these areas, the conditions are suitable for large wind farms (Shi,P. F., 2008).

According to the distribution of wind resource and relative research report, by 2020, the total installed capacity of wind power in Jiuquan area will achieve 12.71 GW. The map of Jiuquan wind power base is shown in Figure 1.

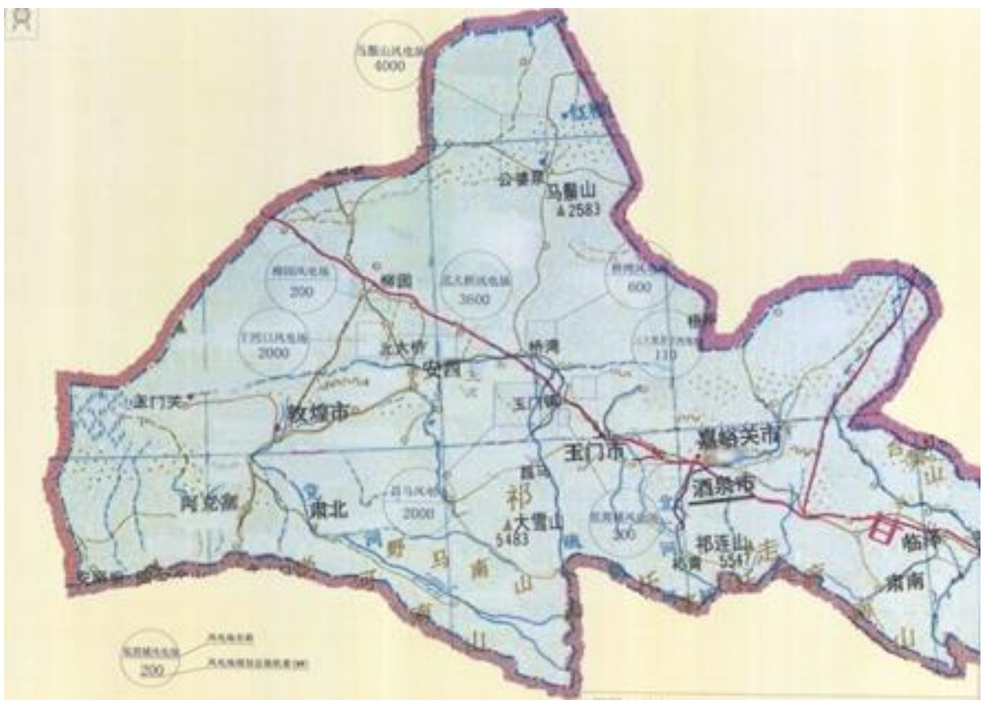


Figure 1: Geographical map of Jiuquan wind power base planning

3. Wind power assembling and transmission planning

3.1 Wind power assembling

The first phase of project is to install 5GW wind power in Jiuquan area. Small amount of the wind power integrates into the local 110kV grid. The rest integrates to the 330 kV boosting substation before being transferred into the 750 kV grid.

Seven 330kV boosting substations namely are planned to collect the wind power. Each 330kV substation collects 2～3 wind farms with a capacity of 200～300 MW. The wind generator output voltage is boosted to 35kV in each wind farm, and then boosted further to 330kV in collection substations, and eventually connected to 330kV side of 750kV substations, allowing the transfer of the wind power through the 750kV grid. The overall scheme is shown in Figure 2.

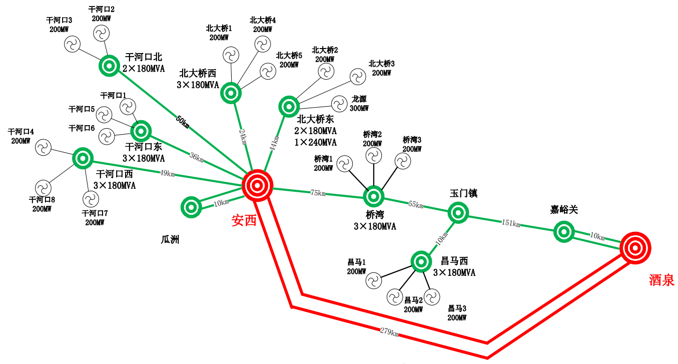


Figure 2: Jiuquan wind power base 1st phase integration scheme

The second phase of project will be 8GW wind power in the Jiuquan wind power base. Following the scheme of first phase, 13 collection substations and one 750kV substation are planned. Wind power from each wind farm with capacity of 600~800MW are collected by these collection substations and then being transferred to power grid through 750kV substations.

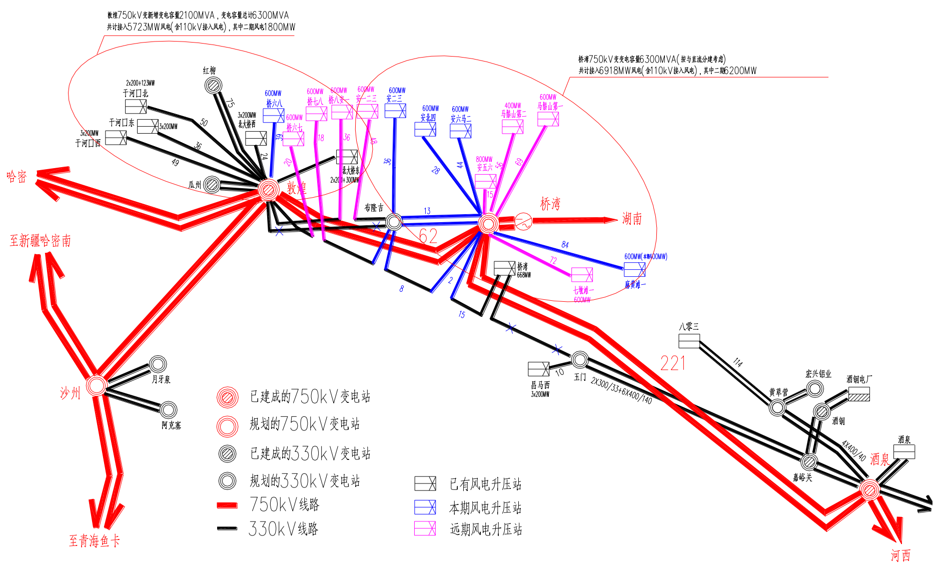


Figure 3: Jiuquan wind base 2nd phase integration scheme

3.2 Wind power transmission planning

After the wind power is integrated to the 750 kV substations, it will be delivered to the load center in the northwest grid through Anxi-Jiuquan-Jinchang-Yongdeng double circuit 750 kV transmission lines, as shown in figure 3. Furthermore, the transmission system will finally connect to Xinjiang grid on the west and to Qinghai grid on the south, which makes a large synchronous grid of north-west area of China.

