ENGINEER - Vol. LVI, No. 01, pp. [63-70], 2023

DOI: http://doi.org/10.4038/engineer.v56i1.7561

# Electricity Cost Reduction of Industrial/General Purpose Customers in Sri Lanka using Solar PV and Battery Storage

**J.R. Lucas and S.V. Herath**

**Abstract:** Many solar installations are coming up to harness solar electricity in Sri Lanka, including on rooftops. Since the Industrial and Commercial customers are crucial for the economic activities, utility providers have introduced several tariff schemes for financial motivation to go for Solarphotovoltaics. However, with rooftop Solar PV systems, the management of excess solar generation has become a challenge for the utility provider who shed the excess solar generation to regulate the grid parameters. As a result, return of investment for the rooftop solar systems has been reduced drastically for industrial purpose(IP) and general purpose (GP) customers in Sri Lanka. The real time management of the PV generation can be conducted with the available Loads and the other generating sources, like Diesel Engines and Battery Storage. The maximum demand cost needs to be considered and the unit costs can be calculated based on the LCOE technique to reflect the lifetime costs of each source and optimization technique can be used to dispatch the generation and loads based on the optimum cost. In this paper, the PV generation optimization of Industrial Purpose/ General Purpose customers has been conducted using quadratic optimization technique to reduce the electricity cost. The results of the study show that for two selected GP and IP consumers, the program derives the optimum size of battery capacity for a given installation and the minimum solar generation requirement for the economic benefit

**Keywords:** Battery Energy Storage, PV Generation, Quadratic Optimization, Levelized cost of Energy

## 1. Introduction

Cost for Electricity is crucial for a business organization for its profitability. In many countries the governments are offering flexible tariff schemes which are based on the three-tire tariff rates [1, 2] for the business communities. However, the higher peak energy cost as well as maximum demand cost has resulted in higher energy bills for these customers. This ultimately results in increasing the operational costs for the businesses.

When considering the cost reduction for the energy consumers, roof top solar installation can be considered as a major option due to feed-in tariff schemes provided. However, in order to have a considerable gain, the intermittency of the solar energy must be addressed to provide a reliable power supply using substitute generation options which can be dispatched as required. This can also ensure the maximum return on the investment of the rooftop PV installations.

In this approach various energy sources like diesel generators, Solar PV and battery storage have been considered as energy sources to ensure the enhancement of the reliability [3,4]. On the other hand, the maximum demand cost controlling could be considered by limiting the maximum demand from the grid. For this, battery banks which can be charged during the daytime using the solar energy can be considered.

In this paper, the management of the energy sources and loads through an optimization program for three-tier tariff customers, has been presented. As the optimization technique quadratic, optimization is used and unit cost calculation for the renewable sources was done using levelized cost of energy.

The optimization is done for a particular period, based on the available solar power and the energy demand of the system. In the

*Eng.(Prof.)* ***J.R. Lucas****, C.Eng., HLFIE(SL), FIEE, B.Sc.Eng. (Hons) (Cey), MSc (Manch), PhD (Manch), Senior Professor, Department of Electrical, Electronics and Telecommunication Engineering, General Sir John Kotelawala Defence University, Emeritus Professor, Department of Electrical Engineering, University of Moratuwa. Email:lucas@kdu.ac.lk*
*https://orcid.org/0000-0001-7215-0815*
***Eng.S.V. Herath****, C.Eng., MIE(SL), MIET, B.Sc.Eng. (Hons)(Mora), MBA (ARU-UK), Postgraduate Student, Department of Electrical Engineering, University of Moratuwa. Email:sasahrt@gmail.com*
*https://orcid.org/0000-0002-9632-989*

program, available solar energy is allocated for loads and battery charging. Based on the allocation, the optimization program is run to identify the operation of each energy source. Additionally, there is the flexibility in the program to check the sensitivity of the output with the maximum demand value, unit costs of each source, and battery bank capacity. The program output is expected to provide the minimum cost option for the consumer while ensuring the reliability of the power supply. This program would be incorporated in a control system to switch the sources and battery systems.

The same program is used to select the optimum battery bank capacity for a particular installation based on the maximum demand input.

