A PUBLICATION OF THE
SRI LANKA ENERGY MANAGERS ASSOCIATION

SRI LANKA ENERGY MANAGERS ASSOCIATION

SLEMA

SLEMA

JOURNAL

VOLUME 20 Nos 1 & 2, SEPTEMBER 2017






IN THIS ISSUE...

Inverter driven air conditioners save 35% of energy, a new study reveals

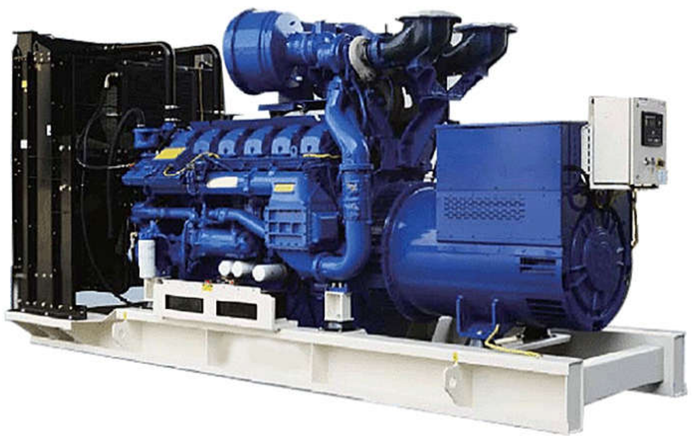
Feature: How much of renewable energy can a power system absorb ?

Why should solar PV inverters idle during night-peak ? Use them to improve line voltage !

Development of renewable energy to serve the needs of a specific industrial customer

POWER GENERATORS

Tempest MADE IN ENGLAND | VOLVO PENTA | Perkins®



AVAILABLE EX-STOCKS

Generators from **5kVA to 2200kVA**

Powered by Perkins Volvo Engines & Stamford, Mecc-Alte Alternators

BRIGGS & STRATTON

- Portable Generators
- Inverter Generators

- *More than 20 Years of Experience*
- *24x7 Island Wide Service*
- *Nine Regional Centers*
- *Fully Equipped Service Center*
- *Well Trained Staff*

CONTACT US ON 011 47 60 500

HAYLEYS ENGINEERING

HAYLEYS ENGINEERING

#180/3, Arnold Rathnayake Mawatha, Colombo 10, Sri Lanka.

Tel: +94 11 4760 500 | Fax: +94 11 2681 141

www.hayleysengineering.com

Hayleys Aventura Innovative Solutions

SRI LANKA ENERGY MANAGERS ASSOCIATION

Contents

The Editorial Board invites papers on energy related issues for publication in the SLEMA Journal.

Cover page designed by Chathuraka Senevirathna, Elpitiya Plantation PLC.

SLEMA Journal is published by the Sri Lanka Energy Managers Association. The Journal is also available on line www.slema.org.lk. All correspondence should be directed to SLEMA Office, No. 29, Fairfield Gardens, Colombo 8, Sri Lanka. (Telephone: +94 11 266 5737) Views expressed in this journal do not necessarily represent those of SLEMA members or its office bearers, and the responsibility rests entirely on the respective authors. All rights reserved by SLEMA. Contents may be reproduced for limited circulation with due acknowledgement. ISSN 2386 - 1304

Comparison of Energy Consumption between a Standard Air Conditioner and an Inverter-type Air Conditioner Operating in an Office Building

Manjula Siriwardhana and D D Ananda Namal (Past President SLEMA)
National Engineering Research and Development (NERD) Centre of Sri Lanka
Ekala, Jaela.

Abstracts

Demand for air conditioners (ACs) has exponentially increased worldwide over the last few years. Countries with booming economies report high growth of sales of room air conditioners. Sri Lanka is not an exception. With the increased gross domestic product (GDP) and warming climates, demand for room air conditioners is expected to further increase. Meeting the increased demand for electricity will be a challenge. Increased use of energy efficient air conditioners has positive impacts on the national grid, especially during periods of high demand. In a regular AC, the compressor runs at a fixed speed and is either ON or OFF. In an inverter AC, the compressor is always on, but power drawn depends on the demand for cooling. The speed of the compressor is adjusted appropriately.

In this study, the energy consumption of a regular and an inverter AC of the same capacity was evaluated in a typical office room, under similar operating conditions. Energy consumption was measured for six consecutive weeks and compared. Results show that the daily average energy consumption (for an 8-hour operating period) was 13.5 kWh for the standard AC and 8.7 kWh for the inverter type AC. Therefore, it is concluded that inverter technology can save about 35% of electricity consumed over a standard air conditioner. With the expected growth of air conditioner use and ambient temperature rise, inverter technology can significantly contribute to reduce the peak demand and energy use.
Keywords: air conditioner, inverter AC, energy efficiency

Introduction

Research work described in this paper was intended to compare the energy consumption of a standard (non-inverter) air conditioner with an inverter-type air conditioner of the same capacity, operated in similar environmental conditions in a normal office room during working hours. With the results, authors investigate the potential energy savings by deploying an increasing share of inverter ACs and the influence it can have on the national grid in terms of peak demand and energy savings, and reduction of GHG emissions from electricity generation.

Worldwide Growth in Sales of Room Air Conditioners

Energy consumption in air conditioners is rapidly increasing around the world. The demand for air conditioners have exponentially increased worldwide over the last few years. Since almost 90% of the homes in high income countries have already installed air conditioners, the recent and future growth is mainly driven by middle income countries. [1, 2]. According to a study conducted by the Japan Refrigeration and Air Conditioning Industry Association [3], the overall world AC sales in 2015 was estimated to reach 92.46 million units. The association divides AC sales into six main geographic areas. They are Japan, China, rest of Asia, Europe, North America, and other countries. Amongst them, the largest market is China, where sales reached 32.33 million units. The second largest market was Asia, excluding Japan and China, and the demand was 15.15 million units. The demand for AC units in North America reached 14.35 million units in 2015.

The largest share of AC sales is in room air conditioners. In 2015, world demand for room air conditioners was estimated to be 79.39 million units. Same as for all ACs, the largest market for room air conditioners was China and the demand reached 30.25 million units. The demand for room air conditioners in Asia, excluding Japan and China, was 13.72 million units. According to these studies, it is evident that countries with rapidly growing economies have a growing demand for ACs. As the economy and population of these countries grow, along with increased access to electricity and warming climates, it is expected that the demand for ACs would increase exponentially, not only for comfort but also as a health necessity [2,4]. According to a report on the global AC demand by Lawrence Berkeley National Laboratory [4], the AC penetration rate in urban areas in China has increased from a few percent to 100 percent in just 15 years. AC sales are increasing in India, Indonesia and Brazil by between 10 and 15 percent per year [4]. India, with over 1.25 billion people, had only a 5 percent penetration of air conditioning in year 2011. Studies have found a clear relationship between household income and AC adoption [4,5]. Sri Lanka is not an exception. Table 1 shows the increasing demand for room ACs in Sri Lanka.

Table 1 - Demand for Room ACs in Sri Lanka [4]

Year	Demand for room ACs (in thousands)
2010	50
2011	62
2012	73
2013	73
2014	74
2015	77

Therefore, it is evident that there is a rapid growth in penetration of ACs, mainly in developing countries, including Sri Lanka. The main challenge would be to meet the increased demand for electricity. If electricity demand is met by fossil fuels, it would generate increased emissions [2,4]. Therefore, it is important to explore new technologies and solutions that would reduce the electricity consumption of an AC. As a solution, AC manufacturers have attempted to make them more energy efficient [4]. Invertor type ACs are one of those newest technologies that manufacturers have introduced to the market more than a decade ago.

The constant speed AC, the dominant type in the market, is now gradually replaced by the inverter ACs. Sales of inverter driven ACs have reached 100% of the market in Japan and a significant portion in the EU (50% in 2008) and Australia (55% in 2008). This trend is promising in terms of energy savings and will help reduce future energy consumption and corresponding reduction in GHG emissions [6].

Difference between an Inverter AC and a Regular AC

The cooling load of an AC is a variable and depends on room occupancy (number of persons), desired comfort level of the customer (set temperature), outdoor environmental conditions and many other parameters. In most ACs, the actual cooling load fluctuates. However, in regular ACs, the system is not designed to handle this variable load, but for the expected peak load. In an AC, the compressor is the component which consumes electricity. In non-inverter type ACs, the compressor is either ON or OFF. When it is ON, it works at full capacity and uses the full amount of electricity it is designed to consume. When the set temperature in the AC is reached, the compressor is cut-off and cooling is stopped. When the thermostat senses that the room temperature has increased, the compressor switches ON again, automatically. That means, in normal air conditioners, the compressor is switched ON and OFF intermittently.

The inverter driven AC with varying cooling capacity has been studied during the last two decades and the well-known technique is to control the rotational speed of the compressor based on its cooling load. A three-phase induction machine (IM) is generally used as the compressor motor. In an inverter type AC, the inverter is used to control the speed of the IM by changing the frequency of the power supply to drive the variable refrigerant flow and thereby regulating temperature of the conditioned-space. The variable frequency drive is used to achieve the desired frequency, and the rotational speed will be proportional to the input frequency. This will adjust the flow rate of refrigerant based on the temperature of the room. With this technology, the compressor of the AC is always ON, but varies the power input depending on the temperature of the return air and the level set in the thermostat [1]. Hence, the flow of refrigerant is dependent on the cooling needs of the space.

Several studies have modelled the variable speed compressor to simulate the inverter AC. Shao et al. [7] by their modelling and experimental investigation, found that the refrigerant flow is determined only by the compressor frequency and is independent of the condensation and evaporation temperatures. They also found that the coefficient of performance (COP) of the inverter air conditioner changes slightly with the speed of the compressor, and the optimal frequency which gives the highest COP is usually the basic frequency [7].

Advantages and Disadvantages of Inverter ACs

Split-type variable speed (inverter-type) ACs were the best available technology in Europe by 2012 [8]. Variable speed or the inverter ACs are more effective when they are run at part load, than the regular constant speed ACs serving a cooling load below its rated capacity. In other words, the efficiency advantage is highest when they run at part load conditions [6,8].

- Inverter-type ACs can keep the temperature more stable, increasing thermal comfort.
- They can initially cool a warm room faster to a convenient temperature.
- They are more energy efficient.

The main disadvantage of an inverter AC is its high initial cost compared with a regular AC.