330 kV grid in Hexi corridor is relatively weak. After the operation of the 750 kV transmission system, power system stability will be improved. But since the main source in Jiuquan is wind generators, the variable wind power output lack support by thermal generators, and also large amount wind power need long distance transmission, the transfer capability of the transmission system need to be enhanced.

In order to meet the requirement of second phase wind power delivery and to promote the stability of power grid, another AC transmission path from Anxi to Geermu is planned, and also a ±800kV DC transmission line with capacity of 8GW are planned to transfer power more than 2500km to the south power grid of China. After that the capability of transmission system will meet the delivery requirement of Jiuquan wind power base.

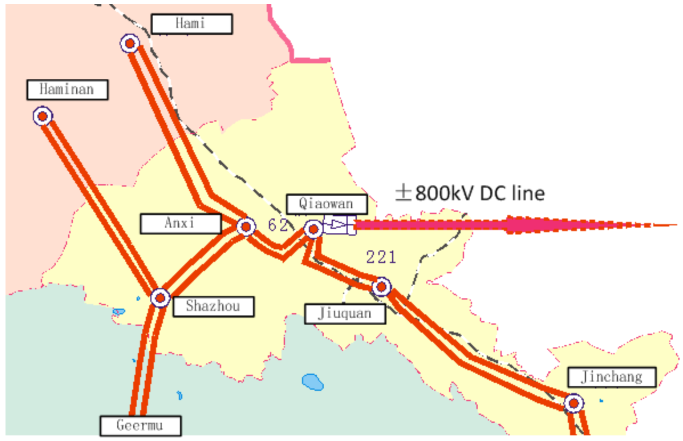


Figure 4: Planning of transmission system of Jiuquan wind base

4. Load peaking capability and packed delivery

4.1 Load peaking capability

The dispatch department plans generators to start up every day to meet the demand of the peak load. While the demand falls down, generators will reduce their output. Load peaking capability is the power gap between the sum of generators' minimum outputs and valley load of the power system. It depends on many factors such as load level, peak-valley load difference, generator output characteristics, and generator types etc. Normally the hydro power plants are the best peaking units in power system. Figure 4 is a schematic of load peaking capability of the power system.

To a certain power system, some generators are peaking units and some generators only supply constant power, but when each operation mode is decided, the load peaking capability is fixed. Under the valley load, if wind power output increases, conventional generators should reduce their outputs to keep power balance. Therefore wind power penetration limit is decided by load peaking capability of power system.

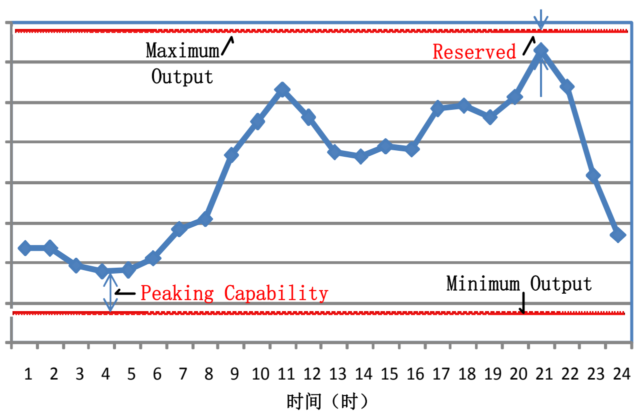


Figure 5: Schematic draw of load peaking capability of the power system

The load characteristics of the whole North-West China Grid is relatively better. The difference of daily peak-valley load is relatively small. Hydro power plant is sufficient. The load peaking capability of North-West China Grid is large. But Gansu grid, as a part of North-West China Grid, the peaking capability is not that much. Since the hydro power plant in Gansu grid only takes small ratio, while some captive power plant cannot be dispatched, if large scale wind power is integrated into Gansu grid and load peaking is done by Gansu grid itself, it is necessary to plan more peaking units. Otherwise load peaking should be taken in the whole North-West Grid. Based on the calculation, the load peaking capacity of Gansu grid is 1.1GW before the first phase of Jiuquan wind power base is constructed. Thus 2.1GW peaking power sources need to be constructed additionally. If the load peaking capacity is insufficient, the renewable energy shall be wasted. So all the new thermal generators integrated to Gansu power grid should be peaking units. If the load peaking is done by the whole North-West grid, the limitation of wind power penetration is 6.6GW.

The results above are drawn without the consideration of the limitation due to the grid capability, and the dispatching restriction on power exchanging between sections. Thus the real capability might be even less than the calculation.

4.2 Packed delivery

Hexi corridor is not only rich in wind resources, but also has good conditions for photovoltaic (PV) power generation, 2015 PV installed capacity in Hexi area will reach 5GW. Some of the PV power can be consumed locally with the left should be delivered. Therefore the ±800kV DC transmission line not only send wind power, but also large-scale PV power. Due to the limited peaking capacity of Gansu, based on the research on output characteristics of PV power and wind power, CPECC has proposed the packed delivery scheme. 7GW installed capacity of wind power and 2.8GW install capacity of PV power can be packed and regulated by a captive thermal power station with strong peaking ability to ensure a continuous and stable power supply for the DC transmission.

5. Low voltage ride through (LVRT) capability

The wind turbines with low voltage ride through (LVRT) capability is shown in figure 5. Without this function, wind turbines will trip from the power system even under a minor disturbance which will further result in a large active power gap, leading to a frequency dip in the whole system. Load shedding devices will cut off some loads to recover the system frequency. Minor disturbance causing load shielding is not allowed in North-West grid. Therefore, in order to avoid the miss-trip, all the wind turbines installed in Jiuquan wind power base should be designed with low voltage ride through capability.

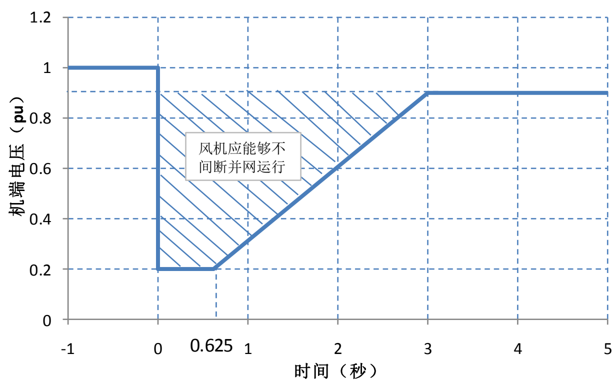


Figure 5: Low voltage ride through of wind turbine

During the LVRT process, performance of generators will affect voltage stability of the power system. If the generators cannot provide dynamic reactive power support, the voltage might not recover to the normal level after the fault is cleared.