## 2. Control Model of the Consumer

### 2.1. Levelized Cost of Energy (LCOE)

As per [5], Levelized cost of Energy is widely used for the unit cost calculation of the renewable energy sources. The life cycle energy cost and production of the power sources are used in this approach to compare and evaluate the investment return.

$$LCOE = \frac{Life\ cycle\ cost\ (LRR)}{Lifetime\ Energy\ Production(kWh)} \quad \ldots(1)$$

The LCOE Eq.(1) can be used for the calculation of the unit cost of solar systems and battery storage [3] giving the Eq.(2).

$$LCOE = \frac{initial\ investment + \left(\sum_{n=1}^{N} \frac{AO}{(1+r)^n}\right) - \frac{RV}{(1+r)^N}}{\sum_{n=1}^{N} (initial\ kWh\ \times (1-SDR)^n \frac{1}{(1+r)^n})} \quad \ldots(2)$$

where

| | |
|---|---|
| initial investment | -*Capital cost* |
| AO | -*Annual operational cost* |
| r | -*Discount rate* |
| RV | -*Residual value* |
| SDR | -*System degradation rate* |
| n | -*operational year* |
| N | -*Operational life of system* |
| initial kWh | -*First year cumulative energy* |

### 2.2. Optimization Concept

In relation to the optimization, [6] have considered economic dispatch optimization as indicated in the Eq.(3),

$$Min\ (F) = \sum_{i=1}^{NG} F_i P_i \quad \ldots(3)$$

subject to active power balance as given in Eq.(4),

$$\sum_{i=1}^{NG} P_i = D \quad \ldots(4)$$

and capacity limits of each source

$$P_{imin} \leq P_i \leq P_{imax}$$

$P_{imin}$,$P_{imax}$ are the minimum and maximum output power of the sourcei, NG is number of sources, $P_i$ is the power output of the source i, D is the total system demand including losses, and Fi is the total production cost of the source given in Eq.(5).

$$F_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \quad \ldots(5)$$

where,

α, β, ϒ are cost coefficients of the energy sources.

### 2.3 Cost Functions of the Sources

The unit cost functions of each generating option are used in the program and the constants of each function to be calculated and fed as inputs to the program. The battery and solar costs are to be decided based on the levelized costs of energy and the grid costs are taken from the rates given by the utility.

Cost functions for the selected Power Generation Options can be illustrated as given in Eqns.(6) to (12). The parameters are such that CF (j), $P_j$, $C_j$ are the cost function, power output and unit cost of energy source j, respectively.

| | |
|---|---|
| DG – | Diesel Generators |
| PV- | Solar Power |
| BC- | Battery Charge |
| BD- | Battery Discharge |
| PVsh- | Solar Power Shed |
| DR- | Controllable Loads |
| GR- | Grid Power |

Diesel Generator

$$F(DG) = a + bP_{DG} + cP_{DG}^2 \quad \ldots(6)$$

Solar PV System

$$CF(PV) = C_{PV} * P_{PV} \quad \ldots(7)$$

Battery Charging

$$CF(BC) = C_{BC} * P_{BC}$$

Battery Discharging

$$CF(BD) = C_{BD} * P_{BD} \quad \ldots(9)$$

Solar Power Shedding

$$CF(PVsh) = C_{PVsh} * P_{PVsh} \quad \ldots(10)$$

Controllable Loads

$$CF(DR) = C_{DR} * P_{DR} \quad \ldots(11)$$

Grid Cost

$$CF(GR) = C_{GR} * P_{GR} \quad \ldots(12)$$

### 2.4. Battery Stored Energy Systems (BSES)

The charging and discharging of the BSES can be modeled using equations and the update of theState of Charge(SOC) is illustrated in [7,13] as per the Eqns.(6) and (7).

SOC Update During Charge is given in equation (13),

$$S(t) = \left((1-\delta)\,S(t-1) + \frac{P_{ch}(t)\times\Delta t\times\eta_{ch}}{C_N}\right) \quad ...(13)$$

and the SOC Update During Discharge is given in Eq. (14).

$$S(t) = \left((1-\delta)\,S(t-1) - \frac{P_{dis}(t)\times\Delta t}{C_N\times\eta_{dis}}\right) \quad ...(14)$$

The SOC is kept between a minimum value and 100%. The range for the SOC was selected as 80% as described in [7,8] and given in Eq.(15).

