Economic Analysis of deployment of DC power and Appliances along with Solar in urban multi-storied buildings

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***Abstract*— Lighting, fans and electronic devices form a significant and growing portion of power-load at homes and need power back-up support in case there are frequent power-cuts. A Diesel generator is generally used today in multi-storied buildings to provide this backup. The DC system, proposed in this paper, provides a far more energy-efficient alternative using renewable power-source for backup. It creates a pull for a home to move towards far more energy efficient DC loads. The solution provides a GREEN option to the existing solution. This paper provides a fresh perspective on the problem of eliminating conversion losses for uninterrupted operation of DC appliances. A cost benefit analysis shows that this DC system can reduce costs to the consumer by eliminating the complex electronics embedded in the inversion process. A rough measurement of the conversion losses for commercially available inverters and battery chargers illustrates that gains of 30% to 45% are easily obtainable**

Keywords—Conversion Loss, DC Appliances, DC-Bus, DC Power, LVDC, Microgrid, Multi-Storied Buildings, Solar.

I. Introduction

The demand-supply gap for power in India has been widening at an increasing rate as India is becoming more industrialized and affluent. The load shedding is the highest in the urban areas and this affects economic development, especially of small and medium sized industries, commerce, residential apartments and educational institutions. Even though there is a renewed thrust to enhance conventional power-generation, the demand-growth continues to outpace generation-growth.

India's domestic energy consumption is 186 TWh/yr in 2012 and constitutes 21% of total energy consumption. In the energy consumption distribution, the ceiling fans and lighting constitute the majority (62%) of energy use of 115 TWh [1]. India’s Residential sector is expected to grow 4x from from 16,000 million sft in 2005 to 64,000 million sft by 2030. This would mean 1 million new homes being added per year currently and increasing to 3 million by 2030 [1].

II. Motivation

A. High Cost of Backup power in Urban areas

Most middle and upper class apartments in India receive back-up power from Diesel Generator (DG) sets. Builders normally supply two types of wiring in every apartment. i) AC mains wiring connected to the grid, subject to frequent blackouts. ii) AC auxiliary wiring (typically about 1kW) connected to Mains and to DG for back-up power. The latter is used to power those appliances, which the apartments consider vital (hereafter referred to as vital appliances). The cost of power from DG is very high. Typical cost is US $0.38 per unit as opposed to US $0.08 per unit for the grid.

B. Power Conversion Losses.

Homes and offices are starting to use decentralized solar panels. The solar panels produce power only in DC form. Similarly all batteries store energy only in DC form. When solar panels and batteries are used with AC power lines at homes and offices, solar power is converted from DC to AC and synchronized with AC mains, AC power is converted to DC to charge battery and DC power from battery is converted to AC before use. All these converters cause significant power-loss. These multiple conversions result in inefficiencies and poor economics. The solar-DC system would therefore be of great advantage. At the same time, it is increasingly getting understood that DC appliances consume about the half the power compared to their AC counterparts. So if the solar-DC system gives DC power output and directly DC loads, it is even better.

This kind of SOLAR-DC system (Fig. 1) is now emerging where no such conversion takes place. DC power from solar is used directly to supply to load and charge battery and DC power output from battery is used to drive the load.

C. Reliability.

The AC-DC and DC-AC conversions not only contribute to losses, but also impact reliability. Unfortunately, electrolytic capacitors, which are known for its short life span, are a necessary component in most converter topologies. The Solar DC system avoids the use of Electrolytic capacitors and other heat dissipating components. The DC appliances are also isolated from power surges, voltage fluctuations and harmonics. This results in an overall improvement in reliability of the entire system as compared to an AC or Inverter powered system

III. GOA SOLAR-DC SYSTEM

Green Offices and Apartments (GOA), is a technology solution developed at IITM. It gets apartments to get its vital appliances powered by DC power. Using solar power, power from grid (when available) and batteries at 48V, 24x7 power connectivity to these appliances is assured (Fig. 2). GOA has a centralized DC power module that supplies DC power and a Remote Buzzer & Metering (RBM) unit at each apartment at 48V DC. The RBM is used to remotely monitor and control the consumption at every apartment. A GOA system supports up to 24 dwelling units, each consuming upto 500 Watts. This line enables use of energy efficient DC appliances such as BLDC fans and LED lights, resulting in substantial reductions in energy consumptions. The module can also be used to power an office-building instead of multiple apartments.

