Standalone Energy System for a Remote Fishing Island in Sri Lanka

A. J. Abeywardana[1], H. M. I. S. Madhuranga[1], A. S. Perera[1], I. H. T. D. Lionel[1], S. Kohombange[1], A.R. I. W. Indunil[1], Ruchira Abeyweera[1], N. S. Senanayke[1], Gwenaëlle Guillerme[2]
[1]The Open University of Sri Lanka, Sri Lanka, [2]T.I.M.E. Association, Paris, France

Abstract
The study presents the design and evaluation of the feasibility of a sustainable electricity generation system for *Buththalangunduwa*, a small island situated in Portugal Bay, off the north–western coast of Sri Lanka. It is a remote fishing island of about 5 km^2 with a population of about 3,000. Fishing and production of dried fish is the main livelihood. A privately-owned diesel generator provides an erratic power supply. Kerosene is predominantly used for lighting and cooking. The proposed project would serve electricity needs in households, a water purification plant and for fish preservation. A combination of solar, wind and Li-ion battery storage is proposed. HOMER-PRO software was used to optimize the system. The optimum system consists of 847 kW of solar PV and 400 kW of wind turbines together with 400 kWh capacity of Li-ion battery storage. Final levelized cost of energy is $ 0.138 per kWh, which is more competitive compared with the present practice of using fossil fuels.

Introduction
Sri Lanka is an island in the Indian Ocean with a population of over 20 million. By end 2016, Sri Lanka had about 4,000 MW of installed power generation capacity including hydro, thermal and renewable energy sources, serving the national grid. The total electricity generation was about 14,000 GWh (2016) comprising 36% from coal, 31% from oil, and the balance 33% from renewable sources such as large hydro, mini hydro, wind and solar [1]. The national electricity transmission network is maintained by the government owned utility provider, Ceylon Electricity Board (CEB). CEB maintains and supplies electricity to 5.96 million customers all over the country except some Western and Southern coastal areas which are served by Lanka Electricity Company (LECO). In 2016, CEB distributed 12,780 GWh of electricity to its customers. Sri Lanka declared achieving 100% electrification in 2016, but constraints to extend the transmission network to isolated areas such as off-shore islands and small communities in difficult terrain remains a challenge. As an option, the government promotes off-grid systems to achieve 100% electrification in the near future [2]. Also, the government policy targets to enhance the renewable energy contribution to the main grid and to produce larger shares of electricity from solar and wind sources.

Improvement of socio-economic conditions in rural areas have created an increasing demand for electricity, mainly for lighting and to operate common household electrical appliances. To meet this demand among remote communities, implementation of renewable energy based off-grid systems is an appropriate measure which is in line with the government policy targets. It will increase the share of power generation from renewable sources and provide access to electricity to all. Although as a share of the country population, the people living in rural communities is small, electrification rate, particularly in most of the islands is very low. One of such island is *Baththalangunduwa*, situated 38 km off the north western coast. [3].

At present diesel generators supply electricity to this island for a limited number of hours, also covering limited public places. Electricity generation from diesel generation is expensive due to difficulties in transporting fuel. Diesel generators also cause air pollution. Hence, development of a thermal power plant of adequate capacity to serve the needs of the population could not be considered as a feasible option. Therefore, designing of an off-grid power system using renewable energy is a good option to meet energy demand of the island.

Since Sri Lanka is situated close to the equator, solar radiation and wind resource are high, and easily be used to develop standalone energy systems for remote communities. The study specifically aimed at designing a standalone energy system to provide sustainable, cost-effective electricity supply for this fishing island using renewable energy technologies in order to meet the electricity demand of domestic lighting and other uses; water purification for drinking water supply, and electricity for fish preservation.

Methodology

The total area of the island is about 5 km^2 and has a population of about 3,000. The main livelihood of the island people is fishing. The standard of living and the prevailing issues were identified through paper articles and documents written by visitors. Electricity demand and load estimation were done through a survey. Wind and solar resource data were collected from available resources (NREL, SLSEA). HOMER Pro Analytical Tool was used to estimate the potential electricity generation from renewable energy sources, selection of sustainable cost-effective technologies and system design and cost estimation.

