Optimized Power System Planning for Base Transceiver Station (BTS) based on Minimized Power Consumption and Cost

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Abstract—**Telecommunication towers for cell phone services contain Base Transceiver Stations (BTS). As the BTS systems require an uninterrupted supply of power, owing to their operational criticality, the demand for alternate power sources has increased in regions with unreliable and intermittent utility power. For the BTS that lie in the regions where power outages are unwarranted, alternate power sources need to be deployed to keep the BTS sites energized. To cater to this growing need, an optimization framework has been developed which optimizes the operational costs of various BTS power system configurations. In this paper, we present three such alternate frameworks for power supply to the BTS in case of a power failure; to supply uninterrupted and continuous power to the sites. In particular, our optimization framework consists of three power system configurations; utility grid with battery backup (configuration 1), utility grid with battery backup and diesel generator (configuration 2), and utility grid with battery backup and solar (configuration 3). These three configurations are then evaluated based on linear optimization by incorporating various system constraints. Upon the application of these configurations in a case study, the results demonstrated that configuration 2 can provide reliable power for up to 8 hours of grid outage per day and provides the best reliability amongst other configurations. But the downside of configuration 2 is its cost. Configuration 3 is economically viable and cost-effective but less reliable power system configuration due to the limited availability of solar PV power. The utility of configuration 3 may be an issue with large blackouts in cases of limited solar capacity. For our particular power source specifications and capacity (including battery specifications, load demand, diesel generator and Solar PV capacity) the findings suggested that for an eight-hour power outage, configuration 2 lumps up energy cost to $12.86 per day compared to the more economically viable configuration 1 and configuration 3, which costs up to $12.44 and $10.56 respectively.**

Keywords*—*BTS, unreliable grid, optimization framework, linear optimization, Solar PV system

I. INTRODUCTION

Base transceiver stations (BTS) form an integral foundation of the mobile cellular service[14]. Mobile phone operators tend to maximize their profits by minimizing system downtime based on the reliable operation of these BTS sites. Therefore, the uninterrupted power supply to BTS sites is paramount in providing cellular service. Having more than three million base stations worldwide, cellular networks as of now approximately contribute three percent of worldwide energy consumption and two percent of carbon emissions[12]. Therefore, when implementing these systems, power system planning and optimized power operation for these BTS sites is a crucial aspect under consideration and is based on three requirements; high reliability, low cost, and, reduced environmental impacts[13, 23]. While in many developed countries the grid outage is minimal, the situation in many developing countries is contrary.

The utility grid in these regions is mainly intermittent. Therefore, reliable and stable power supply to these remote BTS sites is a vital focus for the telecommunications industry[3, 4].

Typically, the provision of uninterrupted power supply at BTS sites is safeguarded through back up by diesel generator systems. While this provides a complete backup to BTS sites at the time of grid outage, the subsequent costs are typically high with a negative impact on the environment[17]. For unreliable grids, the diesel generator system with battery storage is the most conventional and commonly used backup system for BTS sites[10]. The configuration's higher reliability and lower upfront costs are sole reasons for their frequent usage in many of the cell tower sites around the globe. However, despite its impacts on running costs and carbon emissions, most of the telecom companies still use it in many of their sites. The operation and maintenance of diesel generators typically account for 35% of the total cost of ownership (TCO) of the BTS, whereas the BTS site equipment accounts for 65% of telecom operator's operating expenses[20]. The substitute for the diesel generator arrangement is the implementation of renewable-based hybrid systems. The notion of a backup power system based primarily on renewable energy is gaining popularity primarily due to environmental concerns and lowering solar photovoltaic (PV) system costs in recent years[19]. These are typically used in hybrid orientations power system where grid, diesel generators, solar PV and battery bank system work in conjunction for stable power supply[21, 22]. The

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stand-alone hybrid energy is an optimum solution to power a mobile BTS in an urban setting such that its reliance on conventional diesel fuel is lowered[7, 11]. In order to meet sustained load demands of mobile base station during varying natural conditions, different energy sources and converters need to be integrated for extended usage of alternative energy[16].