- Electronic components and control circuitry are more complicated compared with the non-inverter type which makes the AC more expensive.
- There is a controversial statement regarding the effect of inverter AC on the power quality of low voltage distribution networks.

Mirchevski et al. [9] found that inverter ACs form a considerable share of nonlinear load in the residential sector and a source of harmonics on the electricity grid. In contrast, Moller et al. [10] conclude completely opposite results, where the inverter fed AC units utilizing three-phase motors provide the most suitable solution to power quality issues compared with high penetration of non-inverter ACs. Therefore, a comprehensive study on the power quality issue of a large penetration of inverter ACs in the national grid is required.

Materials and Study Methodology

Two AC units, an inverter and a non-inverter, were tested under similar operating conditions. Both were rated single-phase 240V, 50Hz. Each unit was mounted on the same wall of an office room and the temperature control settings of the units were set to 26^{0}C, so that it creates the normal operating load in an office building.

Methodology

The energy consumption of the two AC units was evaluated by using a Circutor™ power analyser. The ACs were operated on alternate days; standard, non-inverter AC on one day, and the inverter AC on the following day. Energy consumption was measured in one-minute intervals over 6 consecutive weeks, so that the effect of fluctuation of ambient temperature may be assumed to be cancelled out. Temperature and relative humidity were logged in one-minute intervals using data loggers.

Name Plate Data of the Two Air Conditioners Tested.

Name plate of non-Inverter Air Conditioner

Make	: Frostaire		
Model	: TFI-18CR/ TFO-18CR		
Capacity	: 18,000BTU/hr		
Rated Current	: 9.1A	Maximum	: 11.8A
Rated Power	: 2000W	Voltage	: 220-240V
Refrigerant	: R22 / 1.06kg		

Name plate of Inverter Air Conditioner

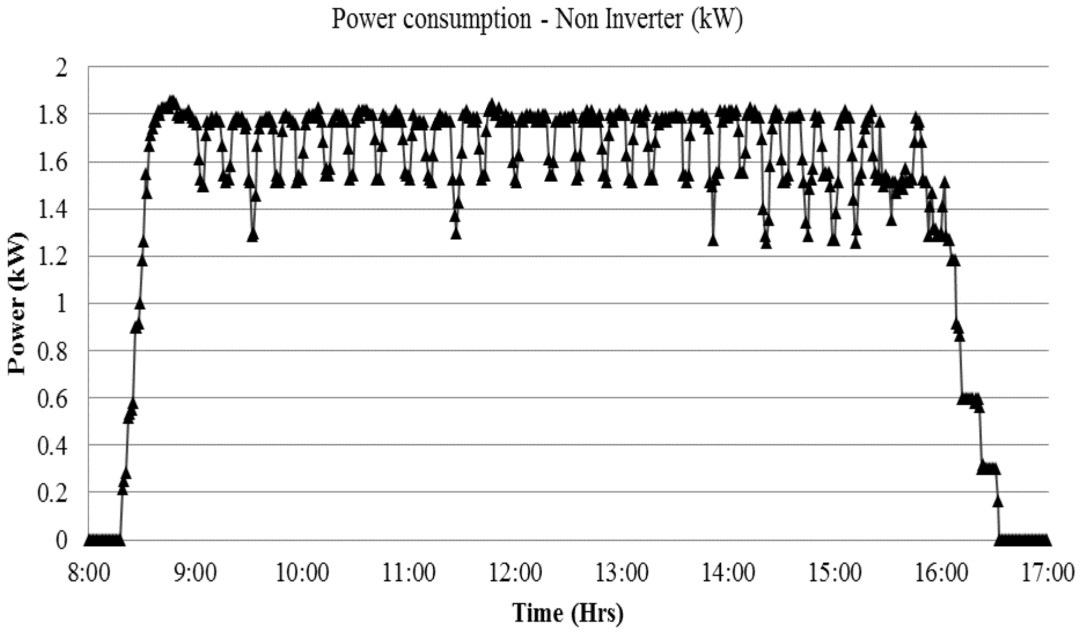
Make	: Hisense		
Model	: AS-18TR45FATG1		
Capacity	: 18,000BTU/hr		
Cooling Power	: 1600kW	Voltage	: 220-240V
Cooling Current	: 7.2A		
Refrigerant	: R410A / 0.32kg		

Results

Figure 1 and Figure 2 show the variation of power drawn by the standard and inverter type ACs, respectively, operating at similar temperature settings during normal office hours 08:00 to 17:00, under similar (assumed) outdoor conditions.

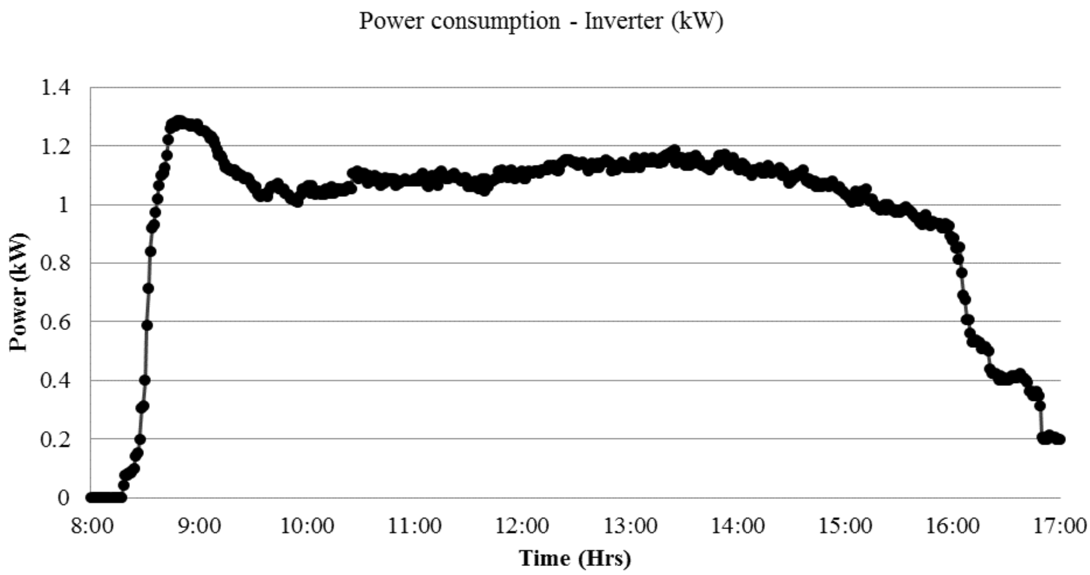
Figure 3 shows the daily energy used in each AC. Since the measurement was done over 6 weeks, fluctuations of outdoor conditions are expected to be cancelled out or similar for both ACs.

Figure 1 - Power drawn by the Non-Inverter (standard) AC during Office Hours



Since the compressor of non-inverter AC frequently switches ON and OFF, the current and the power consumption of the AC fluctuate accordingly.

Figure 2 - Power drawn by the Inverter-Type AC during Office Hours



The power consumption pattern of an inverter AC is smoother than a non-inverter AC because the compressor will not switch between ON and OFF.

Figure 3 – Energy drawn over 8 hours (08:30 to 16:30) at a Temperature Setting of 26 ^{0}C

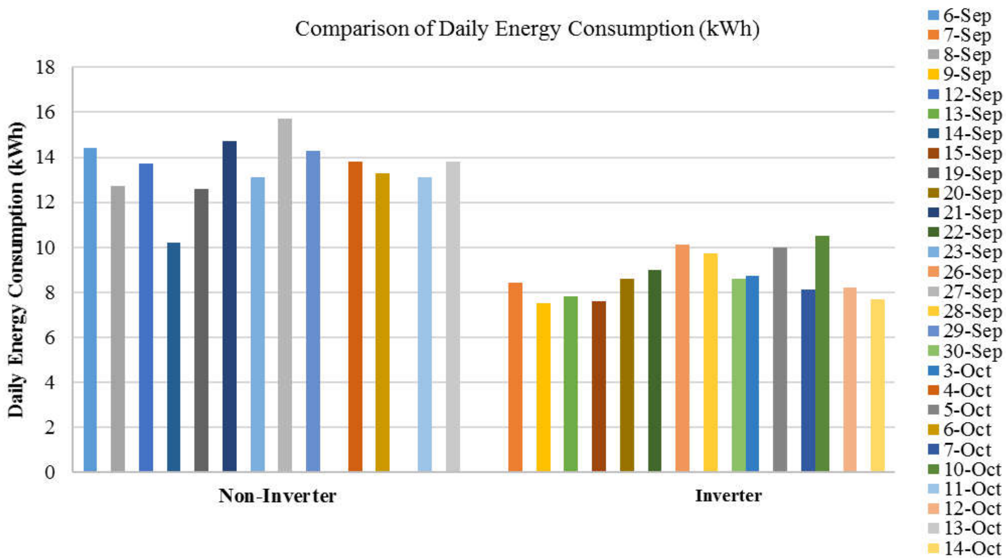


Figure 3 gives the energy consumption of inverter and non-inverter ACs run in the same space on alternate days for a 6-week period. The daily average energy consumption of the standard AC was 13.5 kWh (for 8-hour operating period) and the average energy consumption of the inverter type AC was 8.7 kWh for the same period under similar operating.

There is a clear reduction of energy consumption in inverter ACs.

Conclusions

It is concluded that inverter technology can save about 35% of energy over a standard AC. With the expected growth of AC use and ambient temperature rise due to global warming, inverter technology can provide significant savings

References

[1] Bijli Bachao Team, April 22, 2016, Air conditioners with Inverter technology can help save electricity.

https://www.bijlibachao.com/air-conditioners/air-conditioners-with-inverter-technology-can-help-save-electricity-ac-india.html

[2] Lucas W. Davis and Paul J. Gertler, 2015, Contribution of air conditioning adoption to future energy use under global warming, Proceedings of the National Academy of Sciences, USA. 2015 May 12; 112(19): 5962–5967.

[3] The Japan Refrigeration and Air Conditioning Industry Association, 2016, World air conditioner demand by region, Tokyo.

[4] Chris Mooney and Brady Dennis, The world is about to install 700 million air conditioners. Here's what that means for the climate, The Washington Post, May 31, 2016.

[5] Takao Nagata, Juhri Yasin, Yasuhiro Kishi, Ayumi Wada, Development of the Inverter air conditioner for Southeast Asia in FY2014, Hitachi Review Vol. 64 (2015), No. 2.