Project Location

Baththalangunduwa is an elongated sandy island located in the Portugal Bay in Sri Lanka as shown in Figure 1, extending about 16 km in length from south (8°26'55"N Latitude & 79°48'17"E Longitude) to north (8°32'37"N Latitude & 79°47'06"E Longitude), and maximum width is about 700 m from extending from east to west [4].

Figure 1 - Location of the Baththalangunduwa Island

This island experiences periods of low rainfall, intense sunlight and strong seasonal winds. The average rainfall is 750-1125 mm per year, but heavy rainfall can be observed in April to May, and October to December [4]. Community in the island has basic palm-frond huts, with little fresh water. They do not have basic sanitation or health facilities. The local lifestyle consists of fishing in the early mornings, then preparing and drying the fish, and repairing fishing nets in the afternoon and evenings. People use kerosene lamps and small generators for limited lighting. A few generators are operated in the navy camp and in the church. The closest point of the national grid is 38 km away, in the mainland [3]. There are no gravel or tarred roads in the island, but narrow sandy paths lined with houses have created a convoluted network of routes. Furthermore, transport is mainly with portage while bullock carts are employed at times to haul heavy loads such as water barrels. No land telephone facilities are available in the island, but one mobile network is active in the area. A few shops are available, and goods are very expensive. People use kerosene stoves for cooking as firewood is not available. Potable water is available and only a few water pits are suitable for drinking. They too are not adequate for general use [4].

Electricity Requirement of the Island and Proposed Measures

The people need electrical energy at their homes for lighting and for household appliances. In addition, the island needs electricity for the proposed water purification system to provide potable water and for a few freezer plants for the preservation of fish.

Electricity

Grid electrification is not economically feasible owing to the distance to the country's main grid and the submarine connection required. An off-grid electricity system would be sufficient as an independent source of energy to cater to the demand of this small fishing island. *Buththalangunduwa* is blessed with intense solar radiation and strong seasonal wind, making way for sustainable power generation. Accordingly, a wind and roof-top solar PV based power system is proposed. Due to the intermittent nature and heavy fluctuations of these two resources throughout the year, a battery storage system is proposed as the backup system for the total power system.

Drinking Water

People in *Buththalangunduwa* currently find it difficult to secure drinking water from natural sources and the only solution is to desalinate sea water. This can be achieved with a Reverse Osmosis (RO) plant. It removes salt from sea water producing purified fresh water for drinking, irrigation and industry.

In the RO process, water at high pressure passes through very fine membranes which allow passing of only water molecules through them. RO plant consists of two phases namely pretreatment and membrane filtration. In pretreatment, filtration and coagulation removes the solids and suspended particles. Then, through chlorination and other chemicals, the biological organisms are removed. Finally, pH and hardness of water is controlled by adding relevant chemicals. In the membrane filtration, sea water at high pressure is pumped to the filters and passed through a special membrane wrapped around an inner tube. Then, water molecules are directed to the inner tube as the pressure forces them through the membrane. RO system yields 60% of fresh water and the remaining sea water carries away the collected salt and finally returned back to the ocean.

Fishing Industry
Fishermen and it is the main income source of the island. It has become a hub for migrant fishermen who occupy the island on a seasonal basis. Statistical data related to the island's fish production is not available. Therefore, judgmental conclusions had to be made about the electrical energy requirement for activities associated with the fishing industry. The total production of marine fish is 449,440 metric tons per year in the whole country [5]. The total number of fishing boats employed in the whole country is 42,678, and out of this 11% (4,695) are operated in the Puttalam district where this island is situated [6]. It is reasonable to assume that annual fish production is proportional to the number of boats. Therefore, the estimated annual fish production of Puttalam district is 49,438 metric tons (136 metric tons per day).

Electricity Demand Analysis
Estimated electricity requirement for basic domestic needs is given in Table 1.