6. Reactive power compensation and voltage control

The wind power in Jiuquan delivers through a 750 kV transmission system. Reactive power compensation such as reactors and capacitors installed at the 750 kV substations is designed to meet the requirement in normal conditions. However, in case of wind fluctuations, the compensation devices have to adjust to the variation and this will shorten its lifetime. Voltage control by the wind turbine itself is relatively poor, and thus the voltage control is difficult.

It is better to equip the reactive power compensation devices at the 330 kV wind power substations. Since the compensation devices have to frequently adjust to the wind variation, it is suggested to use dynamic reactive power compensation devices, such as static var compensator (SVC). Based on the calculation, the capacity should be at least 15% of wind farm installed capacity.

7. Conclusion

The wind resources in China are huge. The planned installation capacity is tremendous. The long term planned wind power exceed 10GW in the Jiuquan area. The capacity will be 5GW in the first phase and 8GW in the second phase. Wind power will be delivered to the load center in North-West and South grid of China.

Large scale wind power integration will affect power system security and stability. By initially studying, it can be seen that:

- The wind power and PV power develop rapidly in Hexi, but the peaking capacity is insufficient. CPECC has proposed the packed delivery scheme to regulate renewable power locally.
- In order to increase the transmission capability to transfer the wind power from Jiuquan, 750 kV transmission grid and ±800kV DC transmission systems are adopted.
- The dynamic reactive compensation should be installed at 330 kV wind power substation. The capacity of dynamic reactive compensation should be at least 15% of wind power capacity.
- 750 kV controllable shunt reactors are necessary to be installed on both 750 kV buses and lines.

In this paper, the technical problems facing the wind power planning are analyzed. Problems concerning system operation and dispatch are open for further study.

References

Li, J.F.E. 2013. China Wind Power Report (p.2), Beijing: China Environmental Science Press.

China National Energy Administration. 2015. Wind power industry situation, Retrieved Jun 22, 2015, from http://www.nea.gov.cn

China National Development and Reform Commission. 2007. *Middle and long term program of Renewable energy*.

Shi, P.F. 2008. China Wind Power Installed Capacity Statistic, China Wind Energy Association, March 2008.

Development of Global CSP: Optimization of Thermal Energy Storage Capacity in Parabolic Trough and Solar Tower Plants

F. Tao[1*], Z. Xiaohui[1], L. Xiangdong[2], Z. Xiaochun[1], C. Yuhong [1]

[1]*China Power Engineering Consulting Group, Beijing, China*
[2]*Electric Power Planning & Engineering Institute, Beiin*

Date Received: 22-11-2014 Date Accepted: 29-04-2015

Abstract

Concentrating solar power (CSP) is an attractive zero-carbon renewable energy for electricity, which has been rapidly developed in the world. The main types of CSP plants are described and compared in the review, and then the global CSP capacity and current solar energy activities in China were analyzed. Based on the 50 MW CSP plant in Delingha region in China, the optimization of thermal energy storage (TES) capacity and solar multiple in a parabolic trough and a solar tower CSP plants were studied. It was revealed that the lowest levelized cost of energy (LCOE) could be acquired with optimal TES capacity and it decreases obviously with the increasing of solar multiple (SM). At the same SM, the parabolic trough system needs more TES capacity than the solar tower system to get the lowest LCOE. Moreover, for the 50 MW parabolic trough type CSP plant, solar tower plant has higher annual electricity energy output and higher annual solar to electricity efficiency than parabolic trough plant.

Keywords: concentrating solar power, global capacity, parabolic trough, solar tower, thermal energy storage capacity

1. Introduction

Fossil fuels are accounting for 80% of the global primary energy consumption (Ummadisingu, et al., 2011). It's burning for power generation and transport sector result in at least 90% of carbon dioxide emission which leads to global warming (Erdle, 2010). Moreover, the harmful substances or chemical gases emitted by burning fossil fuels also cause several environmental problems. Therefore, it is necessary to reduce our dependence on fossil fuels for electricity production around the world, and to develop the renewable wind, solar, marine and biomass energies for electricity worldwide.

Concentrating solar power (CSP) is an attractive option in the energy transformation. The electricity is generated by means of the infinite concentrated sun radiation with no emitted carbon dioxide or other pollutants. CSP plants are mainly composed of solar reflectors, receivers, steam turbine and electricity generator. In CSP plants, the solar reflectors can be parabolic troughs, heliostats, Fresnel reflectors or parabolic dishes, as Fig. 1 shows. A brief comparison between four types of CSP plants is illustrated in Table 1. The reflectors focus the sunlight onto the receiver in which the heat transfer fluid (HTF) is heated up to hundreds of Celsius degrees. The HTF goes into a series of heat exchangers to convert water into super-heated steam for power generation. In the continuous CSP plants, the thermal energy from the heat tank or gas as an additional source of energy is used in the night and cloudy days.

Compared to other zero-carbon renewable energies, a great advantage of CSP is that it can generate constant flow of electricity by storing heat in the thermal energy storage (TES) system in the CSP plant. TES capacity is closely related to both the ability of continuous power generation and the lowest leveled cost of energy (LCOE), respectively. Thus the optimization of TES capacity plays an important role in the CSP plant design. In this study, the optimization of TES capacity was discussed in a parabolic trough and a solar tower system, respectively.

[*] *Correspondence:*
ISSN 2478-0669 Print

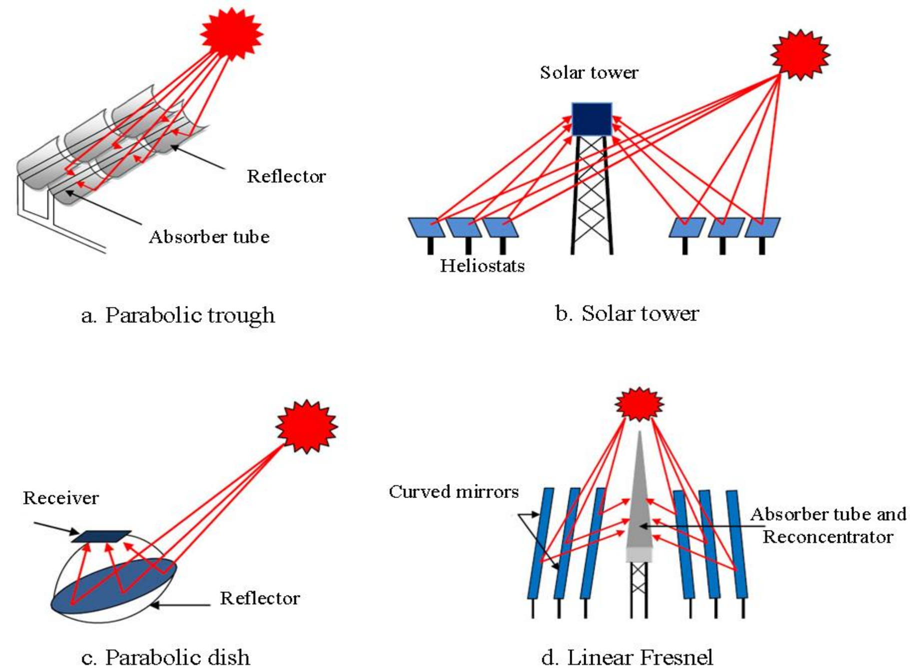


Figure 1: Four types of CSP plants (Ziuku, et al., 2014)