[6] Shah, N., Waide, P., Phadke, A., Cooling the Planet: opportunities for deployment of super-efficient room air conditioners, International Energy Studies Group, Lawrence Berkeley National Laboratory, USA.

[7] Shao, S., Shi, W., Li, X., Chen, S., 2004, Performance representation of variable-speed compressor for inverter air conditioners based on experimental data, International Journal of Refrigeration 27 (2004) 805–815.

[8] Michel, A., Bush, E., Nipkow, J., Brunner, C. U., Bo. H., 2012, Room air conditioners: Recommendations for policy design, Topten International Group, Paris.

[9] Mirchevski, S., Arsov, L., Iljazi, I., 2013, Total power consumption of Inverter air conditioner in household application, Conference paper May 2013,

https://www.researchgate.net/publication/280247091

[10] Moller, L., Robinson, D., Perera, S., Gosbell, V., Bucca, F., 2005, Assessing the impact of increased air conditioner load on power quality in Australia, 18th International Conference on Electricity Distribution, Turin, 6-9 June 2005.

USING SOLAR PV INVERTERS AT NIGHT FOR VOLTAGE STABILIZATION: A Case Study

A. S. Rodrigo[1] & K. K. Navoda[2]

[1]*Senior Lecturer, Department of Electrical Engineering, University of Moratuwa*
[2]*Electrical Engineer, Ceylon Electricity Board*

Abstract
Installation of grid-connected rooftop solar power generation modules has been allowed in Sri Lanka since 2008. The paper analyzes the potential use of solar power inverters at night to feed reactive power to the low voltage (LV) network. The LV network typically has undervoltage issues at the evening peak-time, and the PV inverters distributed along the line can be used to eliminate or reduce such undervoltage issues. The paper proposes an algorithm to determine the suitable operating power factor of each inverter connected to the feeder. A case study of a LV distributor with solar PV inverters is presented, to demonstrate the application of the algorithm. Financial benefits to customer by introducing a reactive power tariff is assessed. The paper concludes that such a system would yield net benefits to the utility.

Key Words
Power factor, PV inverter, reactive power

Introduction
Electricity production from rooftop solar PV systems is rapidly increasing in Sri Lanka. By end 2017, about 100 MW of rooftop solar PV systems were in operation. The annual capacity factor of solar PV installations is limited to about 17% owing to several reasons including the dependence of solar power generation on the availability of irradiation. This means, the inverter installed to convert the dc output of solar PV to ac to feed the utility LV network, largely remains underutilized most of the time. During the night-peak when the solar PV generation is negligible, the inverter remains shutdown.

Kozinda, Beach and Rao [1] demonstrated a number of opportunities to use the potential of inverters for a variety of power system applications.

Under voltage issues occur along distribution lines, partly owing to reactive power required by customers' end-use appliances. Solar PV inverters could be considered as distributed VAR injectors. In late evening when typically, both real and reactive power flows on LV lines are at their maximum, active power generation on each solar module is zero. Therefore, PV inverters may be used during that period to feed reactive power to the system. Operating power factor for each inverter may be decided by the utility, based on measured feeder loading and the calculated voltage profile. This concept has not yet been implemented in Sri Lanka.

If implemented, the strategy involves the utilization of the PV inverter which is a customer's property, for the improvement of the utility's LV system. To encourage customers to participate, a reward scheme may be introduced.

This requires a tariff for reactive power to be introduced in Sri Lanka. Currently, the maximum demand charge for bulk customers is the only indirect charge for reactive power drawn by customers from the grid. The purpose of introducing the maximum demand charge was to encourage customers to manage their demand, and thereby, minimize line currents and voltage drops in the utility network.

General Algorithm
A general algorithm was developed to identify line segments and the inverters selected to serve reactive power, and the output power setting of inverters. The description below is for a typical overhead LV radial distribution line in Sri Lanka. (i) Based on the calculated voltage profile along the feeder, a zone with under voltage would be identified, to confirm that an undervoltage problem exists. (ii) Then the real power loss would be calculated for each line segment with the highest real power loss would be identified, (iii) if customers served by the end-pole of the identified line segment have inverters installed, then the desired power factor would be set on such inverters. (iv) the voltage profile would be re-calculated, assuming the inverters now inject

the desired amount of reactive power, (v) If the calculated voltage at the pole is higher than the limit then increase the power factor and repeat the steps. (vi) If an inverter was not connected at the selected pole then check for the nearest installed inverter and set the power factor. (vii) The same procedure would be repeated until the under-voltage issue is eliminated or minimized along the distribution line.

The calculated power factor could be conveyed to the respective customers and requested to set and operate their inverters at the peak time.

Case Study

Parameters of the sample feeder are shown in Table 1. The 1.5 km long sample feeder is in the western province of Sri Lanka, and has 15 solar PV systems installed along the feeder

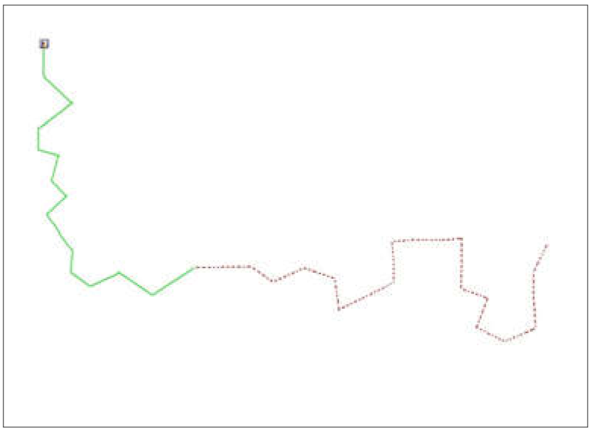
Table 1- Parameters of the Sample Feeder

Length along the feeder (m)	Number of service connections at the pole (node)	Installed inverter capacity (kVA)	Active power load off the node (kW)	Reactive power load off the node (kVAr)
0				
40	2	0.5	1.20	0.60
80	2		1.30	0.60
120	1		0.56	0.40
160	2	1	1.50	0.60
200	2		0.92	0.51
240	3		1.36	0.94
280	1	2	1.11	0.73
320	2		0.75	0.44
360	2		0.64	0.18
400	2		0.45	0.25
440	3	3	1.28	0.30
480	2		1.33	0.61
520	1		0.95	0.70
560	1	0.5	0.64	0.37
600	2		1.20	0.50
640	3	1.5	1.37	0.14
680	1		0.94	0.27
720	3	0.5	2.20	1.20
760	2		1.06	0.52
800	1	2	1.12	0.60
840	2	0.5	1.23	0.47
880	1		0.86	0.70
920	1		0.81	0.50
960	2	2	1.80	0.62
1000	3		2.21	0.72
1040	2		1.25	0.76
1080	1	0.5	0.94	0.45
1120	2		1.68	0.49
1160	1		0.85	0.73
1200	1	1	1.20	0.35
1240	1		0.76	0.27
1280	2	3.5	0.91	0.50
1320	1		0.80	0.20
1360	1	0.5	0.61	0.37
1400	1	1	0.68	0.34
1440	2		0.80	0.26
1480	1		1.50	0.31
1520	1		0.75	0.30
Total	64	20	41.52	18.8

Note: Active and reactive power demand shown in columns 4 and 5 are the peak-time demand of the customer (or cumulative demand of customers) served off the node. Information was obtained from a load research study conducted by CEB in a semi-urban area.

Using the parameters of the feeder and the connected loads and considering the sending-end voltage to be 1 pu, a load flow study was conducted using the SynerGEE model. The study revealed that an under-voltage situation would occur at 640 m along the feeder, at which point the voltage would drop below 0.94 pu, the lowest allowed under Sri Lanka's distribution code. The calculated voltage profile is shown in Figure 1.

Figure 1- LV Feeder Voltage Profile without Reactive Power Injection



Note: Line segments that violate the lower voltage limit of 0.94 pu are shown in dotted lines.

The algorithm presented earlier was applied, to use inverters to inject reactive power to selected nodes. The final operating power factor of each PV inverter is shown in Table 2.

Table 2 - Computed Operating Power Factor

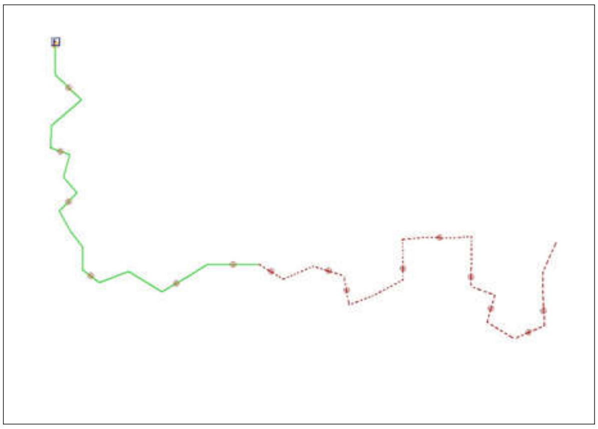
Length along the feeder (m)	Installed inverter capacity (kVA)	Final Power Factor Setting on the Inverter	Reactive power injected (kVAr)
40	0.5	-	-

160	1.0	0.80	0.60
280	2.0	0.93	0.74
440	3.0	0.99	0.42
560	0.5	0.67	0.37
640	1.5	0.99	0.21
720	0.5	-	-
800	2.0	0.95	0.62
840	0.5	0.28	0.48
960	2.0	0.95	0.62
1080	0.5	0.44	0.45
1200	1.0	0.94	0.34
1280	3.5	0.99	0.49
1360	0.5	0.67	0.37
1400	1.0	0.94	0.34
Total	20.00		6.07

Note: The power factor setting on the inverter (column 3) is on the basis of rated active power of the inverter (although no active power is delivered by the inverter during the evening peak period). The calculated reactive power injection is given in column 4.

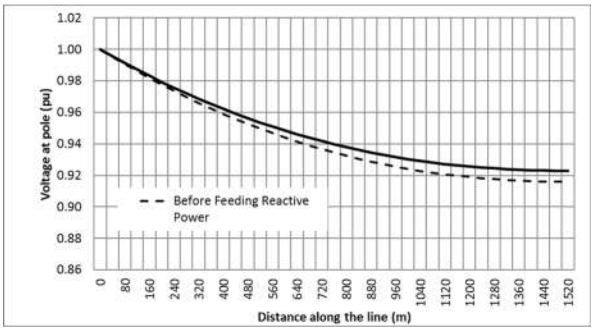
Inverters were now placed along the feeder with their reactive power factor set according to Table 2. Figures 2 and 3 show the calculated voltage profile along the line.