Table 1 - Electrical Requirement of a Typical Household

Location	Electricity Usage (W)		
	Lighting	Mechanical Ventilation	Other
Room 1	9 W (1 LED bulb)	58 W (1 Fan)	50 W (Radio, Telephone Charging etc.)
Room 2	9 W (1 LED bulb)	58 W (1 Fan)	
Kitchen	9 W (1 LED bulb)	-	
Wash Room	9 W (1 LED bulb)	-	
Total	**36 W**	**116 W**	**50 W**

People in *Buththalangunduwa* currently lead a very basic lifestyle with a combination of poor and fairly well-off families, with the majority being poor. With the limited facilities, people fulfill their basic requirements and the sole purpose of the standalone system is to meet the present electricity demand of these people to increase their living standards. Therefore, in the case study, only the basic requirements of the people were considered avoiding unaffordable electricity requirements such as domestic refrigerators. Once the living standard reaches a certain level, an expansion of the system can be considered to meet the additional electricity demand as the next stage of the proposed project. (Mean value of household income per month in the rural sector of Sri Lanka is around $364.50 [7]).

Most of residents are

Table 2 - Time Duration the Appliances are being used

Appliance	Location	Time duration of use per day
Lighting	Rooms	6.00 am 8.00 am & 6.00 pm to 8.00 pm
	Kitchen	6.00 am 7.00 am & 6.00 pm to 8.00 pm
	Washroom	6.00 am 7.00 am & 7.00 pm to 8.00 pm
Mechanical ventilation	Rooms	9.00 am to 4.00 pm & 6.00 pm to 8.00 pm
Radio	-	05.00 am 7.00 am & 9.00 am to 8.00 pm

Considering the time duration (Table 2) the electrical appliances are likely to be used, daily electrical energy use was estimated as follows.

Energy for lighting = 46.21 kWh
Energy for mechanical ventilation = 687.3 kWh
Energy for other use = 434.5 kWh
Total daily domestic electricity Requirement = 1,168.0 kWh
Monthly electricity requirement = 35,041 kWh

Electricity Demand for Drinking Water Supply
As proposed, sea water would be converted to drinking water by introducing a Reverse Osmosis (RO) plant. Estimation of electricity requirement of the RO plant is shown as below.

Water requirement $= 10$ litre per day per person [8]
Population $= 3{,}000$
Total water requirement per day $= 30\ m^3$

Assuming the RO plant operates 5 h/day, a RO plant with a capacity of 6 m^3 per hour was selected.

Power rating of the RO plant is given as **9.69 kW** [9]

Electricity requirement for RO plant $= 9.69$ kW x 5 h $= \mathbf{48.47\ kWh}$

Electricity Demand for Ice Plant

Estimation of amount of fish to be cooled

Electricity demand for the ice plant depends on the amount of fish to be preserved by cooling. Therefore, the daily fish harvest was estimated by using the number of fishing boats.

$$\text{No. of boats (N)} = \frac{F.x.y.d}{n}$$

F - No. of families
x - Percentage involved in fishing industry
y - Percentage amount going for fishing
d - Percentage day factor
n - No. of fishermen per boat

$$= \frac{(790 \times 70\% \times 60\% \times 50\%)}{5} = 33$$

Total fish harvest per day was estimated to be 49,500 kg, considering 1,500 kg of fish per boat. About 60% of fish is preserved by cooling, which means a total of 29,700 kg of fish needs to be cooled. Normally, 1 m^3 space is used to store 300 kg of fish; hence space requirement for cooling is 99 m^3.

<u>Cooling load calculation</u>

Fish is cooled down to -1°C before transporting to other markets. Cooling is to be carried out from around 9.00 am to 5.00 pm over a period of 8 hours. In order to estimate the cooling load, the properties of cooler construction material given in the Table 3 were used.

Table 3 - Material Properties and Specifications of the Cooler

Material	Heat Transfer Co-efficient (W/m^2K)	Thickness (mm)
Fiber Glass (K1, outer surface)	0.036	0.005
Polyurethane (K2, middle layer)	0.042	0.15
Fiber Glass (K3, inner surface)	0.036	0.003

Cooling load consists of two portions:

Q_1 = Heat removal from fish to bring down the temperature from 31°C to - 1°C

Q2 = Heat gain during cooling down period

In order to estimate the above heat transfers, standard heat transfer equations were used as follows.