Table 1: Comparison of the four types CSP plants (Behar, et al., 2013)

CSP technology	Parabolic trough	Solar tower	Parabolic dish	Linear Fresnel
Solar collector	Line focus	Point focus	Point focus	Line focus
Solar receiver	Mobile	Fixed	Mobile	Fixed
Concentration ratio	70-80	>1000	>1300	>60
Working temperature	≥400	≥560	≥1150	≥550
Current efficiency (%)	15-16	16-17	20-25	08-10
Plant peak efficiency (%)	14-20	23-25	30	18
Typical capacity (MW)	10-300	10-200	0.01-0.025	10-200
Technology development risk	Low	Medium	Medium	Medium
Development status	Commercial proven	Commercial proven	Demonstration stage	Pilot project

2. Global CSP capacity developments

The current global CSP capacity is shown in Figure 2. It shows the great potential of CSP development with the rapidly growing global CSP capacity from installed to in construction and in planning (Figure 2a). For the installed CSP capacity, the parabolic trough type has a capacity of 3587 MW accounting for 83.7%, and the solar tower type accounts for 10.9% (Fig. 2b). Within the 1229 MW of CSP capacity in construction, the parabolic trough type occupies 61.4%, and the solar tower occupies 23.0% (Figure 2 c). For the CSP capacity in planning, the other type increases to 43.8%, which mainly is Fresnel reflector type (Figure 2 d). However, it could definitely be revealed that the parabolic trough and solar tower systems are still the main types of global CSP system. The technical innovation of these two systems could strongly support the global CSP development.

2.1 Development of CSP in the world

The CSP market is now dominated by Spain and USA. According to the statistical data, about 51% of installed CSP capacity is in Spain. In the following, nearly 40% of CSP capacity is in USA. Spain built its first CSP plant in 2007 and now about 2200 MW of CSP capacity is in operation. Despite Spain and USA, about 300 MW of CSP capacities have been installed in African and the Middle East countries such as Algeria, South Africa, Morocco, Egypt and UEA. Moreover, India and China have shown their interest in CSP since 2010, with about 200 MW of CSP capacities installed in India and 11 MW of CSP solar tower type in China. Furthermore, CSP plants with capacity below 9 MW were also developed in Italy, Australia, Germany, France and Thailand.

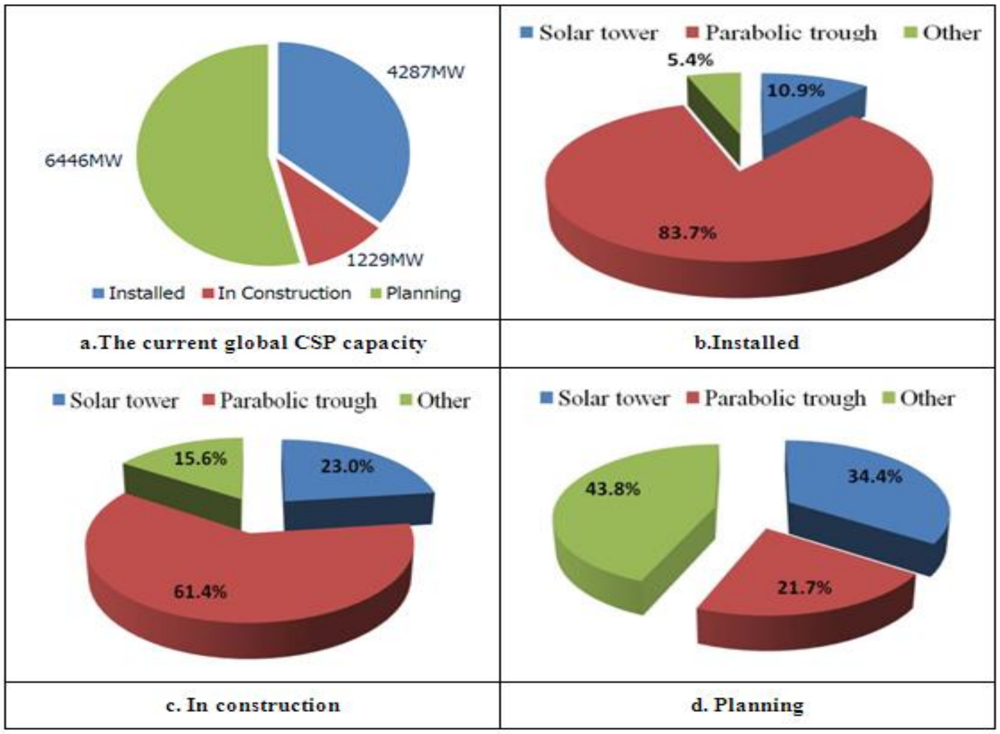


Figure 2: The current global CSP capacity

2.2 Development of CSP in China

China has an abundant solar energy resource. There is more than 700,000 km^2 region that gets the high direct normal irradiation (DNI). It is suitable for CSP installation and can potentially generate more than 51,000 TWh of electricity per year.

There have been 2 CSP plants in operation in China. The first CSP in China and also in Asia, a 1 MWe Dahan Tower plant, was built in the district of Beijing (Yanqing) at Badaling town in 2010. It includes a 42 m high tower with 100×100 m^2 of heliostats. Another one, the Delhi 50MWe CSP is the first commercially operated solar tower thermal power station, and also the largest one currently in China.

In policy matters, National Development and Reform Commission (NDRC) of China greatly supports renewable energy development in its governmental plan (2016-2020). It has confirmed an installed capacity for CSP of 15 GW for 2020.

3. Optimization of TES capacity of CSP system

CSP with TES has a great advantage of continuous power generation, which benefits from that TES system could be incorporated to provide a stable energy supply in response to electricity grid demand. However, increasing the TES capacity would increase investment of project and thus has significant effect on the lowest levelized cost of energy (LCOE). With a certain solar-field area, the optimization of TES capacity could contribute to the lowest LCOE with highest annual solar to electricity efficiency. In this section, the optimization of TES capacity in a parabolic trough and a solar tower CSP plants are discussed and compared. In the CSP plants, the molten salt is set as the TES medium.