Figure 2 - LV Feeder Voltage Profile with Reactive Power Injection



Note: Line segments that violate the lower voltage limit of 0.94 pu are shown in dotted lines. Line segments where inverters are active are marked with a circle.

Figure 3 - LV Feeder Voltage Improvement with Reactive Power Injection



Voltage profiles indicate that in the absence of reactive power infeed, voltage violations occur from 640m onwards. Once the reactive power feed-in from inverters was enabled, under-voltage occurs from 720m onwards. The points at 640 m and 680 m along the feeder were no longer have a voltage issue.

Financial Analysis

There are two types of financial benefits associated with the initiative to inject reactive power at inverters. (i) reduced energy losses along the feeder, (ii) benefits of released capacity that can be used to serve future customers.

Value of reduced energy losses: In the case study, the power loss before and after reactive power injection was 1.954 kW and 1.773 kW, respectively. This reduction of power loss was 0.181 kW (9.3% of the base case).

The operating period of inverters in the reactive power injection mode was assumed to be limited to peak hours (ie 4 hours per day) [2]. This assumption aligns with Sri Lanka's time-of-use tariff, in which the peak period is defined to be from 1830 to 2230 (4 hours).

Energy saving was therefore calculated to be,
Energy saving = Avoided power loss × peak hours × 365 = 0.181 x 4 x 365 = 264 kWh/year

The value of energy at peak-time in year 2015 as published in the bulk supply tariff [3] was Rs 11.97 per kWh. This value is for power delivered at transmission voltage to distribution entities.

The calculated energy saving in this study is along LV lines. Losses saved along medium voltage lines and the distribution transformer were estimated to be 1% and 2% of input the respective segments [4]. Accordingly, saving of losses along LV lines would reflect as 299 kWh/year.

Accordingly, the value of energy saved owing to the reduction of loss by inverter operation was estimated to be Rs 3,525 per year.

Benefits of Released Capacity: Increased line capacity owing to reactive power infeed by solar PV inverters was calculated according to reference [5]. The calculated line current without compensation was 91.4 A, which reduced to

87.0 A with compensation. The released capacity of the line may therefore be estimated to be 3.1 kVA. Sri Lanka's generation and transmission capacity costs have been estimated in [3] to be Rs 2713 per peak-kW, per month. Therefore, assuming a power factor 0.8, the value of upstream capacity saved was estimated to be Rs 6728 per month (or Rs 80,738 per year). The value of capacity saved in distribution transformers and the MV distribution network would be small, and was therefore neglected.

Accordingly, the total financial savings to the utility is estimated to be Rs 3,525+Rs 80,738 = Rs 84,264 per year. Assuming a discount rates of 20%, and assuming all costs remain the same in real terms, the present value of savings to the utility is estimated to be Rs 241,456 for a 5-year period.

Rewards to Customers

A reactive power tariff needs to be determined to compensate customers for their participation in compensation. For determination of the reactive tariff for consumption the Case Study results calculation was computed when a capacitor banks fixed at customer end. The assumptions made are given in Table 3.

Table 3 - Assumptions to derive a Tariff for Reactive Power Injection

Life time of a capacitor bank	5 years
Annual maintenance cost (% of capital cost)	2%
Capital cost	Rs 3000 per kVAr
Discount rate	20%

Considering the pole at 160 m away from the transformer, the reactive power injection required was 0.6 kVAr. Assume that 1 kVAr capacitor bank was installed (which also matches with the rating of the inverter). The capacitor bank operates at the peak time, flor 4 hours per day.

Total reactive energy injected by the customer = 0.6 x 4 x 365 = 876kVArh

If T (Rs/kVArh) is the tariff for reactive energy paid to a customer,

$$T\sum_{i=1}^{5}\frac{876}{(1+0.2)^{i}} - 3000 + \sum_{i=1}^{5}\frac{60}{(1+0.2)^{i}}$$

T = 1.01 Rs/kVArh

The case study LV feeder has a total of 20 kVA of inverters, of which 19 kVA would be used for reactive power injection. Assuming that a cumulative capacity of 19 kVAr of capacitors were installed by customers, the cumulative injection of reactive power will be 6.07 kVAr.(see Table 2). The calculated levelized cost was 1.90 Rs/kVArh, for customers to recover their costs without a financial loss.

Therefore, this study proposes a tariff of 2.00 Rs/kVArh for customers injective reactive power to the system at LV feeder level.

Present value of payments to customers at 2.00 Rs/kVArh = Rs 52,975
Present value of benefits to utility = Rs 241,456
Benefit to cost ratio = 4.6

Conclusion

Solar PV inverters distributed along the feeder even of smaller capacities can be used to reduce the under voltage along LV feeders at peak time.

The proposed tariff for reactive power injection associated with solar PV inverters is 2.00 Rs/kVArh. Further studies are proposed to re-evaluate the upstream capacity benefits in the longer term of reactive power injection at LV, through system-level modelling.

References

[1] A. Kozinda, T. Beach, V. Rao, "Latent Opportunities for Localized Reactive Power Compensation," *Cal x Clean Coalition Energy C226*, 2013.

[2] Statistical Digest 2015, Ceylon Electricity Board, Sri Lanka.

[3] "Decision on Bulk Supply and Transmission Tariffs, effective from 1st July 2015", Public Utilities Commission of Sri Lanka, 2015.

[4] Resource Management Associates (Pvt) Ltd, "A Tariff for Reactive Power in Sri Lanka", *Final Report*, September 2011.

[5] N. Kutkut, "An ac PV Module with Reactive Power Capability: Need and Benefit," *Petra Solar, Inc.*, 2012.

Additional References

[6] Ceylon Electricity Board, "Manual for Interconnection of Micro Scale Renewable Energy Based Power Generating Facilities at

Low Voltage Consumer Feeders of National Grid", August 2016.

[7] SMA Solar Technology, America "Q at Night," *Reactive power outside of feed-in operation with SUNNY CENTRAL 500CP XT / 630CP XT / 720CP XT /760CP XT / 800CP XT / 850CP XT / 900CP XT"*.

[8] Inverter Reactive Power Compensation (2014): http://www.blueoakenergy.com/blog/inverter-reactive-power, Visited, 24th November 2016.

Sustainable Power for Carbon Neutral Operation: A Feasibility Study for Printing Industry in Sri Lanka

Archishman Bose[1], Kiran Raj Rajan[1], Ruchira Abeyweera[2], Janaka Rathnakumara[3], N.S. Senanayake[2], Tharanga Wicramarathna[4], Jeevan Jayasuriya[5]

[1] MSc. SELECT: InnoEnergy, KTH Royal Institute of Technology, Sweden/ Politecnico di Torino, Italy, [2] The Open University Sri Lanka, Sri Lanka, [3] Wijeya Newspapers Limited, WNL, Sri Lanka, [4] Ceylon Electricity Board, Sri Lanka, [5] EIT InnoEnergy, Sweden, KTH Royal Institute of Technology, Sweden

Abstract

A leading printing company in Sri Lanka was selected to evaluate the techno-economic feasibility of renewable power generation to de-carbonize the (low carbon) operations. The study critically looked at the resource, economic and social factors affecting the design of a grid integrated renewable power system in a rural area. Technical challenges of grid integration through fluctuating renewable power along with economic challenges were investigated. Connecting to the closest 33kV bus was considered the most viable grid interconnection option.

The study indicated that a standalone Photovoltaic System (PV) of 4 MW would be necessary to generate the 5.2 GWh/year requirement by the printing facility. To take advantage of the current 60 MW grid connected competitive tender based Solar PV project by the Ceylon Electricity Board, a detailed techno-economic assessment was conducted for a grid connected 1MW system. A tariff of 19.48 LKR/kWh would result in a payback period of around 5 years with a reduction of 1068 tons of CO_2 emission per year. Since the project location is within the coconut plantation belt of Sri Lanka, and because of attractive tariff schemes for bio-power, feasibility of a hybrid power system with biomass was also carried out. Different combinations of solar PV-biomass based hybrid solutions were studied within a maximum capacity of 3 MW due to space constraints. This results in a considerably reduced tariff, as low as 10 LKR/kWh, while maintaining a constant payback period of 5 years. A 2 MW hybrid system incorporating solar photovoltaic and biomass gasification, 1 MW each, is proposed to be the most economical solution, with project capital expenditure of 2.45 million USD.

The operation strategy of the proposed hybrid system could ensure a stable power output of 1 MW at the capacity factor of at least 75% of the year, compared with 17.53% for a 1MW Solar Photovoltaic power system.

Introduction

In addition to implementing sustainable practices for improvement in energy efficiency, medium to small scale industries have begun to produce their own green energy. However, challenges remain. Optimal selection of technologies and size of power generation units is not only driven by technical and economic aspects, but also by local laws and resource availability [1]. Ease of implantation also plays a crucial role in such projects, especially for an industry without any expertise on electricity generation.

Sri Lanka's energy mix has been dominated over the years by hydro power generation. However, with the increase in demand and the saturation of hydro power, coal has recently been added to the energy mix, with a 900MW power plant (Ministry of Power and Renewable Energy, n.d.) that was completed in 2014. Furthermore, with oil being phased out as a source of energy for electricity generation, coal is set to become the major source of electricity in Sri Lanka. Future scenarios predict that the percentage of coal power will continue to rise (Jayasekera, 2014) and may even reach 40% by 2020 and 60% by 2034 (Ceylon Electricty Board, 2016).

The life cycle analysis of newspaper printing has been studied with published reports [4]. The primary energy source for newspaper printing and other related processes is electricity. The national grid inherently has its own specific emissions due to the presence of fossil fuel power generation units [5]. Hence the use of electricity naturally results in net carbon emissions from printing operations. The generation of own power from renewable energy resources would, therefore, result in a decrease of emissions from the printing process.

A leading newspaper company in Sri Lanka was selected to evaluate the techno-economic feasibility of renewable power generation to de-carbonize its operations. The industry selection was based on it being representative of a typical medium scale industry. The present annual energy demand for printing daily newspapers and magazines is 3.5 GWh. However, with a planned 30-40% expansion, by 2020, the annual energy requirement has been predicted to be 5.2 GWh. Further, printing as an industry has reached its peak growth in many countries [6]. In Sri Lanka, it is predicted to reach its peak in 10-15 years' time [7]. Hence, diversification of the business of the printing company was considered as well. Accordingly, a feasibility study on the concept of power generation was carried out.