$$S_{min} \leq S \leq 100 \quad ...(15)$$

The maximum charging rate of the batteries are to be selected as described in section 3.4. The optimum usage of the charging rate (DCH) and battery life (CHG) to be obtained with this selection [9,10] are given in Eqns.(16) and (17).

$$DCH \leq \frac{C_N}{2} \quad ...(16)$$

$$CHG \leq \frac{C_N}{2} \quad ...(17)$$

where

| | |
|---|---|
| S | -State of charge level |
| $\delta$ | -Self-Discharge Rate of the battery |
| $\Delta t$ | -Time Duration |
| $\eta_{ch}$ | -Charging Efficiency |
| $\eta_{dis}$ | -Discharging Efficiency |
| $P_{ch}(t)$ | -Charging Power |
| $P_{dis}$ | -Discharging power |
| $C_N$ | -Rated Capacity |

### 2.5 The Control Concept

As indicated in Figure 1, all the generating sources, as well as loads, are connected to a common system and the switching of each component is possible through the control system. The solar energy can be directly provided to the loads or possible to use for battery charging.

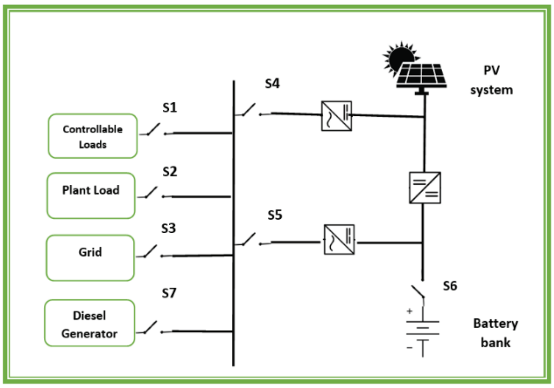


**Figure 1 - System Configuration**

The inputs and the desired outputs for program are indicated in Figure 2.

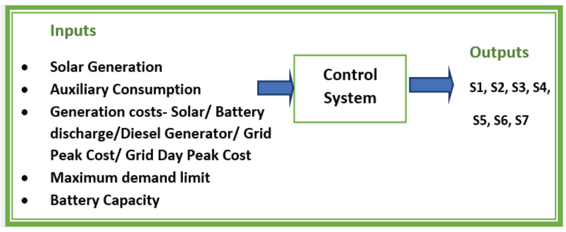


**Figure 2 - Inputs Outputs of the Program**

## 3. The Optimization Technique

### 3.1. Quadratic Optimization Concept

Application of quadrature optimization for a micro grid system dynamic dispatch is widely discussed in [12]. The mix of distributed generation with the energy storage is used to maximize the usage of renewable energy. The daily load is supplied with the optimized operation of the energy sources and the battery bank using dynamic dispatch model developed by quadrature optimization. In this research, this quadrature optimization is selected to be used since it has several types of flexibility in application. As discussed in [12], the objective function is taken as a quadratic function and the constraints are selected in linear equality or inequality form. The objective function defined in equation 4 is expressed in Eq.(18),

$$F(x) = f + g^T x + \frac{1}{2} x^T H \quad ...(18)$$

with inequality constraints given in Eqns.(19) and (20),

$$lb \leq Ax \leq ub \quad ...(19)$$

$$x_{min} \leq x \leq x_{max} (20)$$

and the equality constraints in Eqns.(21) and (22),

$$lb = ub = b_{eq} \quad ...(21)$$

$$Ax = b_{eq} \quad ...(22)$$

### 3.2. Application of Quadratic Optimization

The objective function for the quadratic optimization discussed can be elaborated where addition of all the costs for each cost categories are considered. The minimum value for the total cost to be estimated here to optimize the operation of the system based on the cost.
The objective function is given in Eq.(23),

$$\min j \sum_{t=1}^{T} \begin{matrix} CF(DG) + CF(PV) + CF(BD) + CF(PVsh) \\ + CF(BC) + CF(DR) + CF(GR) \end{matrix} \quad \ldots(23)$$

with equality constraints given in Eqns.(24) and (25),

$$P_{pv} + P_{dg} + P_{bd} + P_{gr} = P_l + P_{pvsh} + P_{bc} + P_{dr} \quad \ldots(24)$$