3.1 Solar field capacity selection

The solar field area of CSP power plant can be calculated as the following formula.

$$A_{hf,d} = SM \times \frac{1000 \times Q_o}{\eta_{opt} \times \eta_{rec} \times \eta_{pip} \times Q_{DNI}} \qquad 1$$

Where;

Q_o	=	heat rate of steam turbine, kW
$A_{hf,d}$	=	solar field area at design point, m^2
SM	=	solar multiple
η_{sf}	=	solar field efficiency at design point
η_{rec}	=	solar collector tube at design point
η_{pip}	=	energy transportation efficiency of pipes
Q_{DNI}	=	direct solar irradiation power instantaneous value at design point

The solar multiple is defined as the ratio of total thermal power output and thermal power of rated load of steam turbine. The difference of heat-collecting capacity and power generation capacity can be identified by solar multiple. The solar multiple of CSP plants without TES is normally from 1.1 to 1.5.

3.2 Optimization of TES capacity

The proposed CSP plant is located at Delingha region in the Qinghai province of China. The quantitative technical assessment is based on annual solar energy resource data. The mean value of DNI is 641.5 W/m^2. The rated net power output is supposed to be 50 MW. The TES capacity and solar multiple is optimized based on the annual hourly DNI value, domestic equipment price, supposed solar field, HTF systems, and TES investment. The optimization results are shown in Figure 3 (parabolic trough system) and Figure 4 (solar tower system).

It is shown in Figure 3 that LCOE decreases with increasing of TES capacity (the storage time, h) until it reaches the lowest value, and then the LCOE increases slowly with increasing TES capacity. The trend is not affected by SM. For example, when SM=2, the lowest LCOE, which is 0.17238USD/kWh, is acquired when the capacity of TES is 6 h. When SM=2.2, the capacity of TES for the lowest LCOE (which is 0.1689 USD/kWh) is 7 h. The results also show that the lowest LCOE decreases obviously with the increasing of solar multiple. The electricity energy output for CSP plants with TES increases with higher solar multiple.

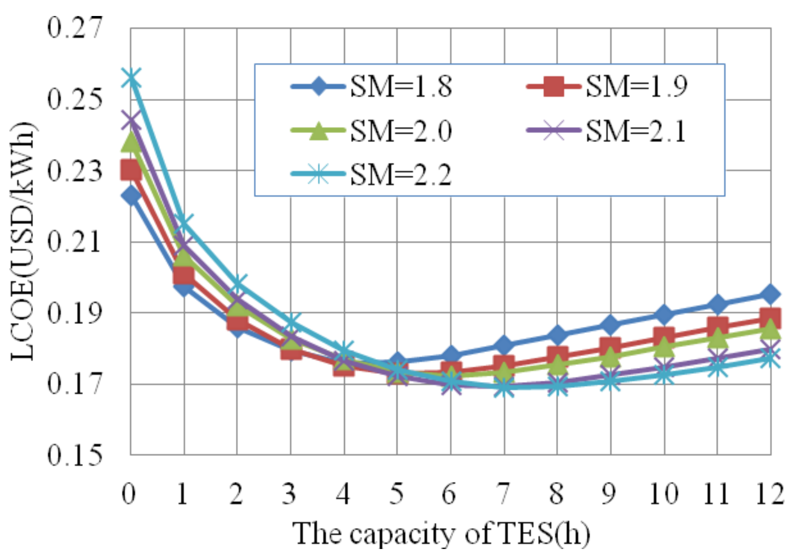


Figure 3: The optimization results of TES capacity and solar multiple in parabolic trough CSP plant

In the same boundary condition, the optimization of TES capacity and solar multiple in solar tower system is shown in Fig.4. It reveals a similar trend of LOCE curve with parabolic trough system. When SM=2, the lowest LCOE which is 0.1730USD/kWh is acquired when TES capacity is 3.5 h. When SM=2.2, TES capacity increases to 4.5 to acquire the lowest LCOE (0.1728 USD/kWh).

Comparing the optimizations of parabolic trough and solar tower systems, it is revealed that at the same SM, which means the same ratio of total thermal power output and thermal power of rated load of steam turbine, the parabolic trough system needs more TES capacity than the solar tower system to get the lowest LCOE.

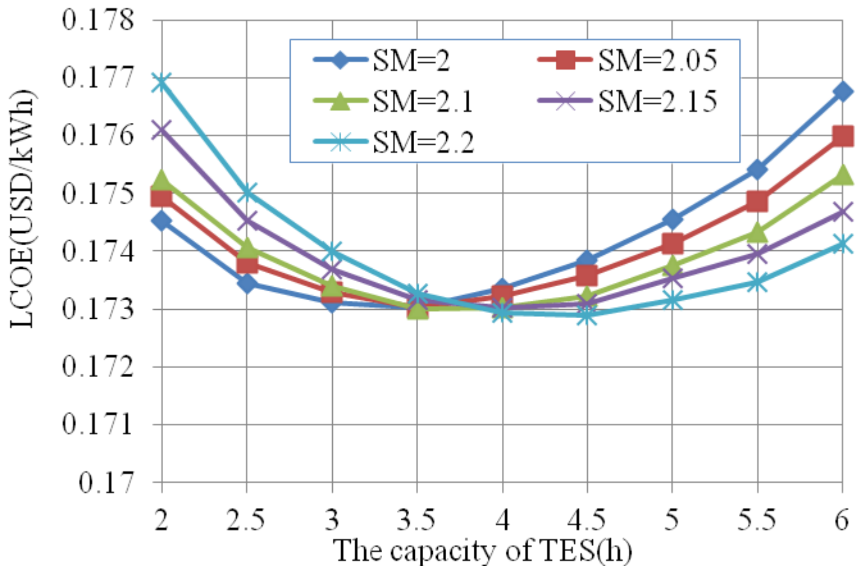


Figure 4: The optimization results of the TES capacity and solar multiple in solar tower CSP plant

Table 2: The main technical index of the 50 MW CSP plant

Item	Unit	Parabolic trough	Solar tower
Annual collected thermal energy of solar field	kWh	9.69E+08	9.67E+08
Annual thermal energy output of solar field	kWh	4.04E+08	3.66E+08
Annual thermal energy input of power block	kWh	3.64E+08	3.62E+08
Annual electricity Generation	kWh	1.32E+08	1.46E+08
Annual solar to electricity efficiency	%	13.62	15.11

The main technical index for the 50 MW CSP plant is shown in Table. 2. It shows that the annual electricity energy output of solar tower, which is 1.46×10^8 kWh, is 10 % higher than that of parabolic trough plant (1.32×10^8 kWh). Moreover, the annual solar to electricity efficiency of solar tower plant is 1.49% higher than the parabolic trough plant.