A typical GOA system supports up to 24 dwelling units, each provided with a restricted backup power of upto 500 Watts. An RBM (Remote Buzzer and Metering) unit limits this load and will trip if the load exceeds the pre-set load. The RBM also turns on the buzzer to alert the user that the power supply has tripped.

The DC system and the savings from the DC system for a residential and commercial buildings have been highlighted elsewhere [3, 4]. The concept of DC microgrid for residential houses with cogeneration system such as gas engine is also studied in [7]. This paper presents a use case from the Indian and South-Asian context where there is a demand-supply gap resulting in frequent and regular black-outs as a result of load shedding.

GOA system consists of GOA Central Unit, Solar panels, Battery bank and 48V DC appliances, and Remote Buzzer and Metering modules (RBMs). The GOA Central Unit is an intelligent device that maximizes the efficiency of the system by directly delivering maximum solar power to the DC appliances, and ensuring optimum charging of the battery. An electronic management interface provides information (and control) on power generated from solar PVs, utilities power consumed, and power delivered to various outlets

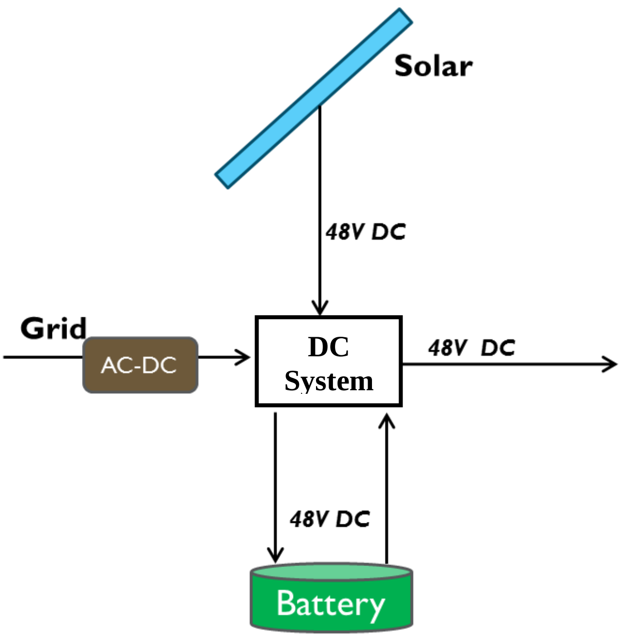


Figure 1: Solar-DC System

A. DC Loads

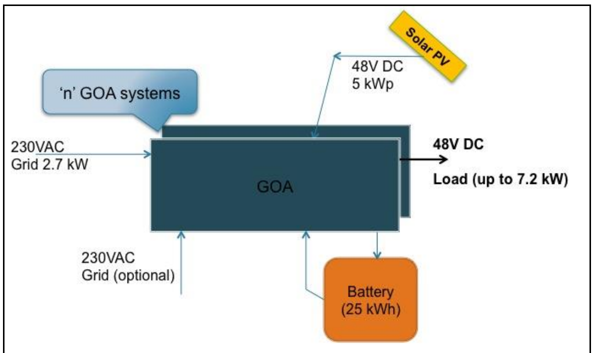
The advantage of DC loads, besides being highly energy-efficient, is that it runs with "native" power generated from solar and no converters are required. Also, the loads are not affected by voltage sag, surge, three-phase unbalance and voltage harmonics, which is a big problem in India. Besides eliminating inverter, it eliminates transformer losses and power factor losses resulting is savings to the customer.