$$Q_1 = MC\Delta\theta$$

$$= 29,700 \text{ kg} \times 4{,}200 \text{ Jkg}^{-1}\text{K}^{-1} \times (31-(-1))^0\text{C}$$

$$= 3{,}991{,}680 \text{ kJ}$$

$$\text{Energy requirement} = \frac{3{,}991{,}680}{3{,}600} \text{ kWh}$$

$$= 1{,}108.8 \text{ kWh}$$

$$\text{Electricity Demand} = \frac{1{,}108.8}{8} \text{ kW} = 138.6 \text{ kW}$$

Heat gain from the walls (Q2) was calculated using the following equation.

$$Q = \frac{\Delta T}{\frac{1}{A}\left(\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3} + \frac{1}{h_0}\right)}$$

Where

Q – Heat loss (W)

L – Thickness (m)

K – Thermal conductivity ($Wm^{-1}K^{-1}$)

A – Area (m^2)

ΔT – Mean Temperature difference (K)

h_o – Convection heat tranfer coefficient at outer surafce ($Wm^{-2}K^{-1}$)

Suffixes 1, 2, 3 for different layers

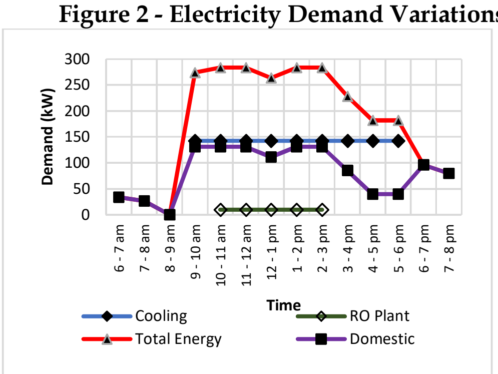
$$Q_2 = \frac{(31-15)}{\frac{1}{10}\left(\frac{0.005}{0.036} + \frac{0.15}{0.042} + \frac{0.003}{0.036} + \frac{1}{10.45}\right)}$$

$$Q_2 = 0.04 \text{ kW}$$

Figure 2 shows the load profiles developed for each customer group, and the composite load profile to be served by the proposed system.

Source: Author's estimates

Figure 2 - Electricity Demand Variations



Technology Options Analysis

Solar Power Potential

Since Sri Lanka is located near the equator, the country receives rich solar radiation throughout the year without a significant difference. *Baththlangunduwa* receives very low rainfall and has a dry climate around the year. It receives 2,000 kWh/m^2 average Global Horizon Irradiation per year which is favourable to harness solar energy [10]. Currently Sri Lanka has 50 MW large solar PV power plants and 100 MW of rooftop solar PV installations. The average capacity factor of large solar PV is around 23% and it varies between 15% to 20% for rooftop solar PV [11].

PVWatts calculator was used to estimate monthly electricity generation. For estimation purposes, a 250 kW PV system was used to check the monthly electricity generation variation. The percentage difference between maximum and minimum electricity generation per month was calculated to be about 32%. The average annual estimated plant factor is around 17% which is satisfactory.

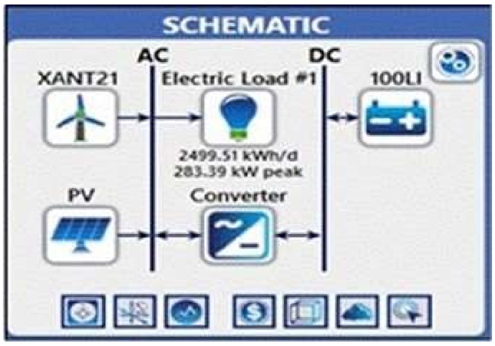
Wind Power Assessment

According to the wind map developed by National Renewable Energy Laboratory with the Ceylon Electricity Board, Buththalangunduwa falls under No. 5 excellent wind class which could provide rich wind power throughout the year. The important feature in this area is the directional and persistence of winds. About 55% of time, wind blows from 1,800– 2,700 direction sector (SW winds) and the NE winds fall between the 00 – 900 sector for 30%. Most of the time, winds from both monsoons remain steady throughout the day. Due to these characteristics of the wind regime, it is feasible to generate power from wind in *Baththalangunduwa* [12]. However, wind power generation rapidly changes with the wind speed as well as with seasonal wind patterns. *Kalpitiya* wind power plant located close by has an average annual plant factor of 30% [11].