Outline of the paper: This paper discusses the optimum operation of the system through optimized scheduling of power sources in the presence of intermittent grid power and also takes account of cost optimization and power usage of the different sources at the BTS sites. Different configurations of the grid-connected solar, generator, battery bank systems are analyzed using mathematical models and simulations to find the most reliable and cost-effective combination of the power sources for the BTS sites of Pakistan. We have divided this paper into three sections; Section 2 describes the system framework based on linear programming, whereas Section 3 consists of an optimization framework and cost minimization objective function with system constraints. Finally, Section 4 discusses a case study on which the optimization techniques and system framework configurations are applied.

II. System Formulation

High intermittency at grid-connected BTS sites requires a proper backup power system solution. Devising a reliable method for electric supply is necessary for the uninterrupted operation of the BTS. Therefore, we propose a system framework which consists of different BTS power system configurations. The elemental functionality of this framework is to maintain a continuous and uninterrupted power supply to the BTS sites. Our framework utilizes the integration of different power sources; utility power, diesel generator, battery banks and increasingly competitive solar PV system technology in a specific configuration with the BTS towers[2]. Inclusion of a renewable technology like solar PV system enhances the economic effectiveness of the system. Moreover, it also ensures the provision of emission-free green energy to power the cell towers. All the secondary power sources in the BTS sites act to cater to the unreliable supply of power by the grid to the BTS. Each power system configuration mentioned earlier has technical and environmental limitations and is implemented for specific usage under different power interruption scenarios. The model of the system framework in this paper, mentions only three of the most effective and reliable combinations of the power sources that have several applications for a specific power outage scenario. The system configurations shown in Figure 1 are cited as follows:

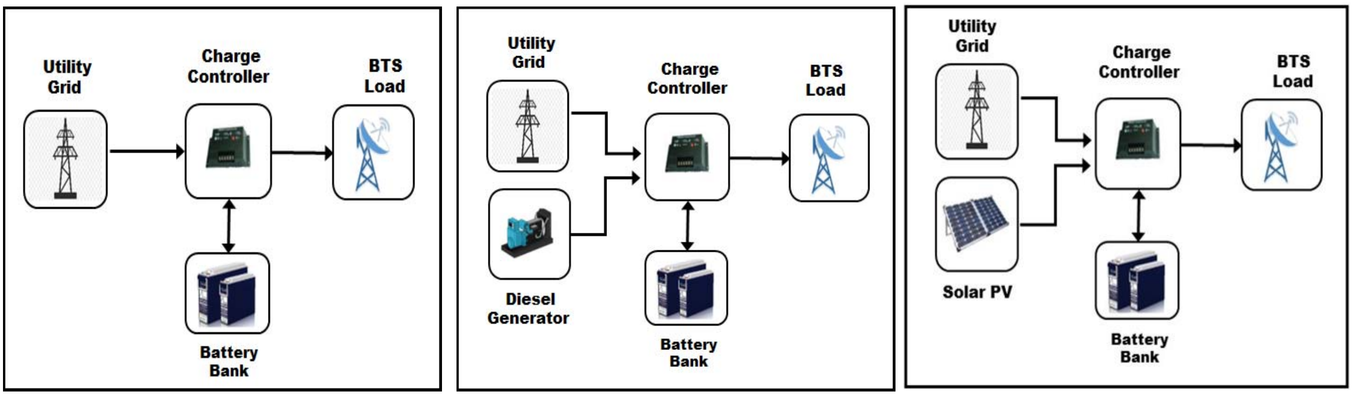
- Configuration 1: Utility grid and battery storage (UPS operation) (Figure 1.a)
- Configuration 2: Utility grid, diesel generator and battery storage (Figure 1.b)
- Configuration 3: Utility grid with Solar PV system and battery storage (Figure 1.c)

A. *Utility Grid and Battery Storage (UPS operation) - Configuration 1*

Figure 1.a shows a system configuration of utility grid power and battery banks. This configuration has a typical UPS operation mechanism, which is capable of powering the loads with grid intermittency. Upon the availability of the grid power, BTS loads are powered simultaneously with the charging of the battery banks. Once the battery banks are fully charged the grid then only provides power to the BTS loads. This complete operation is efficiently monitored by the charge controller. Therefore, when there is a power outage, battery bank powers the BTS load until it reaches its minimum state of charge (SOC) or until the restoration of the grid power. When the grid power is available, all the BTS load is disconnected from the battery and shifted to the grid. This is the standard and primary function of the backup UPS system that provides power to the loads to cover for the intervals when there are power outages. However, the implementation of this configuration for cell sites poses several limitations. The sole dependence of BTS loads on battery storage during the unavailability of the utility grid power is quite an unreliable and expensive system configuration, as for long periods of power outages, batteries remain in a low state of charge (SOC) which shortens their lifetime. Consequently, reliability becomes quite low and OPEX cost of the system increases[24].