B. System Block Diagram

The block diagram of the GOA system is shown in Fig.2. A typical GOA system is connected to 5kWp of Solar PV capacity and 25kWh of battery bank. It drives a DC load of 7.2kW, which typically caters to about 24 apartment units, with an average of 300W per apartment unit.

The detailed system Single Line Diagram showing the solar capacity, PV module stringing, battery stringing and the actual loads for this implementation is given in Fig.3.

The battery used in the DC system is a Valve Regulated Lead Acid (VRLA) battery which has been tested for quick recharge performance and cyclic capability under Partial State of Charge (PSOC) operation [2]. The capacity testing was completed till 1017 cycles at 40% Depth of Discharge (DoD). The Solar PV Capacity is 5kWp. The PV modules are poly-crystalline custom designed for 48V Vmp with the name plate capacity of 125Wp. 5 modules are connected to form a string and there are 8 strings overall. The PV modules are installed over an area of 500 square feet.



Cygni Solution	UoM	Value
Power Generation Mix of GOA system	Solar: Grid: Battery	45:50:5

Figure 2: GOA System Block Diagram

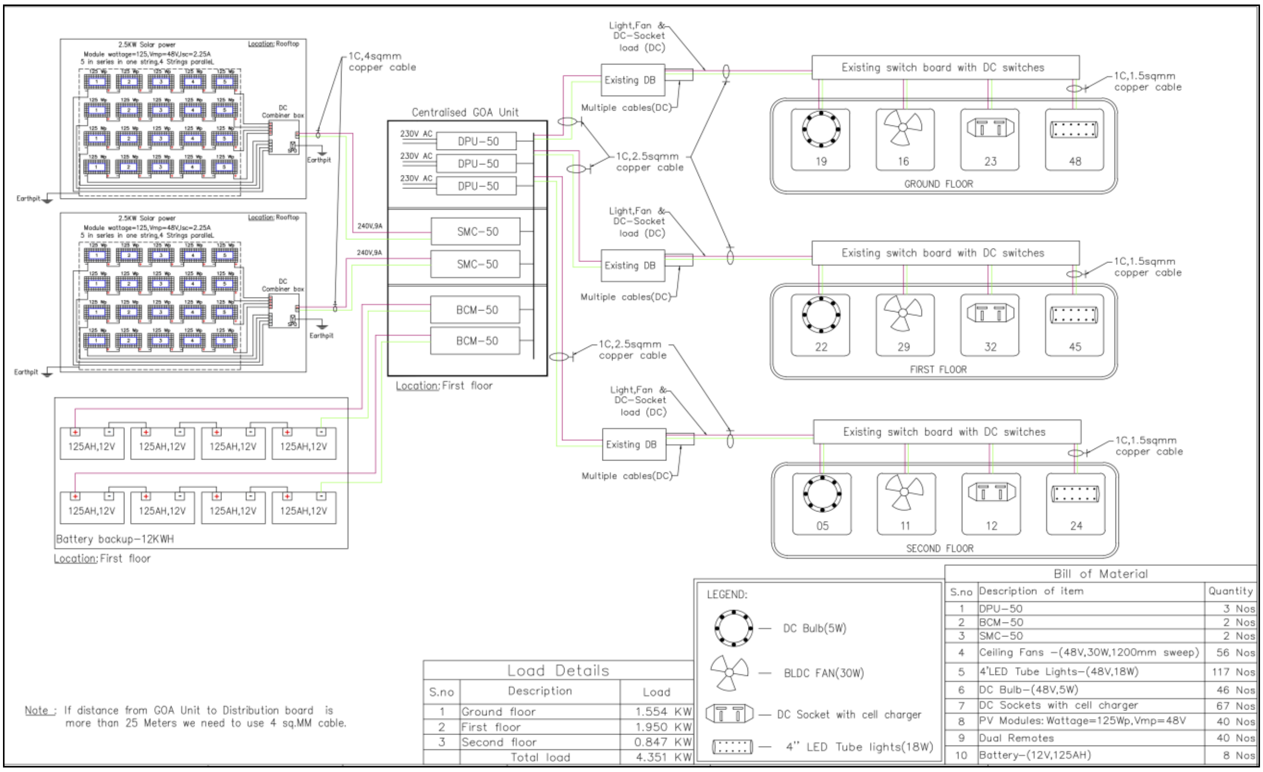


Figure 3: GOA System Single Line Diagram

IV. Economic Analysis

GOA system enables substantial savings on power by highly efficient DC devices such as fans, LED lights and DC powered TVs. As DC appliances are 50% more efficient compared to AC counterparts, there is significant savings on utility charges.

A. Comparison between Conventional Solar AC and Solar DC System:

The table below, compares on a line-item by line-item basis, the conventional solar based AC solution to the Solar-DC solution as proposed in GOA system.

Considering all the above factors, the conventional Solar-AC system is less attractive as against the Solar-DC based GOA system.

B. Comparison between Conventional AC, Energy Efficient AC and Solar DC System:

The DC system and the savings from the DC system for a residential and commercial buildings have also been studied elsewhere [3, 4, 10, 11].

We undertook a study of 3 different systems to discover and demonstrate how such building can be provided with appropriate solar roof-top with 2-hours of battery back-up in a sustainable manner and will therefore act as a model that can be implemented on a large scale. Table I shows the system with conventional loads, where fans are regular fans based on induction motor and lighting is provided through fluorescent tube lights. Table II shows the system with AC energy efficient loads where fans are energy efficient (star rated) AC fans and lighting is through LED AC tube lights. Table III shows the system with DC loads where are fans are with BLDC fans and lighting is through DC LED tube lights. From the Tables 2, 3 & 4 above, the energy consumption with Energy Efficient DC Loads is 27% lower than the equivalent Energy Efficient AC Loads and is 51% lower than the Conventional AC Loads.

C. DC System Savings:

In most commercial and residential solar power solutions, DC power generated is converted to AC to power the appliances at homes and offices. Excess AC power is used to charge the battery, where it is converted back to DC. Similarly, when power is drawn from the battery, it is again converted to AC. These multiple conversions result in inefficiencies and poor economics. As GOA system uses DC power to run DC appliances and that these DC appliances consume about the half the power compared to their AC counterparts, this again translates into better energy efficiencies and lower costs. These results as shown in Table-2, 3 & 4 above and savings are in-line with the potential efficiency gain in residential and commercial sector in US which is estimated at 45% with a potential to save 244 TWh of energy [5].

D. Cost Benefit Analysis

The various parameters for arriving at the cost-benefit analysis is given in Table-5 for deployment of DC power and