Proposed System and Analysis

HomerPro software was used for analysis with initial input data relating to a hybrid system with 100 kW wind turbines and 100 kWh batteries. Total daily requirement was calculated to be 2,499.51 kWh where the peak demand was calculated to be 283.39 kW, as shown in the Figure 3.

Figure 3 - Summary of data input (HomerPro Software)



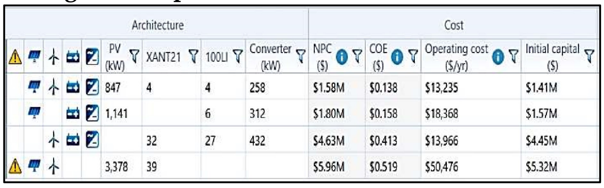
For the analysis of the proposed hybrid plant of wind and solar, necessary data were imported through the NASA Surface Meteorology & Solar Energy Data Base. The average daily solar radiation at this specific location of the island was taken as 5.84 kWh/m^2, whereas annual average wind speed was taken as 4.8 m/s.

Since grid electricity is not available in the island, total electricity requirement will be fulfilled with the energy from the wind turbine and solar system. Owing to imtermittency in wind and solar PV, a battery bank will be used for supplying steady and continuous electricity to the island.

By modeling the hybrid system of wind and solar, the following results were obtained.

1. Net present cost (NPC) of the hybrid plant
2. Levelised Cost of Energy (COE)
3. Total operating cost of the plant per year

Figure 4 - Optimized Alternative Solutions



Architecture									Cost			
					PV (kW)	XANT21	100LI	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
					847	4	4	258	$1.58M	$0.138	$13,235	$1.41M
					1,141		6	312	$1.80M	$0.158	$18,368	$1.57M
						32	27	432	$4.63M	$0.413	$13,966	$4.45M
					3,378	39			$5.96M	$0.519	$50,476	$5.32M

Figure 4 is the screen shot of the HomerPro software that gives the different options and related costs.

The solar-wind hybrid system inclusive of battery storage with an initial capital investment of $1.4 million was selected to fulfill the requirements of the island.

Table 4 gives the annual electricity generation from the selected system whereas Figure 5 shows the expected monthly variation of electricity production of the system.

Table 4 - Electricity Generation of the Hybrid System

Description	Generation (kWh/y)	Percentage (%)
Generic flat plate solar PV	710,667.4	75.9
Wind turbine (XANT M – 21)	225,155.7	24.1
Total	**935,323.1**	**100.0**

Cost Analysis

Table 6 shows the summary of costs of different components of the hybrid system, and Table 7 compares the costs for different options. Salvage cost is a minus value since selling of salvages will be a repayment to the cash flow of the proposed system. Then, the unit cost of electricity produced will be about $ 0.138, which is approximately LKR 24.00.

With the daily average energy requirement of 2,499.5 kWh and the project capital of $1.414 million (LKR 240 million), the simple payback of this project is 11.2 years.