$$P_{pvsh} = P(n) + P_{pv} - \alpha P_{dr} - \beta P_{bc} \quad \ldots(25)$$

and inequality constraints given in Eqns.(26) to (28),

$$P_{ch} + P_{pv} \le P(n) \quad \ldots(26)$$

$$\alpha P_{dr} + P_{pv} + P_{pvsh} \le P(n) \quad \ldots(27)$$

$$P_i^{min} \le P_i \le P_i^{max} \quad \ldots(28)$$

where,

| | |
|---|---|
| CF | *Cost function* |
| $P_i$ *max* | *Upper bound of the power scheme* |
| $P_i$ | *Power output of each scheme* |
| $P_i$ *min* | *Lower bound of the power scheme* |
| $P_{dg}$ | *Power allocated by the thermal generator* |
| $P_{gr}$ | *Power supplied from the Grid* |
| $P$ | *Solar power generated* |
| $P_{pv}$ | *Power portion from Solar to the load* |
| $P_{bd}$ | *Power from battery discharge* |
| $P_l$ | *Power demand in the system* |
| $P_{pvsh}$ | *Solar power subjected to shed* |
| $P_{ch}$ | *Power required for battery charge* |
| $P_{dr}$ | *Power allocated for demand response* |
| $\alpha$ | *Binary variable allocated for switching of controllable loads* |
| $\beta$ | *Binary variable for charge/discharge selection of battery* |

### 3.3 Optimization Program

The block diagram of the optimization program is shown in Figure 3. Program was coded using MATLAB software and simulation conducted.

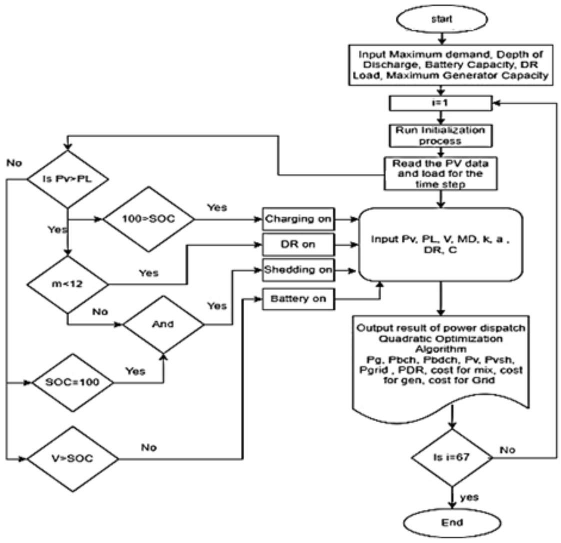


**Figure 3 - Logic Block diagram**

## 4. Numerical Results

### 4.1. General Purpose Customer (GP)

A GP customer with a solar installation capacity of 321 kWp (DC) and optimum AC output is 260 kW (AC) was selected for analysis. Simulation results predicted the annual generation to be 497,500 kWh. LCOE equations 1,2 were used calculate the unit cost considering 25 operational years.

Battery bank capacity optimization was done using the developed program. The calculated unit cost rates and the tariff rates are considered for the program as in Table 1.

**Table 1 - Unit Costs**

| Type | | LKR/kWh |
|---|---|---|
| Solar power (levelized Cost) | | 11.72 |
| Battery charging | | 12.74 |
| Battery discharging (levelized Cost) | | 34.24 |
| PV shedding (25% shed) | | 15.51 |
| Load shifting controllable loads | | 11.72 |
| Grid energy cost | peak | 26.60 |
| | off peak | 21.80 |
| | Day peak | 15.40 |

The load profile for each 15 min time interval is fed into the program. Hence the load profile of the GP customer in Figure 4 is used.

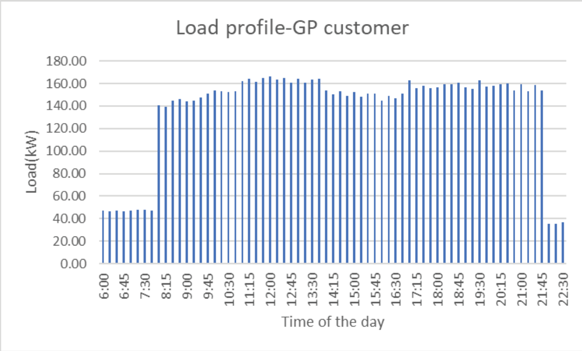


**Figure 4 - Load Profile GP Customer**

The solar generation is varied based on the availability of the solar irradiation. Therefore the program was run for different solar generation curves. A sample variation is shown in Figure 5.