TABLE 1: COMPARISON BETWEEN CONVENTIONAL SOLAR-AC (CAC) AND SOLAR-DC SYSTEM

	CAC	Solar-DC	Comparison
Wiring	Solar + Battery will provide power during power cuts - we need to segregate appliances with separate wiring (based on the solar PCU and system capacity)	Solar-DC also requires separate DC wiring to segregate DC appliances.	The cost is the same whether we use AC or 48V DC for this segregated wiring.
Lights	CFL is typically used.	LED is used	LEDs cost about 2 times the CFL cost for the same lumens. However, the additional cost is compensated by the fact that LEDs last 2 times longer and consume half the power.
Fan	In CAC case, if an existing AC fan is re-deployed for Solar-AC, then about 40W of extra solar + battery capacity is required. Also inverter is required The additional cost of this is about US $64 (taking into account DC-AC conversion losses)	In DC case, we need to procure a new DC fan, which costs about US $32 as opposed to US $23 for AC fan. As volume increase, the gap in prices between two fans will reduce.	The slightly higher cost of DC fan, or even replacement of an existing AC fan is justified by the savings of USD 64, when DC is used
Storage	Battery sizing will be more for AC loads as power consumption is higher. Also, there is at least 20% loss due to the AC-DC and DC-AC conversion	Since battery stores power in DC form, no investment in inverter is required. Also power loss during the conversions is eliminated	Capital cost is reduced by reduced load (for same demand) in the case of DC, and savings due to elimination of inverter. Utilization is also better due to elimination of conversion inefficiencies
Solar system	In CAC case, the system has to be sized for the higher AC. Also inverter costs and costs inherent to conversion losses are inherent in this case.	In DC case, solar power generated in DC form can be used as such, with minimal additional equipment. Also design capacity is lower to reflect lower DC power consumption.	Capital costs are lower in the case of DC, as design capacity for the same requirement is lower. Opex is also lower as conversion costs are eliminated
Flexibility of use	In CAC case, the inverter has to be sized for the higher AC loads. This means the initial investment is high. Also, there are inefficiencies when the inverter is operated at lower capacity	In DC case, systems capacity can be as low as 100-200W per home to start with and solar panels can be augmented as the need arises in a modular fashion	Lower initial costs, and feasibility of incremental investment is a very important benefit for many lower income households
Grid Connectivity	In the CAC case, one can supply surplus power to the grid.	Excess solar power cannot be supplied to the grid. However, the solar capacity can be aggregated and shared through suitable design, to minimize this situation	In a situation where the consumer is perennially in a power shortage situation, inability to feed to the grid is unlikely to be a disadvantage.
Devices	Typically run on DC. So require AC to DC conversion resulting in about 25% losses	Require investment in 48V DC – DC adapters	Adapter cost is offset by elimination of AC-DC converter in the case of DC. Also losses are avoided in the case of DC

[a] 1 USD = 60 INR

TABLE 2: CONVENTIONAL LOADS

		Conventional AC Loads				
Load Description	Qty	Energy Consumption (W)	Total Wattage (W)	Avg. Hrs of Operation	Daily Consumption (kWhr)
Tube light	117	36	4212	9.2	38.75
Light Bulb	46	14	644	4.6	2.96
Fan	60	60	3600	13.7	49.32
Mobile Charger	67	5	335	9.3	3.12
Total Load			8791		
Total Energy Consumption/ Day					94.15

TABLE 3: ENERGY EFFICIENT AC LOADS

		Energy Efficient AC Loads			
Load Description	Qty	Energy Consumption (W)	Total Wattage (W)	Avg. Hrs of Operation	Daily Consumption (kWhr)
Tube light	117	18	2106	9.2	19.46
Light Bulb	46	9	414	4.6	1.90
Fan	60	50	3000	13.7	41.19
Charger	67	4	268	9.3	2.49
Total Load			5788		
Total Energy Consumption/ Day					65.05

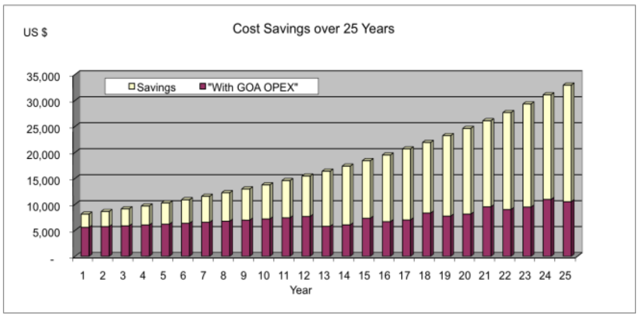


Figure 4: GOA System - Cost Savings

TABLE 4: ENERGY EFFICIENT DC LOADS

		Energy Efficient DC Loads			
Load Description	Qty	Energy Consumption (W)	Total Wattage (W)	Avg. Hrs of Operation	Daily Consumption (kWhr)
Tube light	117	36	1872	9.2	17.30
Light Bulb	46	14	276	4.6	1.27
Fan	60	60	1920	13.7	26.36
Mobile Charger	67	5	134	9.3	1.25
Total Load			4202		
Total Energy Consumption/ Day					46.17

appliances along with solar in urban multi-storied buildings. The urban unit energy utilization is assumed at 50% with 2 hours power-cut per day (1 hour during day time and 1 hour during evening). The system design is done such that power from solar constitutes 50% of the total DC power.

