Performance Assessment of Building Integrated Photovoltaic and Battery Energy System: A Case Study of TERI-Retreat Facilty in India

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***Abstract*—Building integrated photovoltaic (BIPV) with energy storage can play an important role not only in demand side management but also in a micro-grid system in coordination with other distributed generators. The operational analysis of BIPV system and energy storage with contribution to local load profile is needed for its grid connected operation, as well as for integrating it in the micro-grid system. In this work, a typical institution has been selected, where the PV system and energy storage are operated for supplying local load in coordination with the grid. The institutional load profile has been analyzed with essential and non-essential loads for understanding the operation and contributions from the PV and battery energy storage in addition from the grid. Annual institutional load variations and PV system outputs are analyzed for evaluating the installed battery's energy throughput and energy contents. Two typical scenarios, with worst and best cases, are used for performance assessment of the considered energy system. It is observed that essential loads are fulfilled during the grid outage through batteries, but load reliability has significant impact if the grid outage is longer. It is noticed that the battery energy throughput must be maximized for effective PV output utilization to fulfil local demand. Results from this work are going to contribute for developing an institutional micro-grid with appropriate sizing of distributed generator as well as on demand side management with grid constraints.**

Keywords: Building Integrated Photovoltaic (BIPV), Battery Energy Throughput, Energy Storage, Solar Energy.

I. Introduction

The building integrated Photovoltaic (BIPV) system has been increasing exponentially, and they can be integrated with energy storage for meeting the essential and non-essential loads within the community [1]. In order to integrate the BIPV system with the distributed network, a proper coordination with battery energy sources and other distributed energy resources is needed for functioning the local network as a micro-grid as well as for demand-side management [2]. It is also important to have proper load analysis with PV system output for effective utilization of energy storage to fulfil the demand of essential load during the grid outage period [3]. The BIPV system with appropriate energy storage can also be operated as an active generator for dispatching the power as per the requirements through defined control strategies [4].

Many studies have been conducted for analysing the PV system performance based on annual/monthly PV generation and load profiles characteristics [5, 6]. However, few studies have analysed the role of battery energy storage within a grid-connected PV based system, and system performance evaluation based on battery energy throughput. In this work, performance of energy system at the TERI Retreat Building has been carried out with contribution from the battery energy storage especially during the grid outages, and analysis of battery energy throughput for local resources utilization.

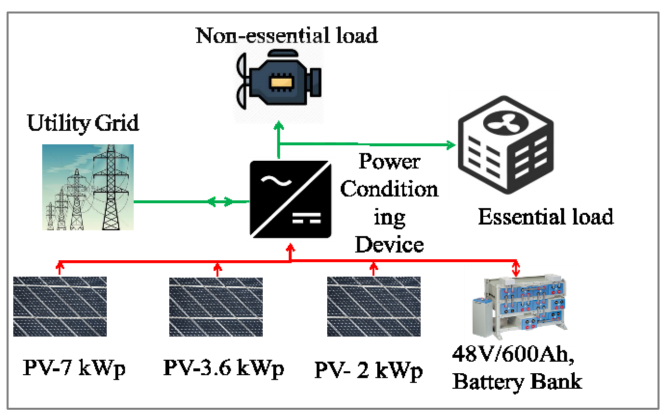


Fig. 1. Block Diagram of TERI's Retreat Facility's Energy System

In this work, institutional load of TERI's Retreat Facility, located at TERI-Gram Gurgaon, Haryana, India (latitude 28.45 and longitude 77.02), has been considered. In the TERI's Retreat

Building, a total of 12.8 kWp PV and 48V/600Ah lead acid battery bank are installed for supplying the electricity to essential loads, and the grid supply for fulfilling the total load demand [7, 8]. The schematic of the installed system at TERI-Retreat Building is shown in Fig 1. The total load has been categorised into the essential and non-essential types. In the system configuration, the battery has been used to meet only the essential load demand during the grid outage conditions. The load pattern analysis has been described in the Section II. Operational analysis of energy system at TERI- Retreat building has explained in the Sections III and IV. The annual battery performance has been assessed and reported in Section V. The results are concluded and their usefulness for developing micro-grid are described in the Section VI.

