Solar-DC Deployment Experience in Off-Grid and Near Off-Grid Homes: Economics, Technology and Policy Analysis

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***Abstract*—India is a power deficit country and one third of its homes are off grid or near off grid. This paper presents an efficient and affordable Solar DC solution for powering such homes. Though several solutions have emerged in the past for powering these homes, those have been expensive and energy inefficient. These solutions rely on several DC to AC and AC to DC conversions, to feed the widely used AC home loads, thus, wasting a large chunk of the expensive power. The proposed Solar DC solution for off-grid homes (OGH) is developed to use the generated PV power efficiently. With this solution, the panel and battery size is reduced by 2 to 2.5 times and the cost to power a house is reduced to nearly half the cost of the existing solutions. The paper also presents a techno-economic comparison between the proposed OGH solution with some existing solar systems.**

***Keywords*—Near off grid homes; off grid homes; solar-DC; solar power**

I. INTRODUCTION

A very large number of the Indian homes (nearly 70 million) are off-grid and probably another 30-40 million are near off-grid (those with black-outs for more than 12 hours a day). Although sun shines brightly for more than 300 days a year for almost 10-12 hours a day in most parts of the country, the potential of decentralized solar energy has not been adequately explored. With most places having more than 1400 equivalent peak hours of sunlight annually, solar energy becomes an attractive choice for bridging the power-shortage. Government of India realizes the fact that encouraging the use of renewable energy resources, especially the Solar energy, can help bridge the current demand-supply gap of powering homes nation-wide. Thus, relevant policies have been framed for promoting solar power usage. The country launched a Solar Mission named Jawaharlal Nehru National Solar Mission (JNNSM) in 2010 targeting to install 20 GW solar power installations by 2022. Encouraged with 3GW installed in 4 years, it has now increased the target to 100 GW by 2022 with 40 GW of this targeted through solar rooftops. Subsequent to the launch of JNNSM, several States also launched their respective Solar Polices. In Tamil Nadu (TN), one of the Indian States, TN Solar Energy Policy was launched in 2012 targeting 3GW. The TN Vision 2023 has subsequently increased the solar target to 5GW by 2023. Realizing the importance of rooftop Solar, Tamil Nadu Government has permitted grid-tied net-metered solar rooftops, mandated rooftops on all government buildings and provided an incentive of INR20,000 per KW to all domestic rooftops in addition to 30% subsidy provided by Government of India. TN is also installing free solar rooftops on 300,000 houses, and converting 100,000 streetlights to Solar. TN is leading the solar rooftop revolution in the country with 50.3 MW rooftops installed out of 285 MW across the country [1].

While the Indian Government is taking steps and framing policies to promote solar power usage, the technology must support efficient, sustainable, economical and scalable solutions. With existing solar solutions in India using multiple AC to DC and DC to AC converters, the systems tend to lose a large amount of generated solar energy. This wastage gets further compounded as loads become increasingly DC (most electronic gadgets use DC) amounting to another AC to DC conversion at the devices. The currently used approach makes the systems highly energy inefficient.

An Inverter-less DC UPS designed at IIT Madras called (OGH), is intended to provide a far superior solution, which is designed to optimally use the solar power directly in DC form minimizing the losses due to conversions. This power is directly fed to the DC loads which are far more energy efficient as compared to the conventional AC loads [2]. The designed features of OGH make this system more energy efficient and economical as compared to the existing solutions.

Some of the highlighted features of this solution are as follows:

- Solar DC power is used directly to feed the loads in contrast to charging the batteries in current solutions. Avoids multiple AC/DC conversions.
- Appliances used are DC, which are mostly fans, lights, TV, other electronics and may be a refrigerator. This reduces the power consumption by 50%.