The overall objective of this study was to determine the techno-economic feasibility of generating power for own energy needs of the factory by using renewable technologies, and to design an energy system by determining feasible renewable energy technologies, country energy policies for Independent Power Producers (IPPs) and limitations of the company or resources available for the project.

Limitations and Assumptions

The power generation facility studied for feasibility is essentially an on-grid system. The system design hence was not based on the real-time load requirement of the printing process but meeting the annual demand of 5.2 GWh required for the printing operations. However, future possibilities of incentives from load following and grid frequency control were considered while selecting the power generation technologies. Following assumptions were also made in the study.

- Timeframe of project implementation was considered as 2020.
- Life cycle emissions were not considered in power plant related emissions. For example, emissions from solar based power systems were considered zero.
- A lifetime of 20 years was considered for all project solutions.
- A reduction of 0.7% output capacity per year was considered for all power generation systems.
- Alternative sites were not considered due to land issues and land costs.
- On economic aspects, the following were assumed:
  Corporate tax: 10%, capital insurance rate: 0.50%, decommissioning factor: 5%, inflation rate in Sri Lanka: 9.72%, cost of equity: 16%, tax holiday period: 6 years (Board of Investment of Sri Lanka, 2017), (Board of Investment of Sri Lanka , 2016).

Considering multiple constraints is essential for projects in developing countries like Sri Lanka. A financial constraint of a net project budget of 3 million USD was considered. Additionally, local policy with respect to Sri Lanka were studied to set up project boundaries.

An upper bound of 10 MW of generating capacity was considered, based on the definition of Sri Lanka's small power producer category.

A lower bound of 5.2 GWh of annual energy needs to be produced, was considered.

Other constraints included space, local knowledge, social acceptance and ease of implementation.

Feasibility Study

Local laws and regulations were analyzed and found to be favorable for the development of renewable energy-based power generation projects in Sri Lanka. Thereafter, the potential site for the development of the project was studied.
The land for project development lies within the dry zone of the country and is located at *Bingiriya* in the North-Western Province of Sri Lanka. The area is essentially rural. The GPS location of the site is 7.684738°N, 79.992582°E. The available land, measuring more than 100 acres (40 ha), comprises a tank, 30 acres (12 ha) of paddy fields and about 70 acres (28 ha) of coconut plantations. The river *Deduru* flows within 1 km from the land. However, an upstream dam results in the river to run dry most of the year. The water available thereby would mostly be from the ground water, or through additional connections of industrial water supply. The latter is however, a high cost solution for a rural area. Other analyses of roads, infrastructure, site vegetation, soil condition, surrounding locality including cultural and environmental aspects were found to favor the development of the project at the specified plot.

A feasibility study in relation to the three-major mature renewable energy technologies, namely wind, solar and biomass were carried out and presented as follows.

Solar Photovoltaic:

The solar photovoltaic (PV) is rapidly expanding in Sri Lanka owing to special government incentives and higher social acceptance [8]. Since the price of solar PV cells has reduced significantly over the years [9], solar power generation has become a promising industry.

The daily average solar insolation at the studied location is 5.42 kWh/m^2/day with a yearly mean daily average ambient daytime temperature ranging from 24-30 ºC [10], making the site suitable for Solar PV power generation. A detailed study of the monthly solar resource shows that an annual capacity factor of 17.5% is feasible. Hence for generation of 5.2 GWh of electricity, a 4 MW of standalone solar PV system has been calculated to be suitable, including losses in transmission and distribution.

Biomass Power:
The plot lies within the coconut belt of Sri Lanka, with the possibility of a supplying feedstock for biomass power generation. However, a plantation of 70 acres is inadequate to supply a considerable amount of woody feedstock to a utility scale biomass power plant. Hence, the surrounding areas were identified as potential source of feedstock. Intercropping of coconut, especially with *Gliricidia,* had been studied to allow better land utilization and presents an attractive stable supply chain and feedstock for biomass-based power generation [11].

Combustion and gasification are the two commercialized technologies in Sri Lanka. However, for small-scale applications, especially for systems below 2 MW capacity, gasification power plant provides the optimum operations [12] with a relatively high efficiency, low water requirement and the possibility to expand with expansion of the supply chain, due to modularity.

Additionally, a detailed analysis of the biomass supply chain is critical. Strategies to ensure a stable supply chain for a maximum of 1.5 MW power systems were analyzed, essentially based on supply chain limitations. For a 1 MW system, the annual fuel requirement is 5,256 thousand tonne of solid fuel, based on a feeding rate of 24 tonne/day operating at an efficiency of 20% and a capacity factor of 60%. Around 670 acres of intercropped land would be required to supply the feedstock after consideration of the transportation and other losses.

The 65 acres of plantation land within the identified plot would be able to supply only 12% of the necessary feedstock required for a full output of 5.2 GWh per year from the 1MW power plant. Out growers or contract farmers have been considered as an essential part of the supply chain with the requirement to fulfil the weekly amount of feedstock. Additionally, a live storage of 3 to 10 days, based on different times of the year should also be ensured to maintain the stable operation of the biomass power plant.

A supply chain within 15 km radius (from the power plant) was identified to be the limiting option for supply from out growers. Economic analysis and other constraints with project feasibility showed that 500 out-growers, located within a radius of 5 km around the gasification unit would be ideal for a stable supply chain. The remaining 38% of the feedstock will need to be covered by bulk suppliers.

Presently, the printing industry re-sells approximately 1,200 tons of waste paper, annually. Estimates show that the cost of transportation from the printing facility to the power generation unit will be less than 0.5 LKR/kg of paper. Calculations show, that any resale price less than 27.50 LKR/kg would provide economic benefits to use the waste paper as a feedstock to the proposed power plant.

Wind Power:
Bingiriya site was found to be in an area with poor to marginal wind potential [13]. The surrounding area, as well as the designated land contains coconut plantations, over 10 m in height. This increases the turbulence intensity, thereby decreasing the wind speed and severely impacting the performance of wind turbines. Nearby lakes also possess a threat to migratory bird mortality. Based on technical, social and environmental aspects, the site was thus considered to be unsuitable for wind power generation.

Grid Integration
Evaluation of available options for grid connection and corresponding technological challenges were considered for the overall technical and economic feasibility of the project. All studies were based on the guidelines set by the Ceylon Electricity Board (CEB), for the grid connection of small scale power plants [14]. Along with these guidelines as per recommendations for small power producers IEEE and IEC international standards were also studied and followed to ensure power quality and reliability of the overall grid.

The land selected is in the *Puttlam* District, and the closest grid substation (GS) available to transfer power is *Madampe* 132/33 kV GS, located about 25.7 km (direct distance) away. If a medium voltage line is to be constructed to *Madampe* GS alongside the existing road, the length would be around 29 km. This would result in the cost of electrical infrastructure including transmission lines and metering equipment to be approximately 0.6 million USD, with considerable impacts on the project economic viability.

Hence, other technologically feasible and less economically challenging options were studied regarding the possibilities of grid integration. A 33 kV medium voltage feeder connecting *Madampe* GS to *Kuliyapitiya* was found within 1 km from the proposed land. Length of the 33kV line was estimated at 500 m. An outdoor switch yard was proposed for the interconnection. Land area required for the outdoor switch yard was estimated to be 60 m^2 including outdoor transformer. The cost of grid connection would thus be around 12,000 USD.

Additionally, the existing 33 kV MV line was studied to be sufficient to transfer up to 3 MW capacity to nearest 33/132kV grid substation. The conductor type lynx (aluminium conductor steel reinforced) is already installed which can carry the additional generation ranging 40 to 45 A through the line any time of the day. Since the area does not have any nearby distributed generation, the connection to the 33 kV MV line is thereby technically feasible.

Hybrid Power System

Power generation systems from a single source have their own limitations [15]. Multiple energy sources, when combined, produce further benefits, both from technology and economic points of view [16].

Hybridization of solar photovoltaic plant modules with biomass based power generation unit had been shown to complement each other to produce a stable power overcoming individual drawbacks [15]. An optimized solution had been developed for developing a hybrid grid integrated renewable power generation power plant that meets the desired demand as described above.

1MW Standalone Solar PV System

The preliminary plant design of a 1 MW on-grid solar PV system comprises a collector array in a string layout, with 3,173 of 315 Wp poly-crystalline silicon (Si) cell modules, deployed in a fixed horizontal tilt of 10°. The conversion efficiency of the modules would be approximately 16.4%, equipped with preliminary plant design MPPT facility corresponding to a net collector area of 6,195 m^2.

The PV generated voltage of 400-440V will be stepped up at the generation site and fed to the distribution voltage of 33 kV. The inverter system employed (capacity 15 x 60 kWe) will have an efficiency not less than 98.5% together with an overall distribution loss of around 2%. To avoid interruptions due to inverter, an extended warranty for 10 years was considered. The system was analysed to produce around 1.5 GWh of electricity, which is around 29% of the net energy requirement of 5.2 GWh.

The net capital expenditure (CAPEX) of the system would be around 0.732 million USD, an annual running cost of around 27,000 USD would be necessary. Accordingly, a capacity factor of 17.5% would result in the levelized cost of electricity production to be 0.08 USD/kWh, or approximately 12.25 LKR/kWh. However, to ensure a payback period of 5 years, a tariff of 19.5 LKR/kWh had been proposed, which is lower than the limit for the highest tariff of 22 LKR/kWh.

Modular Biomass Gasification Power Plant

A modular gasification unit with producer gas fired internal combustion engine-based system for combined generation of electricity and heat was selected as a suitable technology. The heat will be used for drying the biomass to the gasification requirements of moisture content.