The summarized profit for different solar generation scenarios is given in Table 2. In each case, various solar available patterns and changes were used to calculate the profit for the operation of the system. In accordance with Figure 5, daily profit becomes zero when the solar generation is limited to less than 500-600 kWh.

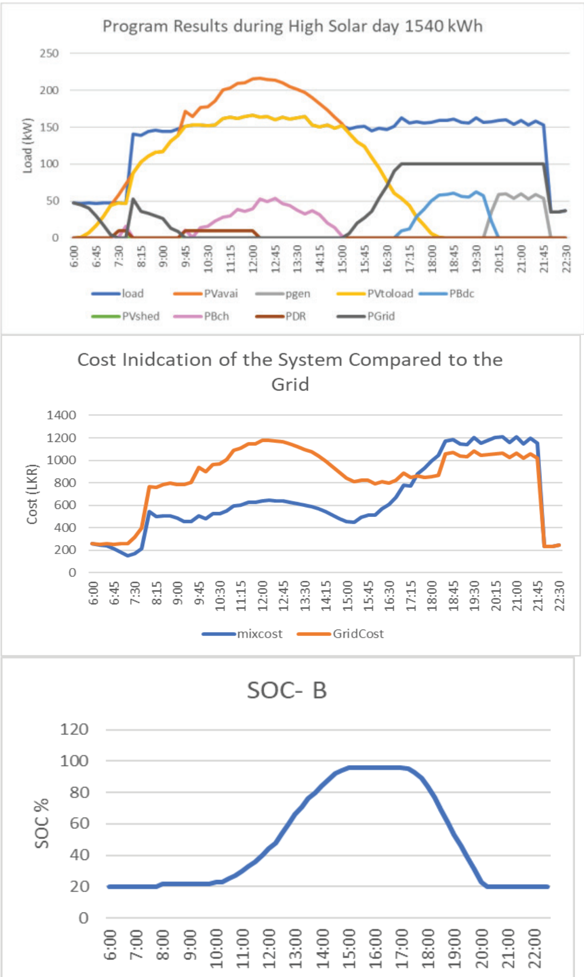


**Figure 5 - Sample Simulation Result GP Customer**

**Table 2 - Summary of Profit against Solar Generation GP Customer**

| Option | Generation(kWh) | Profit (LKR) |
|---|---|---|
| A | 1808 | 10,679.08 |
| B | 1540 | 12,961.92 |
| C | 1450 | 11,958.06 |
| D | 1351 | 10,770.18 |
| E | 1274 | 9,811.25 |
| F | 1089 | 8,105.87 |
| G | 1007 | 6,203.87 |
| H | 726 | 4,204.11 |
| I | 730 | 3,810.76 |
| J | 600 | 1,898.63 |
| K | 524 | 1,392.85 |
| L | 432 | (2,247.49) |

The optimization of the battery bank capacity for the installation was conducted through the program.

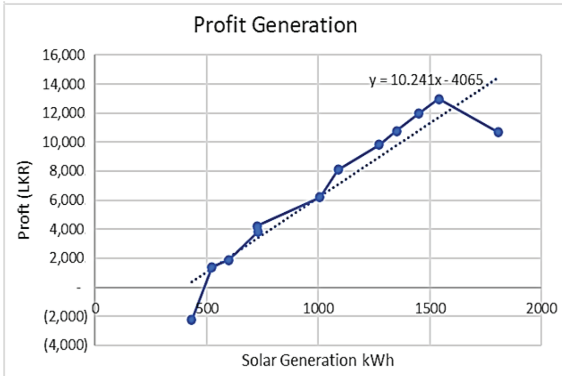


**Figure 6 - Solar Generation against the Profit GP Customer**

As indicated in Table 3, profit for different battery capacities was calculated and the maximum profit scenario is selected as the optimum capacity. Here the maximum profit is reached when the battery capacity is 200 kWh.