II. Load and PV Profile Analsysis

The TERI Retreat Facility's load profile has been analysed for evaluating contributions from the PV with energy storage and the grid. The PV output with load can have impact on the battery energy throughput, and also on developing energy management strategies for local resources utilization with energy tariffs. In the load data analysis, following steps have been followed to analyse the annual load profile.

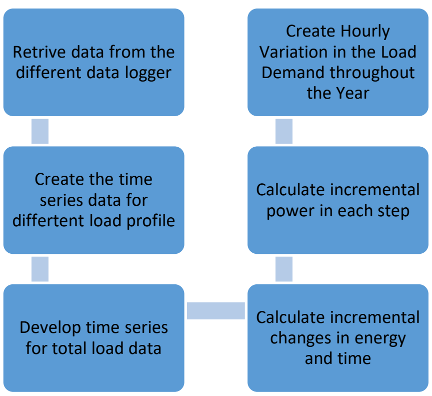


Fig. 2. Steps followed for load data analysis of TERI's Retreat Building

The TERI's retreat facility's load has been analysed through time series data (as explained in Fig. 2), and load profile in per unit (p.u.) is shown in Fig 3. The maximum value of the total load is 11.54 kW and it is considered as one p.u. Through load analysis, it has been found that the annual average of the essential and non-essential loads are 0.19 p.u. and 0.16 p.u. respectively. However, a variation of 20% is testified between the daily load profile and the monthly average load profile [9]. The maximum load has been observed for the month of June. The daily average load is higher in the month of August (i.e. 0.42 p.u.) and lowest in the month of January (i.e. 0.27 p.u.).

As described in the Section I, the total installed PV capacity at TERI's retreat building is 12.8 kWp and its detail has been provided in the ref [7-9]. It has been observed that maximum peaks of PV production are occurred in the March month and the average of the peaks is 0.71 p.u. The yearly PV output at the retreat facility is shown in Fig. 4.

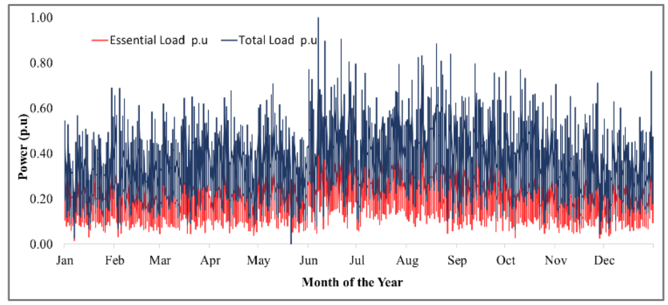


Fig. 3. Hourly Variation of the total Load and essential load of a Year

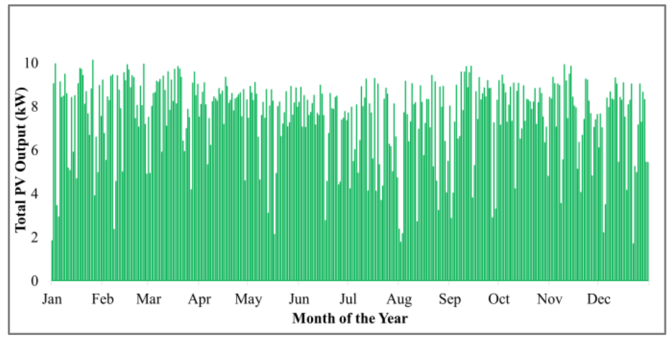


Fig. 4. Solar PV Generation Profile throughout the Year

To analyse the PV output with load profile, a factor (k) is considered as ratio of 'Average Daily PV output' and 'Average Daily Load' within a month. This factor (k) is used for identifying the best and worst months to assess the system performance. Through analysis, it has been observed that February represents the best month as the value of k is maximum 0.74; and the August seems the worst month as k is minimum 0.40. These two months are used for performance assessment of the energy system with more emphasis on battery energy throughput.

III. Annual Performance Analyis

In order to analyse operational performance of energy system at TERI's retreat facility, monthly average load is considered. It has been noticed that monthly load is the highest in the month of August and it is considered as reference (100%) for reflecting the variation of average load for other months (Fig. 5). The installed battery bank capacity is 48V/600Ah and when it is 100% utilized then it can deliver 196 kWh throughput per month with battery lifetime of 10 years. 'Battery's 'Annual Throughput' is defined as the change in energy level of the battery bank, measured after charging losses and before discharging losses in one year'. Daily input charge into the battery has been calculated after the charging losses and before discharging losses for each month. The battery operating conditions are considered with maximum state-of-charge (SoC) 100% to maximum depth-of-discharge (DoD) of 60%. The lifetime energy throughput of 1 kWh battery has been taken 840 kWh with roundtrip efficiency of 80%.