Figure 5 - Monthly Energy Output of Solar and wind Combined System

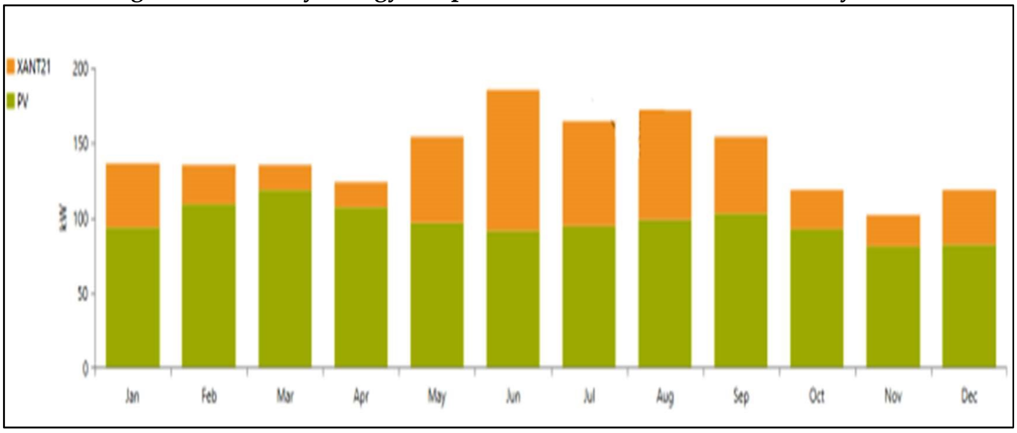


Table 6 - Summary of the Cost for the Hybrid Energy System

Component	Capital ($)	Replacement ($)	Maintenance ($/year)	Salvage ($)	Total ($)
Generic 100 kWh Li-Iron	320,000	74,173	511	(35,594)	359,091
Generic flat plate PV	667,236	-	108,217	-	785,453
Other	80,000	-	-	-	80,000
System converter	77,480	-	-	-	77,480
XANT M-21 (100 kW)	260,000	-	21,885	-	281,885
Total System Cost ($)	1,414,715	74,173	130,613	(35,594)	1,583,908

Table 7 - Cost Comparison of different Combinations

Description	**Solar & Wind (hybrid)**	**Solar PV Only**	**Wind Only**
Total System Cost ($)	1,583,908	1,800,690	4,468,120
Levelised Cost of Energy (COE) ($/kWh)	0.14	0.16	0.41
O & M Cost ($/year)	130,613	146,561	178,532

Conclusions

Three cost factors were considered which are the net present cost (NPC), cost of energy (COE) and total operating cost of the plant per annum. For all the cost factors, the minimum value was for the combination of the solar and wind hybrid plant. The optimum system consists 847 kW Solar PV and 400 kW wind turbine system. Also 400 kWh Li-ion battery is to be integrated in to the system to maintain grid stability. The unit cost of electricity produced through the proposed system is around $ 0.138 (LKR 23.46), which is less than the average electricity generation cost by thermal power generation in Sri Lanka, which is $ 0.247 per kWh.

With the daily average demand of 2,499.5 kWh and the project capital of $1.414 million (LKR 240 million), the simple pay back of this project is 11.2 years. This may not be attractive for a private investor for the project. However, as the objectives of the study was to design a standalone energy system with renewable energy technologies, the proposed solution can be accepted as a viable option which also gives benefits of reducing environmental pollution.

Acknowledgement

The authors express their appreciation to the Top Industrial Managers for Europe (T.I.M.E) Association (www.time-association.org/) for facilitating this study.

References

1. *Statistical Digest 2016, Ceylon Electricity Board, Sri Lanka.*
2. *Performance 2015 and Programs 2016, Ministry of Power & Renewable Energy, Government of Sri Lanka, 2016.*
3. *http://sri-lankan-travelogue.blogspot.com/2014/09/battalangunduwa-bath-thalangunduwa.html/(Accessed on 21-02-2018)*
4. *N.P. Kodippili, J. Katupotha, G.M.T.S. Fernando, Coastal Processes and Causes of Shoreline Erosion and Accretion of the Baththalangunduwa Island in Sri Lanka, The 38th Asian Conference on Remote Sensing (ACRS – 2017)*
5. *Census of Fishing Boat 2006/2007 (http://fisheriesdept.gov.lk/v3/en_US/high-seas-fisheries/)/(Accessed on 21-02-2018)*

6. *Census of Population and Housing of Sri Lanka, 2011.*
7. *http://www.statistics.gov.lk/HIES/HIES2016 /HIES2016_FinalReport.pdf/(Accessed on 22-02-2018)*
8. *B. J. Reed Series, R. A. Reed, G. McMahon, R. J. Shaw, Ken Chatterton, Water, Engineering and Development Centre, Loughborough University, Leicestershire, UK*
9. *https://4.imimg.com/data4/RM/YF/MY-4591361/6000-lph-ro-plant.pdf/(Accessed on 25-02-2018)*
10. *Global Horizontal Irradiation (GHI) in Sri Lanka, Sri Lanka Sustainable Energy Authority.*
11. *Generation Performance in Sri Lanka 2016, Public Utilities Commissions of Sri Lanka.*
12. *www. Winpower.lk/(Accessed on 25-02-2018)*