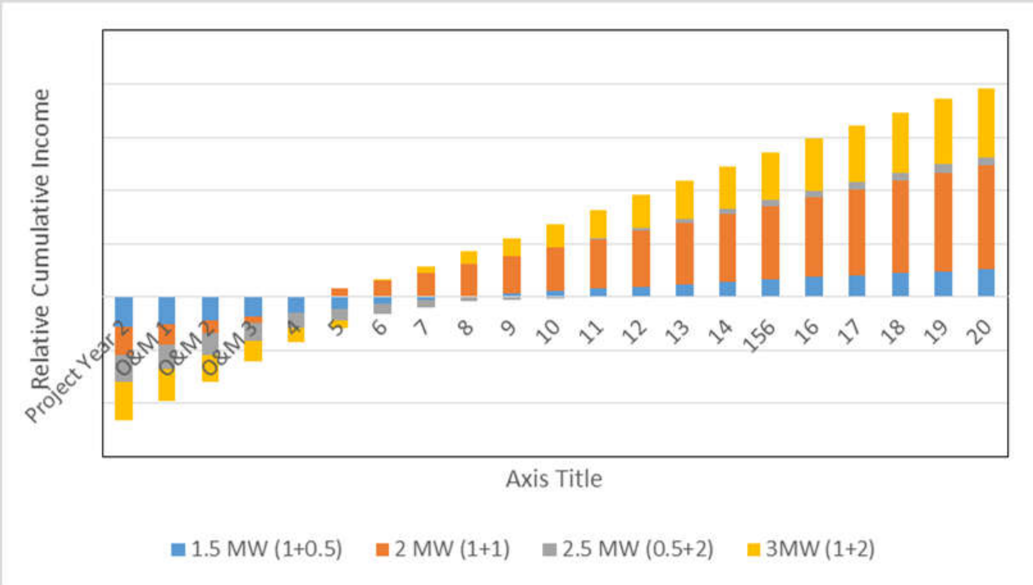
The capacity factor of the biomass gasification unit was considered to be 60% as a conservative approach both with respect to technology, and availability and uncertainty of feedstock. Hence, a 1 MW gasification system was just sufficient to produce the necessary 5.2 GWh of electricity per year at a higher levelized cost of 0.14 USD/kWh. The CAPEX of the system was estimated to be around 1.9 million USD, 74% of which is the cost of the module, the rest being civil, transportation, installation and soft costs.

High moisture content in feedstock is a problem for tropical countries like Sri Lanka. The relatively higher cost of the system is due to the presence of the rotary drier. Although it increases the installation cost to a considerable extent, it increases the overall efficiency by using the waste heat for drying the biomass feed.

Hybrid System Sizing

Techno-economic advantages of a hybrid power system in comparison with a standalone unit are many. For example, a hybrid power unit incorporating both the solar and biomass-based power generation within the same unit greatly reduces upfront cost of labour and site preparation than standalone systems. Moreover, the operation cost reduces to a considerable amount. Technical advantages include special benefits for fluctuating renewable energy sources such as solar PV, with relatively lower capacity factor. Coupling with a system such as biomass-based power which has a stable and a higher power output reduces the net levelized cost of electricity further.

Figure 1 - Project Cash Flow for Different Solar PV-Biomass Gasification Hybrid Systems, where the first number refers to the installed Biomass Capacity and the second to the Solar Capacity



Within the defined financial and spatial constraints, a decision-making simulation was carried out to determine the most economically favourable hybrid system, as shown in Figure 1. It can be seen, the 2 MW hybrid power system, with 1 MW each of solar PV and biomass power generation has the best financial performance among all the low budget projects.

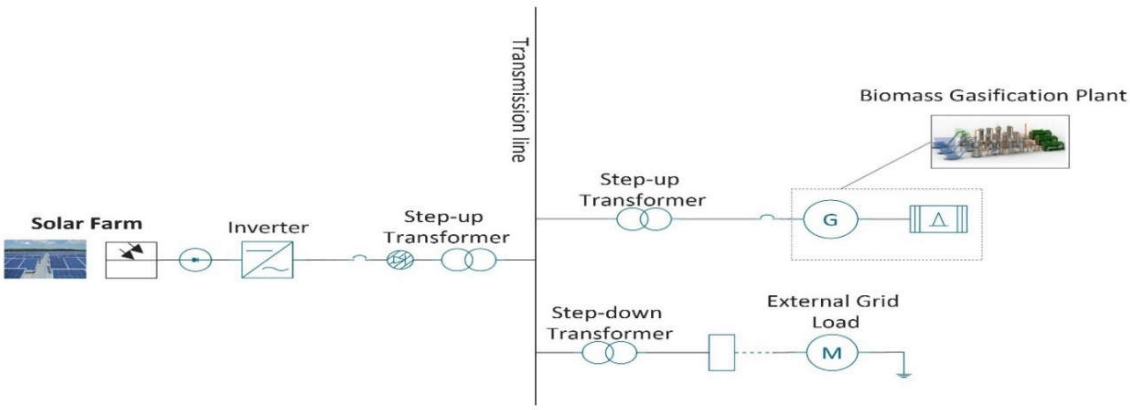
With regard to recent policies in Sri Lanka along with other feasibility considerations and limitations, the 2 MW hybrid power system with 1 MW each from Solar PV and Biomass based gasification system has thus been proposed.

2 MW Hybrid Power Generation Unit

The proposed 2 MW hybrid power system, with 1 MW each from solar PV and biomass-based gasification system has been calculated to have the best financial performance among different combinations. The proposed 1 MW biomass power plant is a single downdraft gasifier, with dual 500 kW, 8 stroke internal combustion engine based modular power plant, the primary fuel being dendro (sustainably grown biomass) and coconut waste (husks, shells, etc.).

The two 1 MW units have been proposed to be connected to the same ac bus that will be connected to the grid. Figure 2 shows the scheme.

Figure 2 - Layout of the 2 MW Hybrid System, 1MW each from Solar PV and Biomass Gasification



In comparison with individual standalone systems, the hybrid system economics are of considerable interest. The summary of the project cost is provided in Table 1. An acceptable payback period of 4 years with 25.4% project internal rate of return has been obtained with a proposed solar tariff of 18LKR/kWh, lower than the highest allowable bid of 22 LKR/kWh. Thus, even with a lower solar tariff, due to hybridization, the project developer would have considerable advantages for the 1MW solar projects over bidders with standalone systems.

Table 1 - Summary of the Hybrid Power Plant Economics

Parameter	Value
Project CAPEX (million USD)	2.45
Proposed Solar Tariff (LKR/kWh)	18.00
Project IRR	25%
Debt Equity Ratio	70:30
Payback period (years)	4

Sensitivity Analysis

To analyze the robustness of the base case scenario, the following sensitivity analyses were conducted. The sensitivity analyses include Dendro and paper as feedstock for biomass power plant, varying debt and equity ratio, fuel cost and solar power purchase agreements.

The results are given in Table 2. A lower capacity factor of the biomass power plant, resulting from inefficient supply of feedstock would significantly lower the project returns. The cost of biomass feedstock, also resulting from an inefficient supply chain has negative impacts on the project economics. As calculated, a 30% rise in the price of feedstock would cause the project returns to drop, even though the payback period remains constant at 4 years.

Table 2 - Results of Sensitivity Analysis

Sensitivity Case	Base Case	Biomass Capacity 70%	Cap Factor 50%	D:B 60:40	D:B 80:20	Fuel Cost 8 LKR/kg
Project IRR (%)	25.0%	30.0%	18.8%	25.6%	24.3%	21.4%
Equity IRR (%)	35.8%	47.3 %	24.6%	34.5%	37.5%	29.5%
Net Present Value (MUSD)	2.31	3.38	1.25	2.16	2.48	1.67
Pay Back Period (yrs.)	4	3	5	4	4	4
Net revenue earned in 20 years (MUSD)	8.98	11.89	6.06	9.17	8.78	6.87

Table 3 - Results of Sensitivity Analysis with varying Solar Power Purchase Agreement (PPA)

Sensitivity Case	Base Case	PPA 5 LKR/kWh	PPA 10 LKR/kWh	PPA 14 LKR/kWh	PPA 16 LKR/kWh	PPA 20 LKR/kWh
Project IRR (%)	25.0%	19.8%	21.8%	23.4%	24.2%	25.8%
Equity IRR (%)	35.8%	26.2 %	29.8%	32.8%	34.3%	37.4%
Net Present Value (MUSD)	2.31	1.4	1.78	2.05	2.18	2.45
Pay Back Period (yrs.)	4	5	4	4	4	3
Net revenue earned in 20 years (MUSD)	8.98	6.69	7.78	8.07	8.62	9.33

An additional sensitivity study with respect to solar PV tariff within the hybrid system was carried out and presented in Table 3. As shown, the solar tariff can be as low as 10 LKR/kWh, while maintaining a project payback of 4 years. This is only possible due to the hybridization of the solar PV with biomass gasification power plant, where the biomass power plant, producing a higher share of energy, provides economic resilience to the operation of the PV plant.

Operation Strategy

Since both the power plants have individual plant factors and grid restrictions, the operation strategy can be fixed to supply 1 MW constantly to the grid. A stable power supply can thus be supplied to the grid. This is additionally assisted by the selection of an internal combustion (IC) engine-based power generation system from biomass.

Project experience from different industries show that these engines have increased the modularity of power generation units over traditional turbine-based systems. In addition to having very high part load efficiency, combustion engines have faster ramp rates and shorter start times with respect to traditional gas turbine systems. These features result in achieving a high ramping capacity with the IC engine-based power generation units, primarily for upstream ancillary services – and, consequently, a reduced marginal cost of provision of those ancillary services.

Whenever the solar radiation is sufficient for the solar plant, the plant is operated at its full capacity. During this period, the biomass power plant can be shut down. After sunset, however, the biomass plant will be operating at full capacity. Both the plants being connected to the common ac bus on the generation side, a relatively stable 1MW power can be supplied to the grid. Considering 1 MW power supplied to the grid, a capacity factor of around 75% can be achieved, which would else be only 17.5% with respect to a standalone solar PV system.

Although the plants are a single hybrid plant, power purchase agreements for both the plants are set individually. Ceylon Electricity Board (CEB) offers separate tariffs for solar based power plants and biomass-based power plants and both are variable on the long run. The system however may provide added benefits of maintaining grid flexibility and stability when the Ceylon Electricity Board (CEB) would decide to offer incentives and bonus for utilities for both the parameters.

Environment Impact Assessment

Environment impact analyses show that the impact of implementing a hybrid power plant on biotic and abiotic resources is not severe. Social impacts and alteration of the local living patterns are considerable, that include the impacts in preconstruction, construction and operational stages. Flooding, clearing vegetation, impact to the utility supplies are to be expected in the pre-construction stage. Excessive land usage, impact on road traffic in the area, impact on flora, fauna and habitat, soil degradation can occur during the construction stage. Water usage, logistics, drainage, harmful fumes, hazardous materials, visual impacts, dust, noise and social impacts are potential impacts in the operational stage. Major physical, mental and social impacts due to the power plants were analysed in the health impact assessment and were not found to be critical.

Several mitigatory measures, can however be proposed, that can include but not limited to public consultation and information disclosure, community development, improving public utilities, establishment of construction camps and offices etc.