4. Conclusion

In the study, the different types of CSP plants, the development of global CSP capacity and the current solar energy activities in China were briefly introduced. It is revealed that the parabolic trough and solar tower systems are still the main types of global CSP system. In these two systems, the thermal energy storage (TES) is closely related to both the ability of continuous power generation and the lowest levelized cost of energy (LCOE), respectively. Thus, the optimization of TES capacity and solar multiple in a parabolic trough and a solar tower CSP plants are performed in the study. The relationship between the lowest LCOE with TES capacity and solar multiple (SM) were discussed. The study supplied basic principles to guide the TES design, which is significant to the CSP plant.

References

Behar, O., Khellaf, A. and Mohammedi, K. 2013. A review of studies on central receiver solar thermal power plants.*Renewable & Sustainable Energy Reviews*, *23*(4); 12–39.

Erdle, S. 2010. The desertec initiative powering the development perspectives of southern mediterranean countries?. *DIE - Deutsches Institut für Entwicklungspolitik*.

Ummadisingu, A. and Soni, M. S. 2011. Concentrating solar power – technology, potential and policy in india.*Renewable & Sustainable Energy Reviews*, *15*(9); 5169-5175.

Ziuku, S., Seyitini, L., Mapurisa, B., Chikodzi, D. and Kuijk, K. V. 2014. Potential of concentrated solar power (csp) in zimbabwe. *Energy for Sustainable Development*, *23*; 220–227.

Driving Cycle Concept to Evaluate Fuel Efficiency of Existing Roads

U. Galgamuwa, L. Perera, S. Bandara*

Transportation Engineering Division, Department of Civil Engineering, University of Moratuwa

Date Received: 27-06-2015 Date Accepted: 05-11-2015

Abstract

Fuel efficiency is one of the major parameters to be considered when evaluating existing road for improvements because the fuel consumption directly affects the GDP of a country and also contributes to environmental sustainability. Many methods have been used around the world to evaluate fuel efficiency on road sections but driving cycles have not been used directly anywhere in the world.

A driving cycle has been developed in Sri Lanka recently for emission estimation for setting up emission standards. Further analysis shows that it is possible to use the same dataset to develop a driving cycle for emission purposes to evaluate fuel efficiency of existing roads. Two road categories based on traffic volumes have been identified for a pilot study and then driving cycles for each road group were developed. These driving cycles were evaluated for each road group according to the guidelines given in literature. Finally, a proposal has been developed to extend this method to evaluate individual roads using representative driving cycles (patterns). Evaluation can be done comparing nine selected target parameters and depending on the criteria used for driving cycle development, fuel efficiency level based on prevailing traffic flow and fuel efficiency level based on infrastructure condition only can be identified. The former is useful to decide on traffic management initiatives while the latter is useful for making decisions regarding infrastructure improvement strategies.

Keywords: driving cycles, fuel efficiency, road evaluation

1. Introduction

Finite nature of the petroleum is one of the major problems affecting the sustainability of any transportation system (Black, 2010). According to rough estimations it has been found that the petroleum reserves will completely deplete in the next two to three decades if the demand continue to increase as at present. Not only does the infinite nature of the petroleum but also the fuel consumption directly affect to the economy of a country. Mainly in developing countries in Asia, such as Bangladesh more than fifty percent of their foreign exchange earnings is spent for fuel (Mozumder, 1981). Since the transportation sector consumes a major share of the fuel in developing countries it has a significant effect on their economy and also it is a significant source of an air pollution (Colvile, 2001). Hence, fuel saving will give sometime for the scientist to come up should be identified. It has been identified that one third of the fuel energy in the passenger car is used to overcome friction such as transmission tire and breaks (Holmberg, 2012). It can be minimized by either improving the vehicle or improving the road system to keep the constant speed throughout the journey by reducing acceleration deceleration states. Furthermore, Abbott et al (1995) has suggested that the design and engineering of the vehicles, the operation of vehicles and the traffic management is few of the factors affecting road transportation emissions. Since there is a significant relation between emissions and the fuel consumption those factors are valid for the on-road fuel consumption as well

In Sri Lanka, transport sector is responsible for the majority share of the fossil fuel usage. According to the Ministry of Transportation, Sri Lanka, ninety seven percent of the fuel consumed by transportation sector is road transportation. The average fuel efficiency of a vehicle compared to developed country is almost twenty percent. Therefore evaluating fuel efficiency on existing roads will be useful for a country to take necessary decisions and for policy making to enhance sustainable transportation.

* *Correspondence: samanjbandara@gmail.com*
ISSN 2478-0669 Print

Sri Lanka has been developing and expanding their road network for more than 100 years but never taken the emission inventories and fuel efficiency in to consideration on the roads. But now the requirement for such method is immerging due to environmental concerns as well as the increasing prices of the fuel. Basically there are two major ways of estimating emission inventories and fuel consumption, namely, travel based models and fuel based models (Xiao et al, 2012). The methodology, driving cycle, falls under travel based models and it can be defined as a series of data points representing speed versus time (Tong and Hung, 2010), speed and gear selection as a function of time (Barlows et al, 2009), speed versus distance (Nesamani and Subramanian, 2011) or time versus gradient (Jeon et al, 2012), in a specific region or a part of a road segment. It's been used to estimate fuel emission inventories on the roads or the regions but not for estimation of fuel efficiency on the roads. A comparison of various established driving cycles in the world to propose a general approach for a developing country has been done by Galgamuwa et al (2015).

A methodology has been developed to construct a representative driving cycle for emission purposes in Colombo, Sri Lanka. It has been identified that the results can be used to evaluate the roads according to their fuel efficiency and, hence decisions can be taken to either improve the roads or adopt alternatives.

2. Methodology

Even though different methods have been used around the world to develop driving cycles, route selection, data collection, cycle construction (Hung et al, 2007) and cycle assessment (Gamalath et al, 2012) can be identified as commonly used steps in driving cycle development. But in the Colombo driving cycle developed by Galgamuwa et al (2015) there is one additional step which is used by few other countries, namely data validation, which is to validate the collected data which truly represent the area of concern.

For this study, two road groups for Colombo area have been identified for the data collection as shown in table 1, according to Average Daily Traffic (ADT). When selecting road groups extreme ends of ADT were selected to identify the effects due to traffic.

Since the traffic volumes on the same road can significantly vary according to the time of the day, a typical day was divided into seven segments. Proportionate to the traffic volumes in respective time segment data was collected as shown in table 2.