**Table 3 - Battery Bank Capacity vs Profit IP Customer**

| Battery Bank Capacity (kWh) | Profit (LKR) |
|---|---|
| 100.00 | 10,856.00 |
| 125.00 | 11,449.00 |
| 150.00 | 12,087.00 |
| 175.00 | 12,566.00 |
| 200.00 | 12,962.00 |
| 225.00 | 12,649.00 |
| 250.00 | 12,649.00 |

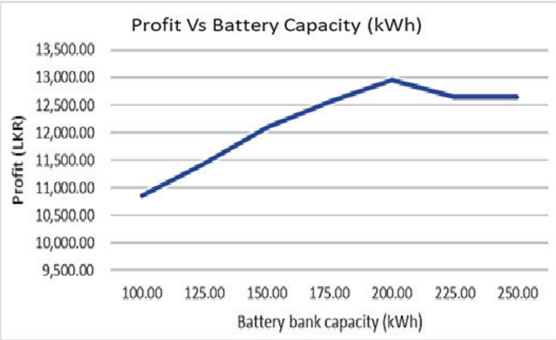


**Figure 7 - Profit Vs Battery Capacity IP Customer**

## 4.2. Industrial Purpose (IP)Customer

An industrial purpose customer, Yugadanavi thermal power plant is selected as a second example. The reduction of the maximum demand was used as a benefit for the LCOE calculation for the battery energy unit cost.

Based on the space availability on the roof, the maximum solar capacity of the consumer is2196 kWp (DC) and the optimum AC output is 1600 kWp. This is expected to generate 3,528,000 kWh of energy. The battery bank capacity was selected as 6MWh and the optimization done.

The unit cost for each energy source and the grid energy cost is shown in Table 4.

**Table 4 - Unit Costs - IP Customers**

| Type | | LKR /kWh |
|---|---|---|
| Solar power (levelized cost) | | 9.37 |
| Battery charging | | 10.19 |
| Battery discharging (levelized cost) | | 15.40 |
| PV shedding (25% shed) | | 12.39 |
| Load shifting controllable loads | | 9.37 |
| Grid energy cost | peak | 23.50 |
| | off peak | 5.90 |
| | day peak | 10.25 |

For simulation purposes, the load profile was selected as indicated in Figure 8. The system behaviour for each scenario is evaluated and the profit is calculated from the program.

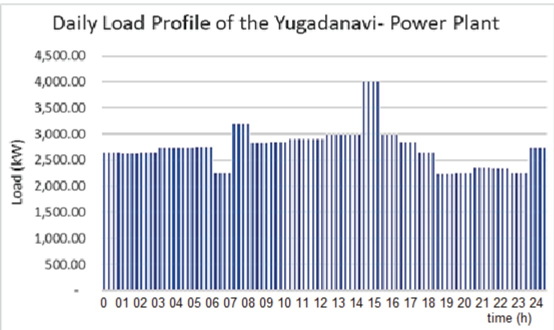


**Figure 8 - Load Profile IP customer**

The profit for different solar generating conditions has been calculated using the program. A sample program result for scenario A is shown in Figure 9 for different solar generation possibilities program results of profit generation are summarized in Table 5.

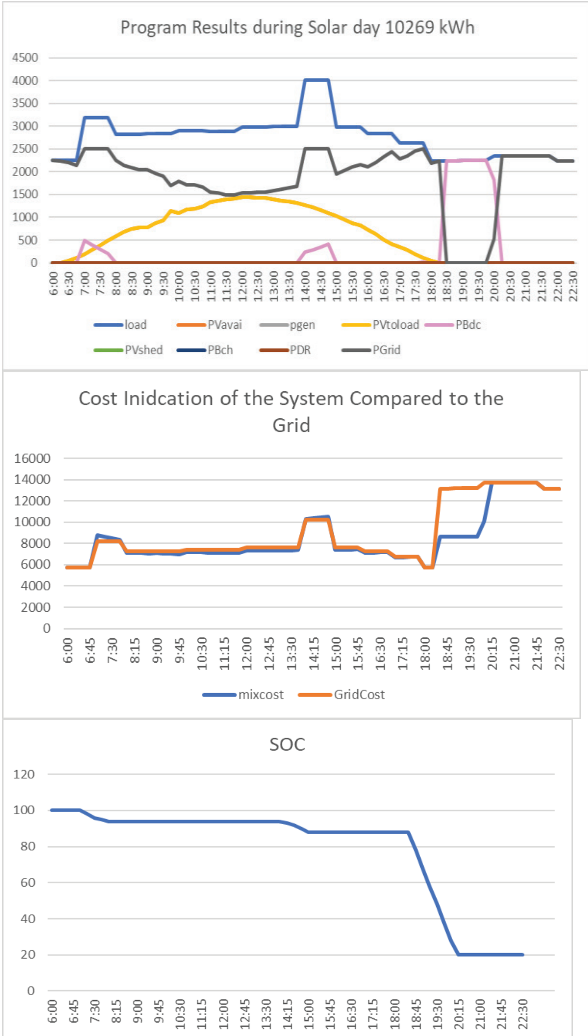


**Figure 9 - Sample Simulation Result IP Customer**

It is seen that the system generates profit when the solar generation is more than 3000 kWh.