Carbon Dioxide Mitigation

Emission from a solar PV power plant is considered zero since the life cycle emissions were neglected in the study. The current grid emission factor of Sri Lanka is 768.9 grams CO_2 per kWh. Therefore, net generation of 1.5 GWh of solar energy would result in the mitigation of approximately 1068 tons of carbon dioxide.

Recent studies in Sri Lanka for biomass-based power plants show that a mitigation of 80% of emissions is feasible. Even though the power generated can be said to be clean, the emissions from production, collection and transportation of biomass have been included to evaluate the net emissions from the system.

Therefore, the 2MW hybrid power system can reduce at least 80% of the emissions from the printing process.

Conclusions

According to the study, the use of wind energy conversion to meet the power demand of the company is not feasible for technical reasons as well as for environmental and economic reasons. It was also observed that a solar and biomass hybrid system is the best option for availability of resources as well as economics, rather than using a single source. Therefore, a 2 MW capacity hybrid system incorporating solar photovoltaic and biomass gasification, 1 MW each, is proposed to be the most economical solution, with project capital expenditure of 2.45 million USD.

By implementing the proposed hybrid energy system, an estimated reduction of emissions of at least 80% could be obtained.

Acknowledgments

This work has been carried out as an extension of the industry involved academic/professional skill development project "Grand Challenge Project in Sustainable Energy System Development" performed by authors.

The financial, logistical and professional support provided by InnoEnergy (Sweden), and Wijeya Newspapers Ltd. (Sri Lanka) are gratefully acknowledged.

The valuable mentorship of the SELECT Grand Challenge projects generally provided by Professor Torsten Fransson of EIT InnoEnergy, Netherlands is specially acknowledged.

References

[1] APS Panel on Public Affairs, Integrating Renewable Electricity on the Grid, APS Physics.

[2] K. Jayasekera, Status of Sri Lanka Cross Border Interconnection with India & Expected Benefits, CEB, Colombo, 2014.

[3] Ceylon Electricity Board, Long Term Generation Expansion Plan, 2015-2034, Ceylon Electricity Board, 2016.

[4] A. S. V. AG, A Life Cycle Assessment of the production of a daily newspaper and a weekly magazine, AXEL SPRINGER VERLAG AG, Zürich, 1998.

[5] Sri Lanka Sustainable Energy Authority, Sri Lanka Energy Balance, 2014. Available at: http://www.info.energy.gov.lk/. [Accessed 22. 03. 2017].

[6] Wikipedia, Decline of newspapers, Wikipedia, 13 03 2017. Available at: https://en.wikipedia.org/wiki/Decline_of_newspapers. [Accessed 22. 03 .2017].

[7] S. Weerawansa and G. Warushamana, The Traditional Newspaper Industry vs. the Technology Driven News Media - Predatory or Complementary Behaviour: Issues, Trends, Prospects and Emerging Realities of the Print Media faced with Emerging Technological Directions in the Sri Lankan Context, Sunday Observer, Associated Newspapers of Ceylon Ltd.

[8] A. Withanaarachchi, L. Nanayakkara and C. Pushpakumara, The Progress of Sri Lanka's Renewable Energy Sector Developments in Mitigating the GHG Emission, Energy and Environmental Engineering, Vol. 2, No. 5, pp. 113-119, 2014.

[9] R. Fares, The Price of Solar Is Declining to Unprecedented Lows, Scientific American, 27 08 2016.

[10] IRENA, Global Solar Atlas, IRENA, Available at: http://irena.masdar.ac.ae/. [Accessed 22. 03. 2017].

[11] M. Deshmukh and S. Deshmukh, Modeling of hybrid renewable energy systems, Renewable and Sustainable Energy Reviews, Vol. 12, No. 1, pp. 235–249, 2008.

[12] Ministry of New and Renewable Energy, Biomass Knowledge Portal, Available at: http://biomasspower.gov.in/. /. [Accessed 22. 03. 2017].

[13] D. Elliot, M. Schwartz, G. Scott, S. Haymes, D. Heimiller and R. George, Wind Energy Resource Atlas of Sri Lanka and Maldives, National Renewable Energy Laboratory, 2003.

[14] Ceylon Electricity Board (CEB), Guide for Grid-Interconnection of Embedded Generators - Part 2, Ceylon Electricity Board (CEB), 2000.

[15] Henrique Garrido, V. Vendeirinho and M. Brito, Feasibility of KUDURA hybrid generation system in Mozambique: Sensitivity study of the small-scale PV-biomass and PV-diesel power generation hybrid system, Renewable Energy, Vol. 29, pp. 47-57, 2016.

[16] K. Janardhan, T. Srivastava, G. Satpath and K. Sudhakar, Hybrid Solar PV And Biomass System For Rural Electrification, International Journal of ChemTech Research, Vol. 5, No. 2, pp. 802-810, 2013.

Feature

Is the world Ready for 100% Renewable Energy-based Power Generation?

Dr Tilak Siyambalapitiya
Past President, SLEMA

A recent research paper by a respected group of researchers has shaken the professional circles: in short, they concluded that a 100% renewable energy-based power system is not possible, based on 24 studies they reviewed [1]. A few months later, an equally respected group of scientists refuted the conclusions of the earlier paper[2] and concluded that "energy systems based on renewables, on the other hand, are not only feasible, but already economically viable and decreasing in cost every year" and went on to conclude that "the 100% renewable energy scenarios proposed in the literature are not just feasible, but also viable".

So, the opinion of the professional world too, is divided. In Sri Lanka too, the same debate is raging, severe at times, softens later. However, there is a difference between how the rest of the professional world debates issues: their debates are based on quantified facts and extensive modelling of renewable energy systems and the power system. Over here in Sri Lanka, the debate is largely based on personal convictions and emotions.

There are many indices with which the technical quality of a power system is measured, largely grouped into indices on reliability and power quality. There are standard indices to measure and report such indices. In Sri Lanka, such indices are not calculated even by researchers; electricity utilities have ignored the government gazette notification in 2017 to begin measuring and reporting reliability and power quality. Therefore, customers are not aware of their present quality of supply and largely accept the quality dished out by the two distributors CEB and LECO, as their fate.

In this backdrop, there are others who propose 100% indigenous energy or 100% renewable by such and such a year, entirely based on hearsay such as "when I went up country, I was blown out, and that's where we should be building wind power plants".

The Anatomy of a Blackout

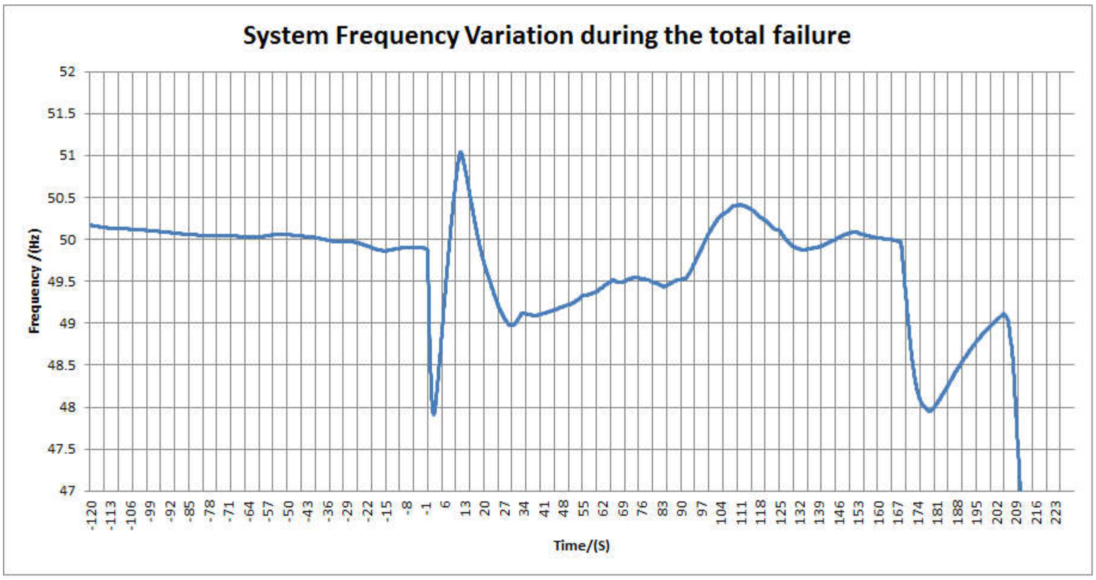
The date was 27th September 2015 and the time was 11:51 pm. It was a Sunday and a poya day, too. Much of the country was asleep, except the workers manning machines in 24-hour industries, staff providing essential services such as health and security, and of course, the staff at power plants, vital substations and the power system control centre in Colombo 9. The power system was recording a demand of 930 MW, somewhat lower than on a typical day, owing to favourable weather that pulled the temperatures down across the country.

One generator at Norochcholai power plant tripped out at 11:51 pm, the reason for which was later found to be an over-sensitive protection device. In the attempt to halt the catastrophic failure, between 11:51 and 11:54 pm, about 40% of customers were automatically disconnected, but the power system could not be saved. Remaining generators slowed down to release the stored energy in them, to help bridge the gap, but with little success. By 11:54 pm, it was all over. All generators tripped out and the country was in darkness. The frequency (Figure 1) and the voltage went haywire, until the final collapse at the 209th second. Within three minutes from the first event, the power system was gone and dead.

It took four hours to restore the electricity supply to all customers in the country.

Although many "committees" were appointed to investigate the outage and its aftermath, none of their reports were released in the public domain. In any other country, there would have been several workshops organized by the utility to explain what happened; institutions of engineers would organize seminars to discuss; several research projects would be initiated at universities to deeply examine what could have prevented such a collapse. None happened in Sri Lanka; but that is not the subject of my discussion today.

Figure 1 - The Power System Struggled for 3 minutes and collapsed at the 209th second



Planning Power Systems is Complex

Planning and operating an electric power system is a complex task. To be honest, every electric power engineer does not understand all aspects of the utility business: power system planning, construction, operations, economics and finances. Even in the University, many give up the sections on economics; others give-up the sections on stability. Finally, all good electrical engineers in service develop expertise in their chosen area of work, after graduation. Others settle down to do less technically challenging tasks.