Table 1: Classification for road groups

Group Number	Total Traffic Volume (No of Vehicles)
1	Up to 15,000
2	Above 50,000

Table 2: Number of proportionate data samples for each group

	Morning Off-peak	Morning Peak	Inter Peak1	School Peak	Inter Peak2	Evening Peak	Night Off-peak	Total
Road Group 1	1	3	14	3	7	10	2	40
Road Group 2	9	23	20	17	21	25	7	122

Two methods, namely chase car method and on board measurement method (Tong et al, 2000) have been used around the world for data collection. For this study on board measurement method was used due to difficulties of adopting chase car method in Colombo city such as aggressive and irregular driving pattern of the drivers. Driving cycle for emission purposes was developed by combining the data collected from all the road groups. But for evaluating the fuel efficiency, driving cycles have been developed for road group 1 where the traffic volumes are low and the road group 2 where the traffic volumes are high.

Four methods have been widely used around the world for cycle construction, namely micro trip based (Tong, 1999), segment based (Zito and Primerano, 2005), pattern classification (Andre, 2004) and modal based (Lin and Niemeier, 2003) cycle construction. Among these four methods, modal based cycle construction method was used to develop representative driving cycles for Sri Lanka with some modifications.

After developing the driving cycles nine target parameters were calculated for respective road group to evaluate the road performance with guidelines specified in the literature. Furthermore those nine target parameters were used for cycle evaluation which is an important step in driving cycle development (Tong, 2010) to make sure that the developed cycle is truly representing the collected data set.

3. Results

Nine target parameters calculated for the two driving cycles were developed to represent two different road groups as summarized in table 3.

In the road group 2 where the traffic volumes are high the average speed is 17.9 kmph and the average speed of road group 1 is 25.5 kmph. Also in road group 2, percentage of idling is close to 30% whereas in road group 1 it is 20%. A significant difference in Positive Kinetic Energy (PKE) can also be seen in two road groups where in group 2 it is 2.15 km/h^2 and in group 1 it is 1.15 km/h^2. Graphical representation of the developed driving cycles for group 1 and group 2 are shown in figure 1 and figure 2.

Table 3: Parameters of the developed driving cycles

Parameters	Road Group 1	Road Group 2
Average Speed(kmph)	25.50	17.90
Average Running Speed(kmph)	32.28	24.52
Average Acceleration(kmh-1s-1)	1.87	2.36
Average Deceleration(kmh-1s-1)	1.79	2.59
Acceleration Proportion	0.33	0.36
Deceleration Proportion	0.31	0.34
Idling Proportion	0.21	0.27
Cruising Proportion	0.15	0.03
PKE(kmh-1ss-1)	1.15	2.15

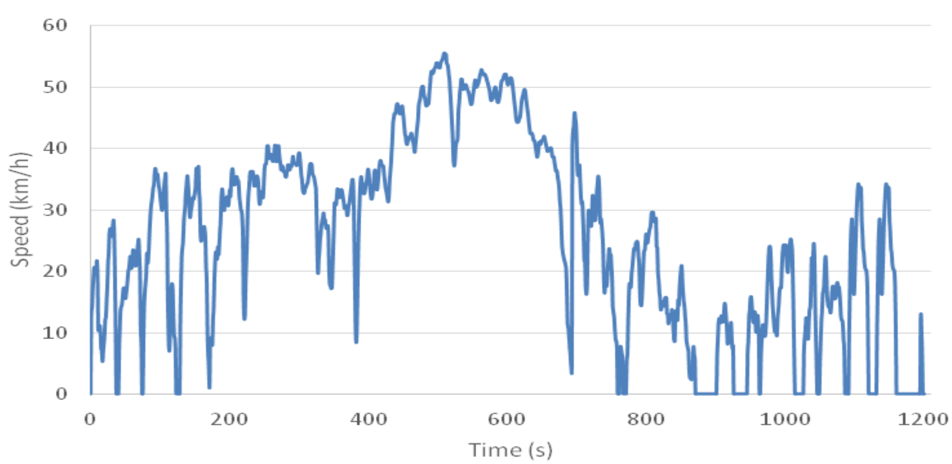


Figure 1: Driving cycle for road group 1

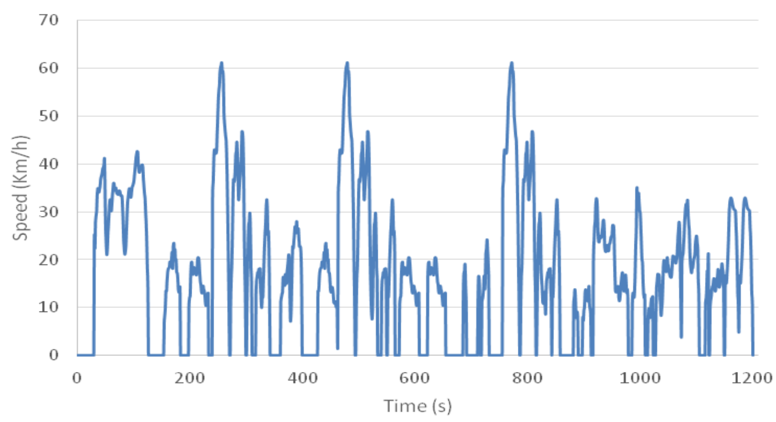


Figure 2: Driving cycle for road group 2

To compare the results with the ideal situation where the traffic flows smoothly, driving cycle for southern expressway was used. To assess the driving cycle nine parameters considered were used and the results are shown in table 3.

The graphical representation of developed expressway driving cycle is as shown in figure 3. The Expressway results show no idling and over 50% cruising proportion. Despite higher speeds, acceleration and deceleration levels are relatively small as compared to urban roads. Positive Kinetic Energy (PKE) is also relatively low for the expressway.

Table 4: Parameters of driving cycles developed for Southern Expressway

Parameters for Driving Cycle Evaluation	Selected Candidate Cycle
Average Speed(km/h)	80.645
Average Running Speed(km/h)	80.645
Average Acceleration(m/s2)	0.452
Average Deceleration(m/s2)	0.247
Acceleration Proportion	0.210
Deceleration Proportion	0.231
Idling Proportion	0.000
Cruising Proportion	0.559
RMS Acceleration(m/s2)	1.036
PKE(m/s2)	0.138

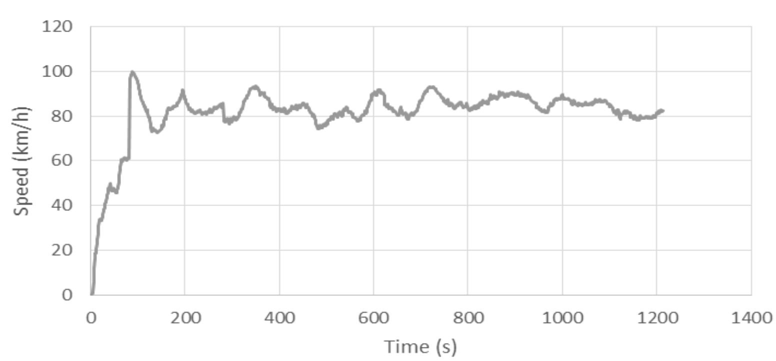


Figure 3: Driving cycle for Southern Expressway

4. Discussion

The developed driving cycle for Southern Expressway (Galgamuwa, 2015) was considered as the baseline to evaluate the selected road groups due to few reasons. Here, the speeds are within acceptable limits. Even though the acceleration and deceleration rates are high the percentage time of acceleration and deceleration are less. Therefore the time spent in each mode are less. Also it can be seen that there is no idling and for more than fifty percent of the trip the vehicle has been in the cruising mode and very low PKE values indicating the effects of road conditions.