**Table 5 - Summary of profit against Solar Generation IP Customer**

| Generation | Daily Solar Generation kWh | Profit (LKR) |
|---|---|---|
| A | 12053.1 | 41,451.30 |
| B | 10269.4 | 36,516.30 |
| C | 9664.4 | 35,052.90 |
| D | 9005.3 | 32,941.80 |
| E | 8493.1 | 32,575.40 |
| F | 7260.0 | 27,762.70 |
| G | 6714.6 | 26,316.30 |

| | | |
|---|---|---|
| H | 4840.0 | 20,341.00 |
| I | 4866.1 | 14,064.00 |
| J | 4002.2 | 12,760.70 |
| K | 3495.4 | 8,357.90 |
| L | 2885.7 | (8,480.10) |

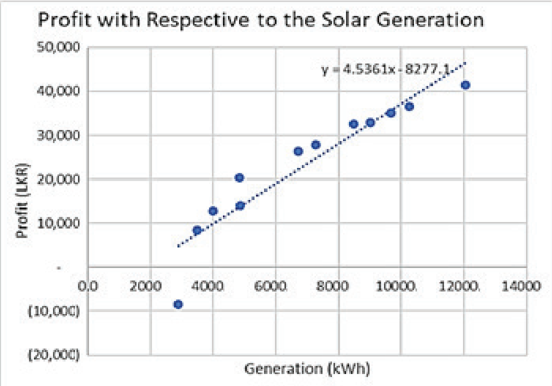


**Figure 10 - Profit vs Solar Generation IP Customer**

Figure 10 shows the plot of profit vs solar generation. The battery bank optimization was done using the same program and shown in Table 8. The maximum profit generation is found to be when the battery bank capacity is 6MWh as seen from Figure 1. For each case, LCOE is separately calculated and fed into the program.

**Table 6 - Battery Bank Optimisation IP Customer**

| Battery Capacity (MWh) | LCOE Cost (LKR) | Profit (LKR) |
|---|---|---|
| 3 | 14.76 | 19,832.00 |
| 4 | 15.08 | 25,796.00 |
| 5 | 15.27 | 30,675.00 |
| 6 | 15.40 | 36,516.00 |
| 7 | 17.76 | 31,139.00 |
| 8 | 19.83 | 22,736.00 |
| 9 | 21.52 | 13,032.00 |
| 10 | 22.87 | 4,796.00 |

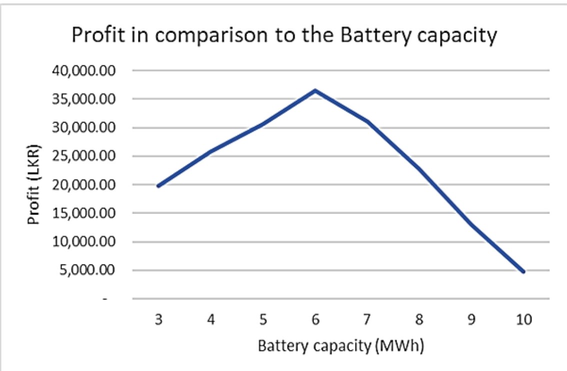


**Figure 11 - Battery Capacity Vs Profit IP Customer**

## 5. Conclusions

The paper has presented a method of electricity cost reduction for both General Purpose customers and industrial customers in Sri Lanka using Solar PV and Battery Storage. A program has been developed based on quadrature optimization which can estimate the optimum capacity before selecting the solar panel size and the battery bank based on the load curve for a particular installation. The program has the flexibility to check the dispatch of the sources, varying the parameters. The intermittent solar generation can be predicted in different scenarios and fed into the program. The risk for the investment due to highly fluctuating solar generation can be analyzed using this program. Also, in this program, changing the maximum demand (MD) value provides the opportunity to the customer for selecting the optimum MD for a particular load profile.