In India, the grid outage (or the load shedding) is occurring very often, therefore, the role of energy storage becomes more critical during this period for providing the uninterrupted power supply to the load. The typical grid outage, during peak load season, varies from 5 to 180 hrs per month [9]. In this paper, 2 hours grid outages in a day has considered, and it is randomly distributed throughout the year for system performance assessment.

In the Figure 5, the average monthly load, contribution from the PV, grid and the battery energy throughput, are illustrated. It has been found that the annual average PV and grid contribution to meet the TERI's retreat building load are 53% and 47% respectively with battery energy throughput of 37%. It has been observed that even after considering 2 hours random outages throughout the year, the TERI's retreat building load requirement has fulfilled. During the year, it is noted that excess PV production has been 3.68% of the load and it may be due to the existing configuration of the system as shown in Figure 1. It has been observed that monthly throughput of the battery mainly depends on grid outages and load profile.

As described in the previous section, the February month has been considered as the best month and the August month as the worst. In February month, PV has been contributed to load by 67% and remaining 33% has been provided by the grid with battery energy throughput has been 30%. However, in the August month, PV and grid have contributed 40% (i.e. lowest compare remaining months) and 60% respectively to meet the load demand whereas the battery throughput has been 33%. It has been analysed that the battery has been providing more than 50% energy throughput for the months of March, October and November whereas in the remaining 9 months, the battery energy throughput has been less than 45%, out of which, January and June months have lowest battery energy throughput of 28% and 23% respectively. Detail performance analysis, for the selected months (e.g. February and August), has been carried out in the subsequent section.

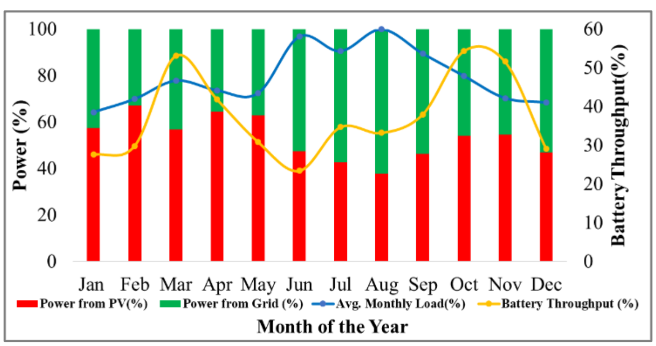


Fig. 5. Energy Contribution from PV, grid and battery throughout the Year

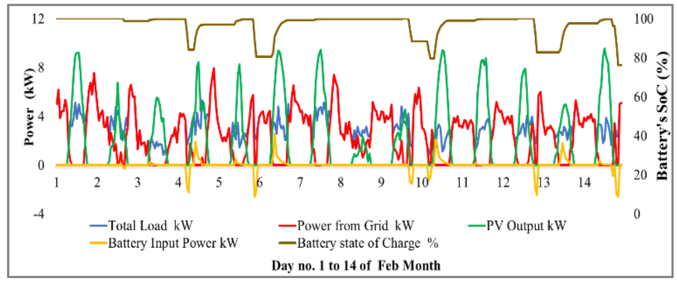
IV. Performance Assessment for Selected Months

As discussed in the Section II, the February month has considered the best month as factor 'k' is the highest 0.74 and the August represents the worst month as factor 'k' is 0.40. This section is focused on the system performance.

A. Performance Assessment for February Month

In this section, the energy system performance has been assessed for the February month. The daily contribution from different energy sources e.g. electricity from the grid, PV output, battery power and battery's State-of-Charge (SoC), are illustrated in the Figures 6 & 7 for February month.