B. *Utility Grid with Diesel Generator backup system and Battery Storage Configuration 2*

Figure 1.b shows a system configuration of utility grid power with diesel generator backup and battery banks. In this configuration, when the grid is available, the battery is charged, and the BTS loads are powered at the same time. In case of a power outage, the power backup system acts as ‘configuration 1’ for a specified period. When the battery reaches a minimum SOC, the system shifts to diesel generator which then acts as a primary power source. It charges the battery and powers the BTS simultaneously. When the grid power is available again, all the BTS load and battery banks are disconnected from the diesel generator and, are then shifted to the utility grid. Smart energy controller efficiently transfers the load from the generator to the grid. The presence of a diesel generator as a backup system enhances the reliability of the system as it can provide power for long intervals of a power outage. It also prolongs the lifetime of the batteries as they do not have to operate near minimum SOC as often as in the case of Configuration 1. This optimization can be achieved by transferring the load from generator to battery when the battery is at its maximum SOC and then transferring the load back to the generator again when the battery is at its minimum SOC. This method helps to maintain lower fuel consumption thereby incurring lower running costs of diesel generator and at the same time increases the battery life as it continues to operate in a partial state of charge (PSOC). Owing to this continuous operation of batteries in PSOC, the system becomes more efficient and reliable in terms of power supply[26].



(a) (b) (c)

Fig. 1. Various configurations for BTS Power Supply systems

C. *Utility Grid with Solar PV backup system and Battery Storage - Configuration 3*

The main aim of the implementation of this configuration is to incorporate solar energy into the energy mix which then reduces the operational hours of diesel generator, and a reduction in fuel, operational costs and carbon emissions are also observed[8, 22]. As shown in Figure 1.c, this configuration incorporates solar PV with the grid and allows optimum operation regardless of the state of the utility grid during sunlight hours. The solar PV system also ensures that storage battery banks are always charged and have sufficient power to support the BTS site loads[2]. This optimal utilization of solar and storage resources minimizes dependence on power utility grids. However, the battery size has to be designed appropriately to provision the load during night time[17]. Dependence on solar PV alone as a backup system is not a reliable and secure way, but the various optimal configurations can play an essential role in enhancing the reliability of the system.

D. *Optimization Framework*

The block diagrams of the optimization framework for the three configurations are shown in figures 2- 4:

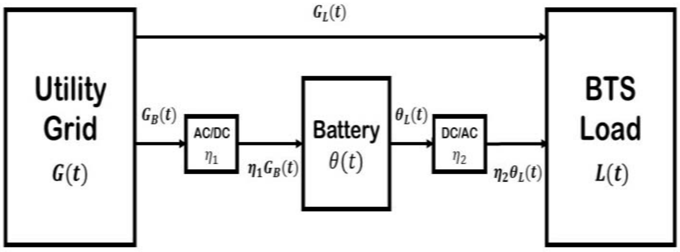


Fig. 2. Block diagram for configuration 1 with state variables

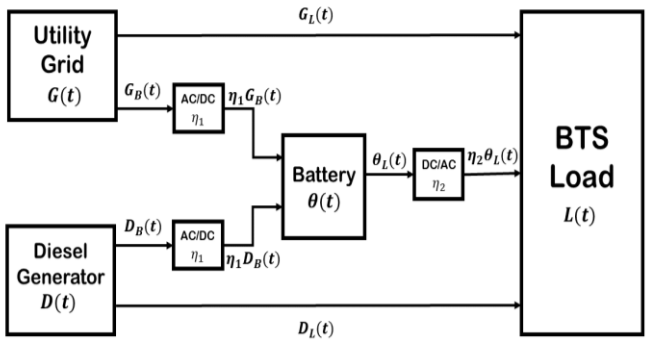


Fig.3. Block diagram for configuration 2 with state variables

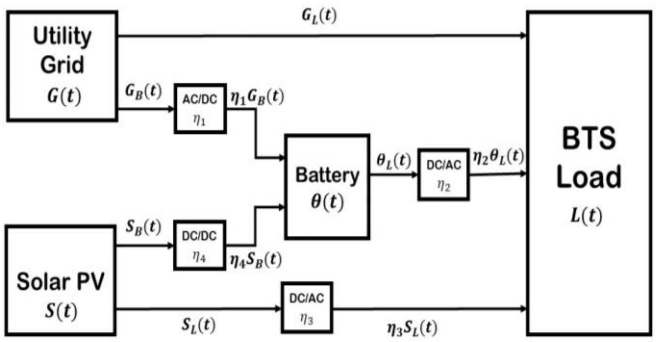


Fig.4. Block diagram for configuration 3 with state variables

1) *Objective Function*

The overall cost minimization objective function of the respective three configurations as shown in figure 2, 3 and 4, are given below for which the interval of observation is 1 hour, while energy and power have been used interchangeably throughout the text for defining state variables

- *Configuration 1:*

$$min \sum_{t=1}^{T}[(z(t) \times P \times G_B(t)) + (z(t) \times P \times G_L(t))]$$

- *Configuration 2:*

$$min \sum_{t=1}^{T}[(z(t) \times P \times G_B(t)) + (z(t) \times P \times G_L(t) + (\beta \times D_B(t)) + (\beta \times D_L(t))]$$

- *Configuration 3:*

$$min \sum_{t=1}^{T}[(z(t) \times P \times G_B(t)) + (z(t) \times P \times G_L(t) + (\gamma \times S_B(t)) + (\gamma \times S_L(t))]$$

In the above mentioned objective functions, *z(t)* shows the status of the power grid. i.e. $z(t) = 0$ if there is a power outage while $z(t) = 1$, when the grid is supplying power. Moreover, P, β and γ are per unit cost of grid power, diesel generator power and solar PV power, respectively.

2) Inequality Constraints:

$$\theta(t) \geq \theta_{min} \;\; ; \forall t = 1 \dots T+1 \quad (1)$$

$$\theta(t) \leq \theta_{max} \;\; ; \forall t = 1 \dots T+1 \quad (2)$$

$$\theta_L(t) \leq \theta_{max} - \theta_{min} \; ; \forall t = 1 \dots T \quad (3)$$

a) Maximum Battery Capacity Constraint:

- *Configuration 1*

$$z(t) \times {\eta^1}_1 G_B(t) \leq \theta_{max} \; ; \; \forall t = 1 \dots T \quad (4)$$

- *Configuration 2*

$$z(t) * \eta_1 G_B(t) + \eta_1 D_B(t) \leq \theta_{max} \; ; \forall t = 1 \dots T \quad (5)$$

- *Configuration 3*

$$z(t) \times \eta_1 G_B(t) + \eta_1 S_B(t) \leq \theta_{max}; \forall t = 1 \dots T \quad (6)$$

3) Equality Constraints:

a) Load Demand Constraint:

- *Configuration 1:*

$$z(t) \times G_L(t) + \eta_2 \theta_L(t) = L(t) \; ; \; \forall t = 1 \dots T \quad (7)$$

- *Configuration 2:*

$$z(t) \times G_L(t) + D_L(t) + \eta_2 \theta_L(t) = L(t); \; \forall t = 1 \dots T \quad (8)$$

- *Configuration 3:*

$$z(t) \times G_L(t) + \eta_2 S_L(t) + \eta_2 \theta_L(t) = L(t); \forall t = 1 \dots T \quad (9)$$

b) Optimum Battery Operation Constraint:

For the optimal operation of the battery, it is used recursively. The present state $\theta(t)$ of the battery is used to determine the next state $\theta(t+1)$ of the battery while the energy $\theta_L(t)$ is provided by the battery to the load.

- *Configuration 1:*

$$\theta(t+1) = \theta(t) + z(t) \times \eta_1 G_B(t) - \theta_L(t); \forall t = 1 \dots T \quad (10)$$

- *Configuration 2:*

$$\theta(t+1) = \theta(t) + z(t) \times \eta_1 G_B(t) + \eta_1 D_B(t) - \theta_L(t); \; \forall t = 1 \dots T \quad (11)$$

- *Configuration 3:*

$$\theta(t+1) = \theta(t) + z(t) * \eta_1 G_B(t) + \eta_1 S_B(t) - \theta_L(t); \; \forall t = 1 \dots T \quad (12)$$

III. CASE STUDY

The optimization framework above is applied to a case study for a typical power supply system of a BTS site incorporating important factors of cost and capacity generation with different power sources. For the case study, in particular, we have taken a BTS site that has a load demand of 2kW and encounters a daily power outage of four to eight hours due to being powered by an intermittent utility grid.