Average speed and PKE have direct relationship to the emission and fuel consumption of the vehicle. According to Olsvic (2011), fuel efficiency of a motor vehicle is better when the speed is between 50 to 80 kmph and fuel efficiency is high if the acceleration proportions are less, even though the average acceleration rate is high, because the vehicle consumes more fuel in the acceleration state. The PKE value shows the smoothness of the driving. The average speeds are not in this range as in road group 1 and road group 2, indicating lower fuel efficiency. In Southern Expressway the PKE value is low and it implies that the driving is smooth in the expressway. However, in two road groups the PKE value is high which shows changing driving conditions.

In Colombo, the average speed of the roads is low due to number of reasons. One reason is that even though the roads are wide (four or six lanes) the traffic volumes and conflicts at intersections are high as in road group 2. In some roads the traffic volumes are less but due to number of lanes and the road condition speeds are low as in road group 1.

Based on the results the road group 1 is performing better in the terms of fuel economy than in road group 2. Furthermore, for road group 1 and 2 running speeds are 32.28 kmph and 24.52 kmph respectively. It implies that if the stop go condition is eliminated using traffic management measures fuel efficiency of the roads can be improved up to some extent. In addition, by improving road infrastructure condition such as eliminating bottlenecks, improving road width and surface condition fuel efficiency can be further improved. Results of this study shows that this approach could be fine-tuned to compare different road segments for fuel efficiency level and also that raw GPS travel time data could be used to identify bottlenecks.

5. Conclusions

The average speed alone cannot be used to evaluate fuel efficiency of the road designs as it does not reflect the actual fuel usage conditions. It is necessary to consider the actual driving condition that reflects the effects of traffic and road conditions. A driving cycle that identifies the average acceleration, acceleration proportion and PKE will be more suitable to elevate the fuel efficiency and also for comparison of different roads. If it is necessary to minimize the effects due to traffic flow and compare the fuel efficiency level due to road infrastructure alone, driving cycles developed using non-peak time segments can be used.

Acknowledgement

Authors wish to thank Dr. Thusitha Sugathapala for the guidance and motivation given and acknowledge the support of Sustainable Energy Authority by providing resources for the success of this research and the University of Moratuwa for other in kind contributions.

References

Abbott, P.G., Hartley, S., Hickman, A.J., Layfield, R.E., Mccrae, I.S., Nelson, P.M., Phillips, S.M.and Wilson, J.L. 1995. The environmental assessment of traffic management schemes: a literature review. Transport Research Laboratory Report 174.

Andre, M. 2004. Real-world driving cycles for measuring cars pollutant emissions– Part A: The ARTEMIS European driving cycles.Cedex, INRETS-LTE.

Barlows, T. J., Latham, S., McCrane, I. S. and Boutler, P. G. 2009. A reference Book of Driving Cycles to use in measurement of road vehicle emission. 3rd ed. TRL.

Black, W. R. 2010. Sustainable Transportation problem and solutions. Guilfold press, New York, USA, chapter 5.

Colvile, R.N., Hutchinson, E.J., Mindell, J.S. and Warren, R.F. 2001. The transport sector as a source of air pollution Atmospheric Environment. 32; 1537-1565.

Galgamuwa, U., Perera, L., and Bandara, S. 2015. Developing a General Methodology for Driving Cycle Construction: Comparison of Various Established Driving Cycles in the World to Propose a General Approach. *Journal of Transportation Technologies*, 5; 191-203.doi: 10.4236/jtts.2015.54018.

Gamalath, I.M., Galgamuwa, U. N., Fernando, C.M., Perera and Bandara, J.M.S.J. 2012. Methodology to Develop a Driving Cycle for a Given Mode and Traffic Corridor: Case Study for Galle Road,Colombo, Sri Lanka. *Proceedings of the Civil Engineering Research for Industry Symposium, University of Moratuwa*. 45-50.

Holmberg, K., Anderssona, P. and Erdemirb, A. 2012. Global energy consumption due to friction in passenger cars. *Tribol. Int.* 47; 221–234.

Jeon, C.H., Han, D.S., Choi, N.W., Cho, S.L., Yang, J.S., Kim, K.S., Yoo, W.S. 2012.Characterization of driving patterns
and development of a driving cycle in a military area. *Transportation Research Part D*, 17; 519-524.

Lin, j. and Niemeier, D.A. 2003. Regional driving characteristics, regional driving cycles.*Transportation Research Part D*, 8(5); 361-381.

Mozumder, S.Z. 1981. The Energy Situation in Bangladesh and a Strategy for Future Development. National Energy Plans in the Asia–Pacific Region**.** Proceedings of Workshop III of the Asia–Pacific Energy Studies Consultative Group (APESC), 809–816

Nesamani, K. S. and Subramanian, K. P. 2011. Development of a driving cycle for intra-city buses in Chennai, India. *Atmospheric Environment*, 45; 5469-5476.

Tong, H.Y., Hung, W.T. and Cheung, C.S. 1999. Development of a driving cycle for Hong Kong. *Atmospheric Environment*, 33; 2323-2335.

Tong, H.Y., Hung, W.T. and Cheung, C.S. 2000. On-Road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions. *Air and Waste Management Association*, 50; 543-554.

Tong, H.Y. and Hung , W. T. 2010. A Framework for Developing Driving Cycles with On Road Driving Data. *Transport Review*, 589-615.

Olsvic I. Measures to reduce GHG emissions and improve air quality. *NORDIC Road and Transport Research* 2011. 2(11).

Xiao, Z., Dui-Jia, Z. and Jun-Min, S. 2012. A Synthesis of Methodologies and Practices for Developing Driving Cycles. *Energy Procedia*, 16; 1863-1873.

Zito, R. and Primerano, F. 2005. *Drive Cycle Development Methodology and Results.* Transport System Centre, University of South Australia.

Published By:

Ministry of Power and Renewable Energy

&

Center for Sustainability, Univeristy of Sri Jayewardenepura

Sponsored By:

Sri Lanka Sustainable Energy Authority

ISSN 2478-0669

9 772478 066000