In the February month, it has been observed that battery has been mainly charged through the PV output and discharged during grid outage as well as during the lower PV production. The PV has contributed 67% to meet the load and remaining power of 33% has been supplied by the grid whereas battery energy throughput has been 30%. During the grid outage, grid power has been zero, and its random variation has shown in

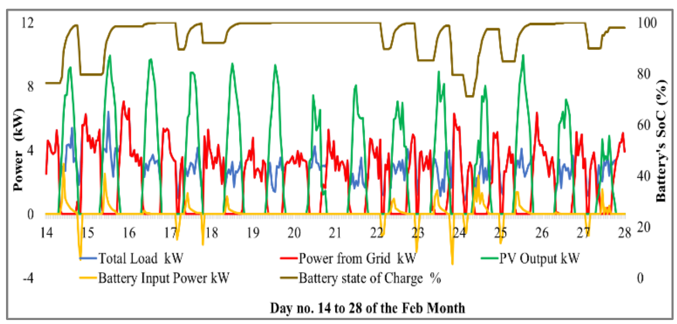


Figures 6 & 7.

Fig. 6. Contribution from PV, grid and battery to meet the load for 1to14 days of February month

Fig. 7. Contribution from PV, grid and battery to meet the load for 14 to 28 days of February month

It has been analysed that on days 1, 2 and 3 of the February month, battery has been fully charged with SoC 100%. During these three days, the total load demand has been fulfilled by the PV and Grid. In the mid-day 4, the grid outage has occurred, and the PV output has not been enough to support the load and then the battery has fulfilled the load demand and its SoC has been reduced to 89%. It has been observed from the Figures 6 & 7 that the battery's SoC has reached to 71% for only 2-3 hours in



the February month, and it has maintained the SoC level 80 to 100% during the whole month. The excess PV power generation in the February month has been 11% of the total excess power generated throughout the year, and its contribution has been highest compare to remaining month of the year.

B. Performance Assessment for August Month

As described in the section II, the August month represents the worst-case scenario as PV contribution has been 40% (i.e. lowest in the whole year) and remaining 60% power has been taken from the grid to meet the TERI's retreat building load demand. In the August month, the battery energy throughput has been 33% and it has been 3% higher as compare to February month. It has been observed from Figures 8, 9 and 10 that the battery has adopted the similar characteristics as for the February month, but on the days no. 12 and 13 battery's SoC has reached to 62%. The two days energy system performance has shown in Fig. 10.

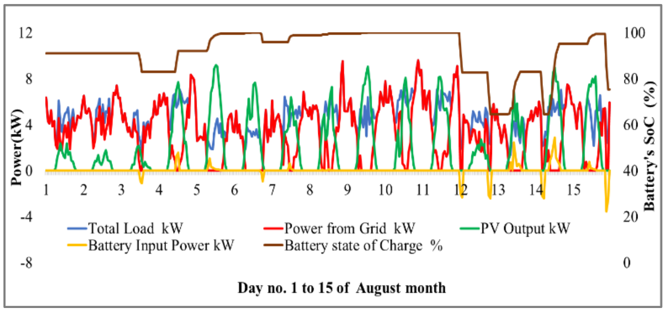


Fig. 8. Contribution from PV, grid and battery to meet the load demand for 1 to 15 days of August month

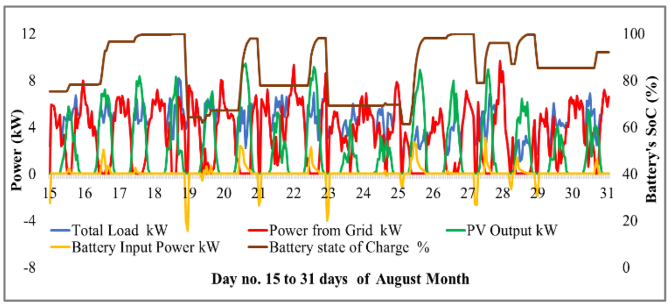


Fig. 9. Contribution from PV, grid and battery to meet the load demand for 15 to 31 days of August Month

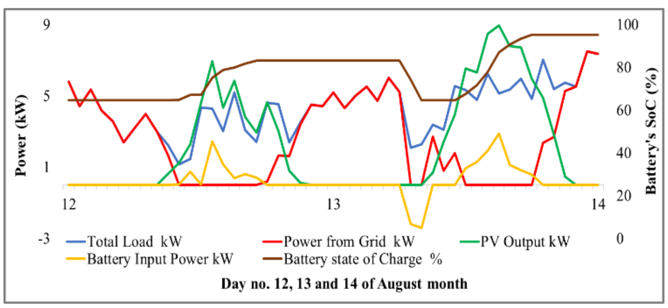


Fig. 10. Contribution from PV, grid and battery to meet the load demand for 12 and 13 days of August Month

It has been observed from the Fig 10 that due to the limited capacity of the battery, it has been contributing only to the essential load during grid outages and there have been some instances e.g. day 13, when battery's SoC has reached to 62% (i.e. 22% higher than DoD). Although, battery's SoC has never reached to the minimum level of 40% but it may lead to a blackout situation if, no other sources are available to supply the load during for longer grid outage period.