In fact, each lecture and tutorial in University finally become useful to a practicing electric power engineer; be it numerical analysis, least-square fit, LaGrange principles, the Bellman's principle of optimality; or the equal area criterion. Transient reactance and inertia constant, as well as the operating curve, are day-to-day terms of a power system engineer. Complex numbers, which many engineers simply erase from their memory after university, is day to day work for a power engineer. Advances in technology have so far not been able to let us do away with the fundamental principles of power system design and operation.

Let us come back to the incident of 27th September 2015. That was a serious event. What we do know is that in a live power system, generators trip out all the time. When that happens, the remaining generators pick-up the lost power generating capacity by automatically opening their water valves or fuel valves. That takes a few seconds, typically five seconds. In other words, the time constant of the valves and the associated systems are in the 3 to 8 second range.

Until fuel valves and water valves open, stored kinetic energy in all remaining generators and customer motors would be converted to electricity and released almost instantly. No controls are needed; it happens automatically.

What happens when you start a motor in your factory? Surely you do not telephone the power supplier, CEB or LECO, to tell them that you want to start a motor. There was a time you would have had to do that, but that was about a century ago, when electric power system engineering was in its infancy. Now all those restrictions are gone, and you simply switch it on. Until the fuel valves and water valves open, all generators in the power system slow down, and convert their stored kinetic energy to electrical energy, and allow you to start your motor and run it. Right at the moment you switch it on. Certainly not 5 seconds later.

Just Imagine !

If there were no rotating generators in the power system with stored kinetic energy? If all the generators are solar photovoltaics (no moving parts), or wind and mini-hydropower (slow-moving parts)? Then the power system has no kinetic energy to instantly convert to electrical energy, to allow you to start and run your precious motor. What is more? There are no fuel valves at all in an all-renewable energy system, and water valves are already fully open. So, there is no additional energy that the power supply system can provide in 5 seconds or in 5 minutes, because solar energy and wind energy cannot be stored. Hydropower can be stored in a reservoir, but since the resources are limited, hydropower will supply a diminishing share of electricity demand. So what can we expect when a new motor is started, on the day when the entire power system (as visualized by some) is using only renewable energy?

The power system will simply collapse. First the voltage will drop, and the lowered voltage will cause the renewable energy generators to trip out one by one, until all of them drop out.

So, is there no other way to solve this problem? Well there is; one conventional approach and one novel approach. The conventional approach is to build "pumped storage" power plants. In such power plants, there are two reservoirs, not one. Water is pumped into the upper reservoir when extra power is available. Say during the day when solar power is abundant. (Do not ask me what happens when the water pumping is on and if someone again wants to start a motor! Just believe that every problem has a solution, but at a price). This would require more reservoirs to be built; some of them may not even be associated with existing hydropower plants but will be built brand new. One reservoir above and the other below, both artificial. There will be sacrifices to be made; houses demolished, dams built, tunnels dug, and all the problems that come with such projects, but they can be done.

The second method is to use batteries. That is how electricity was stored in smaller quantities for portable equipment. Now research worldwide has turned on heavier and larger batteries. In theory, batteries can respond very fast, and they are as good as rotating generators, in responding to a sudden demand for power. They can help the grid to meet a generating capacity shortage or a sudden increase in demand. Today, the sudden increase in demand is served first by the rotating generators, followed by opening water valves and fuel valves of all generators that have spare capacity. Both the emergency actions have stored energy of larger quantifies behind it, as water or fuel. However, a battery cannot absorb fuel or water and give electricity out, like a power plant. It can store electricity and later give electricity out. It cannot provide electricity for a long period, without being fed with electricity.

So it will be some time, may be a few more years or even decades, before limitations in batteries are resolved to at least theoretically enable a 100% renewable energy grid, that would provide electricity at the same level of reliability and the quality, the modern society expects.

What do we do until then? What shall we get our electricity from?

This is the question that was heavily debated in Sri Lanka over the past two months, to the extent that it triggered a trade-union action by electricity utility engineers. Electrical engineers were pushing for a mix of all the principal sources: coal, gas, hydro, wind, solar and biomass, with limited support from oil. The Public Utilities Commission is alleged to have altered the plan of the utility and approved a plan in which basically coal was replaced with gas, thus making the plan gas-dominant. More on coal and gas later.

Figure 2 - Sri Lanka has about 130 MW of Wind Power Generating Capacity

With so many variables, some quantified and others non-quantifiable, determination of the generation plan of a country is a difficult task. Sri Lanka has no open market for power generation. Bangladesh, Pakistan and Nepal are similarly closed markets, but India is in the process of establishing a competitive market. As such, India has de-licensed the power generation business. Both utilities and private sector build power generation, and the private sector gets both short-term and long-term contracts. While there is some degree of competition to secure contracts, the system is not entirely transparent or corruption-free. It is not unusual to hear of power generating companies going bankrupt, as they could not get contracts to supply power, after building the power plant.

Sri Lanka does not have a competitive market for power generation. The only competition is when selecting a contractor (for a utility power plant) and when selecting an independent power producer (for a private power plant). Since both types of power plants are effectively "solicited" by the buyer (the CEB), it is logical to continue with the preparation of the long-term generation expansion plan. Once a free market is established, if ever, then the long-term plan may be replaced with a strategic plan. There again, a plan is required because a power system has to produce electricity right at the time it is requested by customers; not before, not after, but right at that moment. There is no other commodity that must be produced right at the time when the customer wants the commodity.

Engineers reading this would certainly have more questions than answers.

Can we not have roof top solar and batteries at home, so that the grid is not required or will standby only to supply when more electricity is required? Yes, of course, it is like keeping a standby generator, and that has a cost. Someone, and that is you (not the poor person who has no solar roof top, no fridge, no fan), must pay that cost, and if not, the investments on the grid will decline and would not be reliable to be a true supplier of last resort.

Figure 2 - The country's solar PV capacity exceeds 200 MW, half of it on rooftops

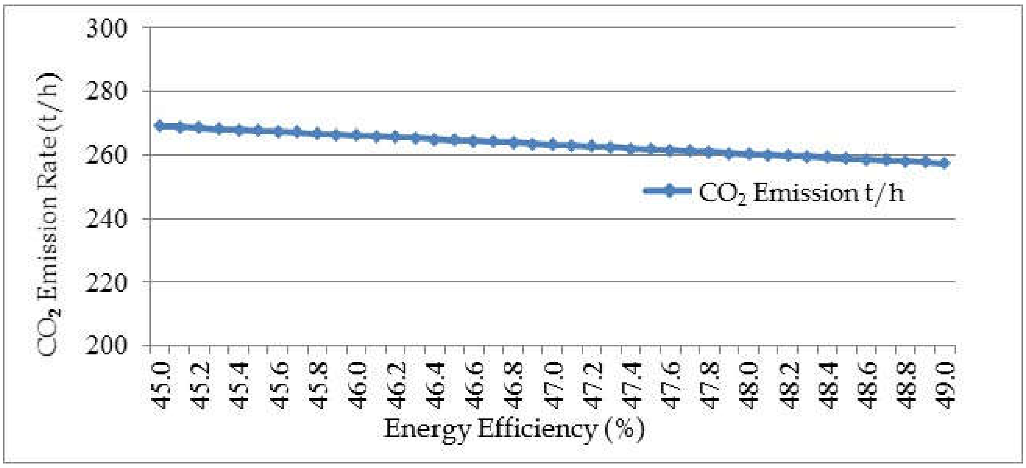
Do you know? One island off Jaffna, "Eluvaithivu" is presently served with electricity entirely from solar PV and wind power. Batteries store during the day and provide electricity in the night. A diesel generator is standing by. Very soon, three more islands off Jaffna, including Nagadeepa, will have similar wind-solar hybrid power systems. The whole system may be considered as a pilot project, to help understand how such systems work.

References

[1] B.P. Hearda, B.W. Brookb, T.M.L. Wigleya, and C.J.A. Bradshawd, "Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems", *Renewable and Sustainable Energy Reviews* 76 (2017) pp1122–1133.

[2] T.W. Browna, T. Bischof-Niemzc, K. Blokd, C. Breyere, H. Lundf, and B.V. Mathieseng "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems", *Renewable and Sustainable Energy Reviews* 92 (2018) pp 834–847.

Correction – The Figure 9 -The Variation of Boiler Steam Generating Cost with Boiler Exergy Efficiency of "Potential of exergy efficiency improvement of coal power plants in Sri Lanka " paper in SLEMA Journal, Volume 19, No. 2, September 2016, page 22



SLEMA JOURNAL

Call for Papers and Subscription

SLEMA Journal is dedicated to energy sector professionals of Sri Lanka. Published twice a year since 1984, the SLEMA Journal carries research papers, articles, reviews and news about the status and new developments in the energy sector of Sri Lanka.

The Journal is circulated free to over 500 members of SLEMA and is also available in libraries in universities and energy sector institutions.

Guide to Authors

SLEMA welcomes submissions by authors from Sri Lanka or abroad, to be published in the Journal.

Coverage: You may submit papers to the Editor, SLEMA Journal any time for consideration for publication. There is no specific deadline. Papers should cover one or more of the following areas of focus:

- Energy Policy
- Energy economics
- Energy efficiency, demand management and conservation
- Renewable energy development
- Rural energy and social dimensions
- Training on energy and related subjects
- Energy measuring instruments
- Energy auditing
- Worldwide trends in energy sector development
- Energy sector management

Format and Style: Papers should be written in a style and language suitable for a professional publication. They should consist of an abstract, introduction, followed by the body of the paper. Conclusions should be clearly stated, after which acknowledgements and references should be listed.

SI units should be used throughout, with the standard abbreviations. Papers should be prepared on MSWord. All graphs, diagram and photographs should be available in soft copy form, and embedded in the paper at a place close to where they are referred to in the text. All figures, diagrams and photographs should be identified as figures and numbered sequentially. Similarly, all tabulations should be numbered. All figures and tables should be referred to in the text of the paper. References to individuals, institutions and brand names should be minimised. Extracts from other publications should be acknowledged.

For more information for authors, please contact:

Dr Tilak Siyambalapitiya, Editor, SLEMA Journal
email: tilak.rma@gmail.com
or contact SLEMA office:
Chandanie Gamanayake
Administrative Coordinator
SLEMA Office
Phone: 011 266 5737
email: slema@sltnet.lk
or visit www.slema.lk

Subscription: SLEMA Journal is published in two issues per year in March and September. SLEMA Members of all categories: free, all other institutions and individuals may subscribe as follows: One year (2 issues): Rs 600/-, Two years (4 issues): Rs 1000/-. Please contact SLEMA office (address above).