The analysis provides details on the cost of electricity with AC and DC loads while comparing it with the cost of power from a DG set. The analysis is provided for a streaming business model, where the cost of GOA system, solar and storage for the 24 apartment unit is provided by an oprating company. The customer pays monthly charges for the DC energy consumed and also pays a fixed monthly cost towards the cost of GOA system. In this system, the energy bill for the consumer is 30% of the "as-is" energy cost (because of energy efficient DC equipments, GOA system with solar and intelligent selection of power sources). The consumer also pays a fixed monthly cost of $11.30 per month per apartment unit towards cost of GOA equipments. Even after this the effective savings is 30% of his original energy bill. The cost savings over a period of 25 years is shown Fig. 4.

In the analysis, the cost of GOA system is US $7,750. With a 70:30 debt:equity ratio and with a rate of interest at 14%, the equity IRR for the debt investment is at 24%. Hence it is win-win model for both the consumer and the investor.

TABLE 5: PARAMETERS FOR COST-BENEFIT ANALYSIS

No	Details	Value
	GOA System Configuration	
1	No. of homes per GOA system	24
2	Solar Capacity (in KW)	5
3	Battery Capacity (in KWh)	25
4	Customer AC Load ("as-is" in KW AC)	14.4
5	GOA System Capacity ("to-be" in KW DC)	7.2
	Power Tariff & Availability Details	
1	Grid Power Tariff (US $)	0.10
2	Cost of Back-up Power (US $)	0.29
3	Equipment Utilisation Factor (US $)	50.00%
4	No. of Hrs of Utilization (Hrs)	12.0
5	No. of power cut hours per day (Hrs)	2.0
6	Weighted Avg Cost of power (US $)	0.13
7	Avg. Cost of Yearly Power Escalation (%)	6%
	GOA OpEx Details	
2	GOA OPEX Tariff (US $)	0.10
3	GOA OPEX Term (Years)	12
4	GOA Warranted System Life (Years)	25
5	Fixed GOA OPEX Yearly Escalation Rate (%)	4%
	Yearly Energy Consumption & Cost	
3	Energy Consumption per year ("as-is" - in kWh AC)	63,072
4	Energy Consumption per year ("to-be" - in kWh DC)	31,536
5	Power Generation from Solar per year (in kWh)	7,500
6	Net Energy consumed from grid per year ("to-be" in kWh)	24,036
	O&M Cost	
1	O&M Expenses to customer (% of CAPEX)	10.00%
2	O&M Expenses per Year (US $)	1097
4	O&M Yearly Escalation (%)	4%
5	Battery Replacement Cost (%)	8.8%
6	Battery Replacement Cost (US $)	968

V. CONCLUSION

The GOA DC system changes the paradigm from a centralized generation and distribution system of power delivery to a system, which is more decentralized and more flexible. This system is energy efficient and more compatible with the fastest growing segment of the load today: lighting, fans and electronic devices.

The GOA Central Unit provides efficient DC power system for Apartments and Commercial buildings. The Solar and rectified Grid power are efficiently shared in a manner to maximize solar power usage. The new 48V DC appliances developed, such as fans and lights, are highly efficient, resulting in less than 50% power consumption as against conventional AC loads. Also, as this falls under Safety Extra-low Voltage (SELV), all the devices are safe, reducing the risk of electric shock

This paper provides a fresh perspective on the problem of eliminating conversion losses for uninterrupted operation of DC appliances. A cost benefit analysis shows that the DC system can reduce costs to the consumer by eliminating the complex electronics embedded in the inversion process. A rough measurement of the conversion losses for commercially available inverters and battery chargers illustrates that gains of 30% to 45% are easily obtainable.

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