A. System Sizing and Cost:

The case study uses the optimization framework with the following system specifications [1, 20, 21, 22].

System deployed	System Sizing	System Cost[2] (per units)
BTS site Load Demand	2kW	$0.30
Battery Bank Back up[3]	750Ah at 12V	$5.06[4] (per day), $200 per 100Ah
Diesel Generator	2.4kVA at 0.8 p.f.	$0.15
Solar System nameplate rating	6 kWp	$0.07

IV. RESULTS AND DISCUSSIONS

To carry out the operation and cost optimization for three configurations, the specifications mentioned above are used. The MATLAB tool is used to carry out the optimization problem.

A. Optimized Power Operation and minimized costs for – Configuration 1

Figure 5 illustrates the daily power outage profile of the utility grid for 4 hours and 8 hours. Optimized results in the form of optimized battery state and power sources operation achieved for configuration 1 by incorporating the power outages are shown in figure 6. Figures 6a and 6b depict the optimized

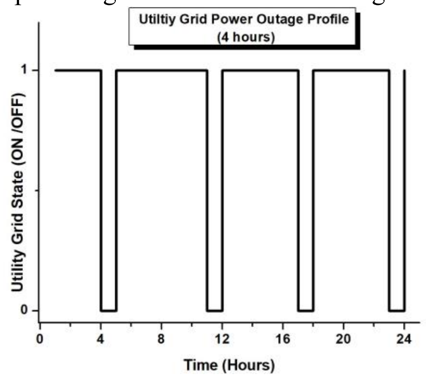
[1] The configurations shown in Figure 2-4 make use of the converters which are assumed to have 85% efficiency each, i.e. $\eta_1 = \eta_2 = \eta_3 = \eta_4$.

[2] All these system costs are incorporated in terms of their LCOE (Levelized Cost of Electricity).

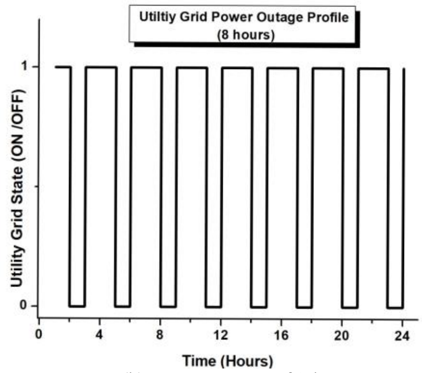
[3] Battery bank has a backup of 2 consecutive hours, 2000 × 2 = 4kWh, with total cost of battery including maintenance charges as $1850.

[4] Batteries are assumed to have 100% round trip efficiency.

results of different power sources operation for 4 hours and 8 hours of a power outage, respectively. The results show that this configuration has a typical UPS operation mechanism, which is capable of powering the loads vulnerable to grid intermittency.



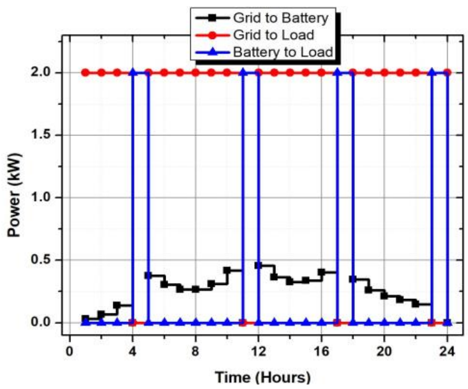
(a) Power outage of 4 hrs



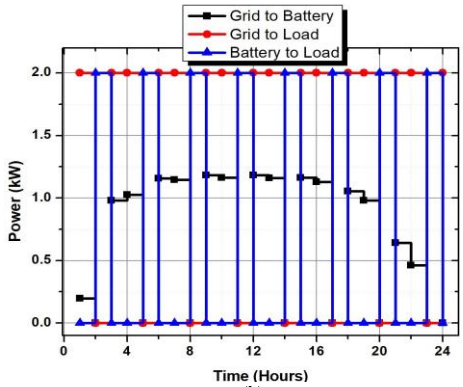
(b) Power outage of 8 hrs

Fig.5. Utility Grid Power Outage Profile

The energy cost per day with this configuration for a 4-hour power outage comes out to be \$11.98 while the costs are elevated for an 8-hour power outage i.e. \$12.44. The increase in costs is due to the fact that during a power outage, battery bank powers the load through the converters with 10% to 20% inefficiency. A significant amount of energy consumption is associated with a higher number of power outages, as battery bank and converters take in more power than required for the load to cater for the losses associated with them.