To overcome these issues, two options are identified based on the economic factors and availability of appropriate distributed energy source (DES). The first option is to increase the capacity of battery energy storage bank so that it could meet the total load demand. In the first option, the new battery capacity was estimated 112 kWh and it is needed more than 40% investment as compare to the existing system at TERI's retreat building. It has also observed that battery will never get fully charge during the daytime as installed PV capacity at TERI's Retreat Building is 12.8 kW and therefore additional power should be taken from the grid to full charge the battery. Another option is to have a DG and it is going to be considered based on its market availability and possibility to be integrated with the existing system at TERI's Retreat Centre facility. It has been observed that the DG has two main advantages e.g. low investment cost and it operates only during the grid outage conditions. Due to low investment cost of the DG and its active role during grid outage condition, a DG is option is considered and integrated with exiting system [14].

V. Analysis of Battery Energy Storage

The performance of a battery depends on the various parameters e.g. charging/ discharging rate, temperature etc. This paper has analysed the battery performance based on its charging discharging pattern, lifetime throughput and battery's SoC and DoD levels. To understand the battery charging and discharging patterns and its contribution to the meet the load demand, hourly 'battery power' has been examined. Positive and negative values of 'battery power' represent the charging and discharging of the battery respectively.

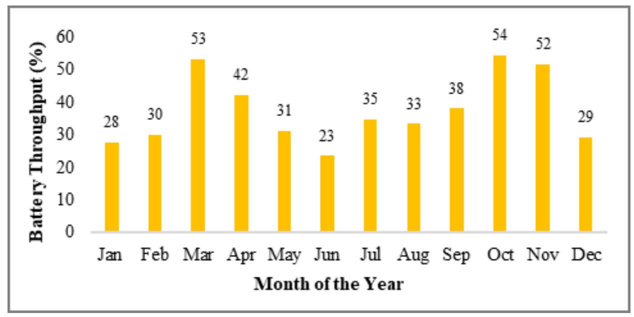


Fig. 11. Monthly Variation in the Battery Throughput

In this work, performance of the battery has been evaluated based on the hourly variation of battery's SoC level and its energy throughput. Monthly variation of the battery throughput has been illustrated in Figure 11. The battery energy throughput has been more than 50% for the months of March, October and November and below than 30% for the months January, June and December. However, for the remaining months of the year (i.e. Feb, April, May, July, August and September), battery energy throughput has been varied in between 30 to 50 %.

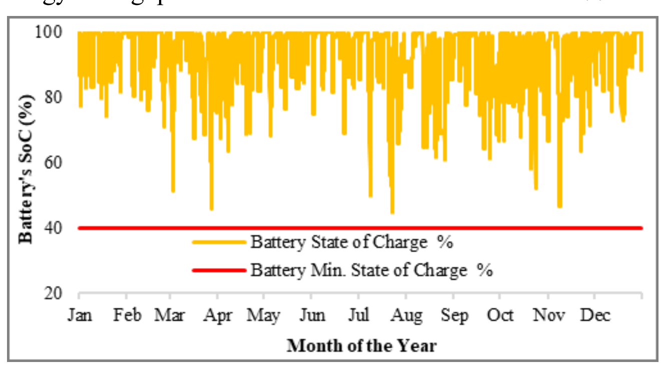


Fig. 12. Hourly variation in the Battery State-of-Charge

The six months from 'April to September' has been represented the summer season and the remaining six months 'October-March' has represented the winter season. It has been observed that the average throughput of the battery for the summer and winter are reported 33.67% and 41% respectively. It concludes that battery can be used more during the winter season as compare to the summer season. Fig. 12 shows, most of the time battery's SoC level has been maintained in between 75% to 95% and it has never gone below 60%, therefore the effective utilization of the battery is required for improving the system performance at TERI's Retreat building.