After installation of PV and battery system this program is created to optimize cost through an operation pattern of the Solar system, battery bank, DR loads, Diesel Generators, and Grid power. This ensures the optimum economic dispatch of the sources.

The program has been run for both a general-purpose (GP) customer with a 321 kWp and an industrial purpose (IP) customer with 2196 solar installations. The results of analysis show that for the GP customer, the maximum gains occur with a 200 kWh battery-bank, and that solar generation must exceed about 500 kWhand for the IP customer when the battery bank capacity is around 6 MWh, and the daily generation exceeds about 3 MWh. The program developed is very general and the principles are not limited to Sri Lanka or to any particular type of consumer.


## Acknowledgement

Authors wish to acknowledge the assistance given by their colleagues in carrying out this study.


## References


1. Lucas J. R. "What Guarantee can be given for the Electrical Power Output from a Fixed Rooftop Solar Installation?", *SLEMA Journal, 2021, Vol 24, No 2, pp 1-7.*

2. Siyambalapitiya T, "Tariff Appraisal Study Balancing Sustainability and Efficency with Inclusive Access".

3. Aluthge D, Hemapala U. K. T. M., and Lucas, J. R., " BESS as a UPS to Power Systems With High Solar Penetration" *Frontiers in Energy Research, Open Access Journal, Published: 16 July 2021, doi: 10.3389/fenrg.2021.653015 pp. 1-13.*

4. Ma Y., Yang P., Guo H, Wang Y, "Dynamic Economic Dispatch and Control of a Stand-alone Microgrid in DongAo Island" *J Electr Eng Technol.*2015;30-40.

5. Campbell, M., SunPower Corp., San Jose, California, US "Minimizing Utility-Scale PV Power Plant Levelized Cost of Energy using High-Capacity Factor Configurations" *online.*

6. Ramabhotla, S., Bayne S., Michael Giesselmann, "Operation and Maintenance Cost Optimization in the Grid Connected Mode of Microgrid" *IEEE Green Technologies Conference 2016.*

7. Bo, D., Wenzhou, L., "Research on Control of Energy Storage by Intelligent Micro-grid for Wind/Photovoltaic/Energy Storage" 12th IEEE Conference on Industrial Electronics and Applications (ICIEA), 2017M. Young, *The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.*

8. Wang, P., Setyawan, L., and Xiao, J., "Optimal Depth-of-Discharge Range and Capacity Settings for Battery Energy Storage in Microgrid Operation" *IEEE 2017.*

9. Environment and Health Safety office, "Lithium Ion Battery Safety Guidance" *2017 March.*

10. Tesla.com/Energy "Tesla Mega pack brochure", 2020 Rev 1.8.

11. Lai, C. S., and McCulloch, M. D., "Levelized Cost of Energy for PV and Grid Scale Energy Storage Systems", *2016.*

12. Wibowo, R. S., Firmansyah, K. R., Aryani, N. K., A. Soeprijanto, "Dynamic Economic Dispatch of Hybrid Microgridwith Energy Storage Using Quadratic Programming" *IEEE Region 10 Conference (TENCON*), 2016.

13. Eason, G., Noble, B., and Sneddon, L. N., "On Certain Integrals of Lipschitz-Hankel Type Involving Products of Bessel Functions," *Phil. Trans. Roy. Soc. London, Vol. A247, pp. 529–551, April 1955.*

14. Maxwell, J. C., Treatise, A., on Electricity and Magnetism, 3rd ed., Vol. 2. Oxford: Clarendon, 1892, pp.68–73.

15. Jacobs, I. S., and Bean, C. P., "Fine Particles, Thin Films and Exchange Anisotropy," in Magnetism, *Vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.*

16. Yorozu, Y., Hirano, M., Oka K., and Tagawa, Y., "Electron Spectroscopy Studies on Magneto-optical Media and Plastic Substrate Interface," IEEE Transl. J. *Magn. Japan, Vol. 2, pp. 740–741, August 1987 [Digests 9th Annual Conf. Magnetics Japan, p. 301, 1982].*

17. Young M., The Technical Writer's Handbook. *Mill Valley, CA: University Science, 1989.*