(a)

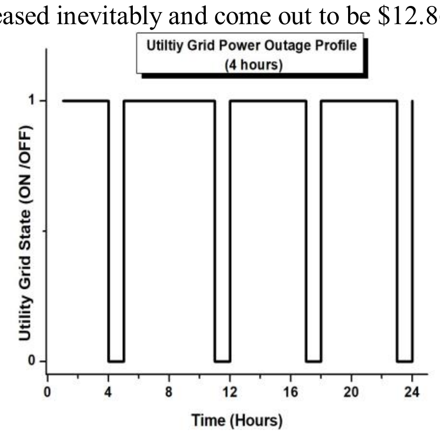


(b)

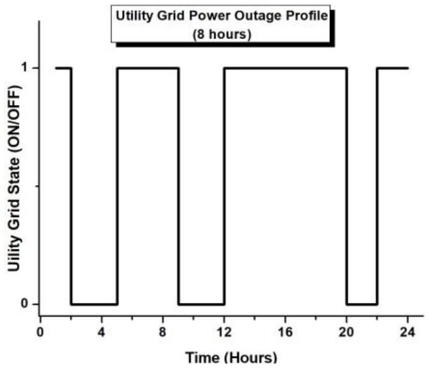
Fig.6. Optimized power operation of configuration 1

B. Optimized Power Operation and minimized costs of – Configuration 2

The power outage pattern of 4 hours is considered to be the same, as shown in figure 5a. However, the power outage profile for 8 hours is assumed to be different from the one shown in Figure 5b for this configuration. A modified power outage pattern for 8 hours, as shown in Figure 7b, is considered to gauge the response of diesel generator on an irregular outage interval. Figures 8a and 8b show the optimized operation of the different power sources for configuration 2 when there is a power outage of 4 and 8 hours, respectively. For a 4-hour power outage, the battery bank powers the load while the diesel generator remains powered off as the battery has enough backup of 2 hours for the load. The power operation of configuration 2 is similar to configuration 1 for 4 hours outage while in case of a power outage for 8 hours, the diesel generator significantly contributes to power the load. The operating costs are now elevated as the utilization of the diesel generator has increased for the power outage of 8 hours. This operational cost of the diesel generator when incorporated in the overall utility grid energy cost gives a total expenditure of \$7.80 per day. The battery only has the backup for 2 hours. When the power outage takes place for more than 2 consecutive hours, diesel generator acts to power the load while the SOC of the battery starts to drop. In case of the power outage of 4 hours, the per day energy costs for the utility grid and battery bank combined comes out to be \$11.98, but for a power outage of 8 hours, the energy cost has increased inevitably and come out to be \$12.86.

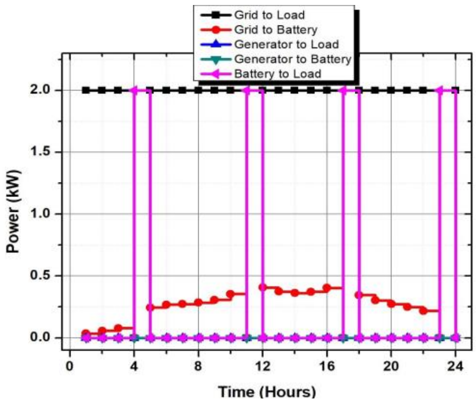


(a) Power outage of 4 hrs

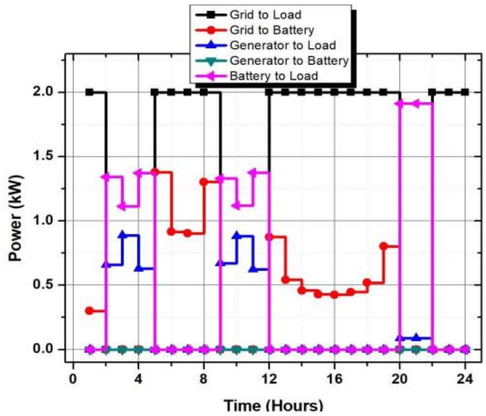


(a) Power outage of 8 hrs

Fig.7. Utility Grid Power Outage Profile for the configuration



(a)