VI. CONCLUSIONS

This paper has evaluated the yearly energy performance of the installed system at the TERI's retreat building in India. The two months (best and worst) have been selected to have more detailed analysis of the energy contributions from the energy sources. It has been estimated that the annual average PV and grid contribution to meet the load demand have been 53% and 47% respectively. In the February month, average PV and grid contribution have been 67% and 33% respectively, whereas in the August month, PV has contributed to 40% and grid contribution is 60% for fulfilling the TERI's retreat building load. The annual battery energy throughput has been 37% however, battery energy throughput for the selected months February and August have been 30% and 33% respectively. The results of this paper have clearly indicated the need of an appropriate DG for effective utilization of battery energy storage and the local PV production for fulfilling the local load during grid outage.

Future work of this study will focus on effective utilization of the local PV production and optimum utilization the battery for an institutional micro-grid. The work will include use of demand-side management strategy and Time-of-Use energy tariffs.

ACKNOWLEDGMENT

This work is partially supported by the Norwegian Ministry of Foreign Affairs through the Royal Norwegian Embassy, New Delhi under the framework agreement with TERI (India) and University of Agder (Norway) for the project theme 'Sustainability and Clean Energy'

REFERENCES

[1] A. N. Azmi and M. L. Kolhe, "Photovoltaic based active generator: Energy control system using stateflow analysis", 2015 IEEE 11th International Conference on Power Electronics and Drive Systems, Sydney, NSW, 2015, pp. 18-22, 2015.

[2] M. A. M. Yassin, M. L. Kolhe and A. N. Azmi, "Battery capacity estimation for building-integrated photovoltaic system: Design study of a Southern Norway ZEB house," 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Torino, pp. 1-6, 2017.

[3] A. Sharma, M. Kolhe, U. Nils, K. Muddineni, A. Mudgal and S. Garud, "Voltage Rise Issues and Mitigation Techniques Due to High PV Penetration into the Distribution Network," 2018 International Conference on Automation and Computational Engineering (ICACE), Greater Noida, India, pp. 72-78, 2018.

[4] A. N. Azmi and M. L. Kolhe, "Photovoltaic based active generator: Energy control system using stateflow analysis," 2015 IEEE 11th International Conference on Power Electronics and Drive Systems, Sydney, NSW, 2015, pp. 18-22, 2015.

[5] Twaha and M. A. M. Ramli, "A review of optimization approaches for hybrid distributed energy generation systems: Off-grid and grid-connected systems," Sustainable Cities and Society, vol. 41, pp. 320-331, 2018.

[6] S. Xin, C. Yan, Z. Xingyou and W. Chuanzhi, "A novel multi-microgrids system reliability assessment algorithm using parallel computing," 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, pp. 1-5, 2017.

[7] A. Sharma, M. Kolhe, U.-M. Nils, A. Mudgal, K. Muddineniand S. Garud, A report on 'Technical Analysis of Real Time Operational Results of Micro-Grid at TERI's Retreat Centre', funded by the Royal Norwegian Embassy, New Delhi under the framework agreement with TERI (India) and UiA (Norway) for the project theme 'Sustainability and Clean Energy'Oct 2018.

[8] A. Sharma, M. Kolhe, U.-M. Nils, A. Mudgal, K. Muddineniand S. Garud, A report on 'Performance Evaluation of Micro-grid for Energy Management and Control', funded by the Royal Norwegian Embassy, New Delhi under the framework agreement with TERI (India) and UiA (Norway) for the project theme 'Sustainability and Clean Energy' May 2019.

[9] A. Sharma, M. Kolhe, K.M.S.Y.Konara, U.-M. Nils, A. Mudgal, K. Muddineniand S. Garud, "Performance Improvemnent Strategies for Operating Institutional Hybrid Energy System as a Micro-Grid" 5th International Symposium on Hydrogen Energy, Renewable Energy and Materials (HEREM June 2019) (Paper accepted)

[10] V. Natarajan, S. Amit, A report on 'Statistical Analysis of Cost of Energy Due to Electricity Outages in Developing Countries' IARIA, 2012.

[11] A. Sharma, M. Kolhe, U.-M. Nils, K. Muddineni, A. Mudgal, and S. Garud, "Comparative Analysis of Different Types of Micro-grid Architectures and Controls " vol. Paper Accepted in IEEE International Conference on Advances in Computing, Communication Control and Networking (ICACCCN), India Oct 2018 (In Press).