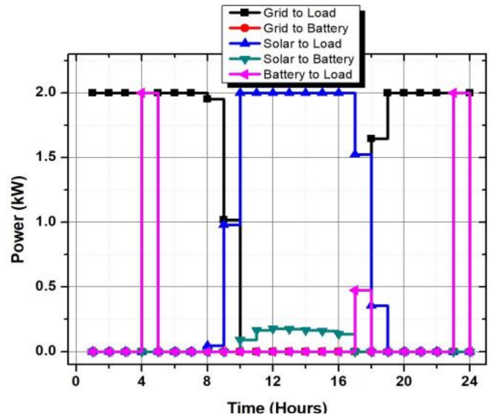


(b)

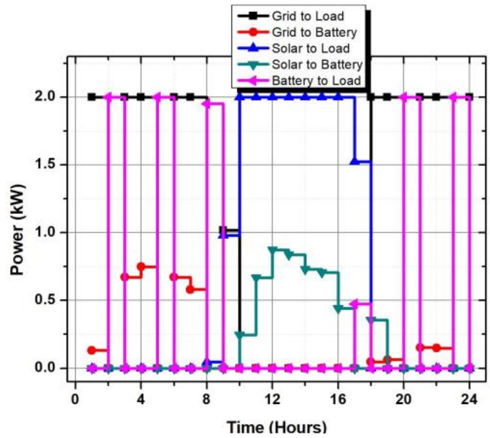
Fig.8. Optimized power operation of configuration 2

C. *Optimized Power Operation and minimized costs of – Configuration 3*

Owing to the maximum utilization of solar PV and battery power and limited usage of the utility grid; the results show that the total per day operating cost of configuration 3 is less than that of the other two configurations mentioned earlier. In this scenario, the power outage profile, as presented in Figure 5, have been deployed. By incorporating the fixed battery costs of $5.06 with the combined operating cost of the utility grid and solar PV, i.e. $5.47, the total per day operating cost comes out to be $10.53. It is also observed that despite the availability of the utility grid during the hours when there is sufficient sunlight, the system configuration primarily utilizes the energy from solar PV to power the BTS loads. This leads to a reduction in the overall cost of the power operation as an optimization framework which takes account of the fact that the cost of electricity generated from solar is quite less than that from the utility grid. Figures 9a and 9b show the optimized results of battery state and different power sources operation for 4 hours and 8 hours of a power outage, respectively. The results show that the inclusion of a renewable energy source to an unreliable power grid resulted in reduced operational hours of diesel generator, consequently leading to a reduction in fuel and operational costs.



(a)



(b)

Fig.9. Optimized power operation of configuration 3

D. Cost Comparison of Power System Configurations for BTS

Costs	Configuration 1		Configuration 2		Configuration 3	
Power Outage(hrs)	Four	Eight	Four	Eight	Four	Eight
Operation Cost ($/day)	6.92	7.38	6.92	7.80	5.47	5.48
Battery Cost ($/day)	5.06					
Total ($/day)	11.98	12.44	11.98	12.86	10.53	10.54

V. CONCLUSION

The urgency to reduce carbon emissions and operating costs along with efficient and optimized energy operation have instigated the telecommunication industries to move towards a reliable framework that comprises of battery banks and solar PV systems. Different configurations of power sources with unreliable utility grids, including UPS operation, diesel generator backed system, and solar PV system is analyzed by the use of optimization techniques. Operating costs and optimized power operation of the system are the vital aspects of this analysis. A case study has been taken into account and application of different configurations of the framework for the power outage scenario in this case study has resulted in key findings. The findings suggested that the utility grid combination with a diesel generator and battery bank is costlier especially when the 8-hour window is taken into account; costing up to $12.86 in comparison to the $12.44 and the $10.54 operation costs for configuration 1 and configuration 3, respectively. However, this diesel configuration also appeared to be a reliable power system configuration to meet the BTS load demand, while utility grid combined with a solar PV system and battery bank is an economical and a cost-effective but a less reliable power system configuration due to the limited availability of solar PV power. The optimized power operation of the system framework is also devised that has helped in minimizing the overall costs and enhancing the reliability of each system configuration to power BTS loads at cell sites.

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