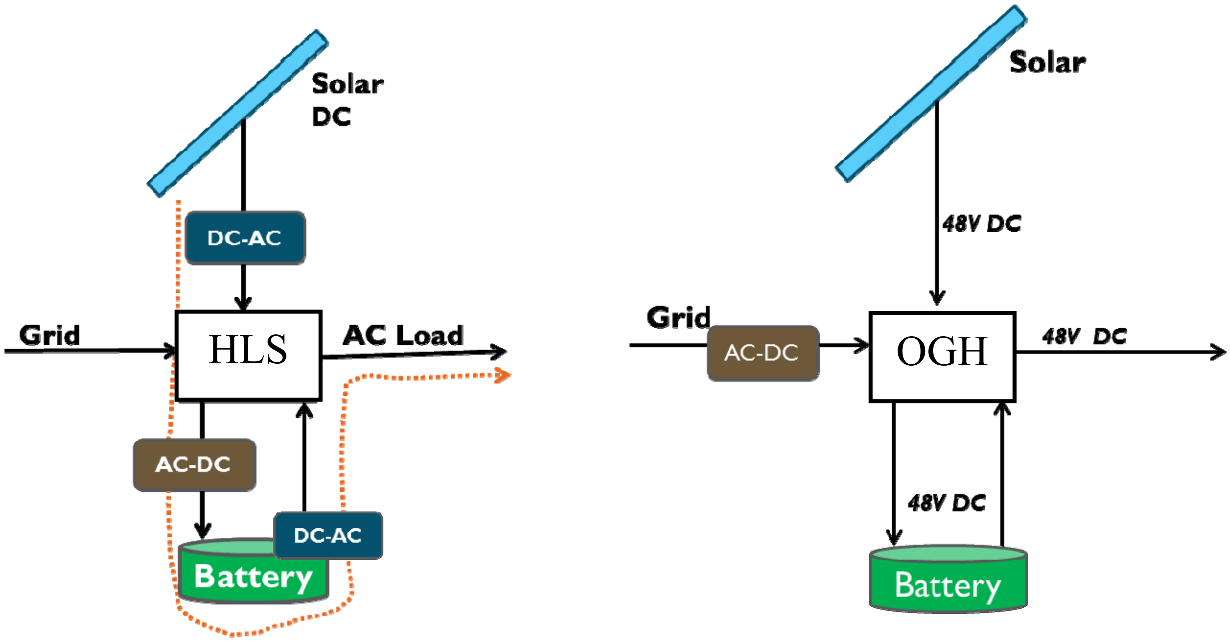

Fig.1: Concept of Solar Systems: a) Conventional solar Home Lighting Systems (HLS) b) Proposed Off Grid Home (OGH) System

- Works efficiently with or without the grid.
- Solar panel operates at maximum power point tracking (MPPT), and there is an optimal matching between
  Solar PV, battery and Grid.
- Metered solar generation and consumption, as well as overload protection. This permits shared systems between multiple houses. It also supports pre-paid billing.
- A separate emergency output permits drawl of minimum power for a considerable length of time, once the battery goes below a certain discharge level.

The rest of the paper is organized as follows. Section II presents the concept behind OGH. Section III provides some technical details of the OGH system; it also discusses the current policy and presents a brief report on deployment of OGH in off-grid homes. Section IV provides a comparison of proposed OGH system with available systems in the market.

II. PHILOSOPHY BEHIND OGH

Fig.1a presents the conceptual implementation of currently available solar systems in India. All earlier available systems are categorized as Home Lighting Systems (HLS). These typically use three convertors. The DC solar power-output is first converted to AC and synchronized with the grid; then when battery is used the AC power is converted to DC to charge the battery. Finally, the output DC power from the battery is converted to AC to power the loads. For low-power systems (typically 250W) deployed at homes, each of these conversions causes about 15% power-loss amounting to a total of almost 45% total loss. To this the battery losses have to be added. With the increasing availability of DC consumable appliances such as LED Lighting, Television and Computers, the situation worsens, as these further require another AC-DC conversion stage. This is a huge wastage of expensive Solar power.

The proposed system in contrast is energy efficient and does minimal conversion only once while converting grid AC power to DC at homes. The concept used for the OGH is as shown in Fig. 1b. The generated solar DC power is used directly to feed the DC loads and charge the batteries. As the output from batteries is also DC, there is no conversion required for feeding the DC loads. A smart technique is applied so that grid-converted power, the solar MPPT power and battery charging and discharging are almost at the same voltage, almost eliminating converter losses. In addition, the system also gives us the benefit of efficient energy consumption due to DC loads, and require no further conversion for driving such loads [3].

III. OGH SYSTEM

A. OGH Technology

The system is designed to integrate the power supplies from solar photovoltaic (PV) plant, batteries and Grid for powering the loads at homes. The block diagram of OGH is given in Fig.2. Prioritized power feeding is done through PV, followed by Grid and then the battery that is done based on per unit cost of these supplies. Based on the concept presented in previous section, the system supports direct feeding of DC loads.

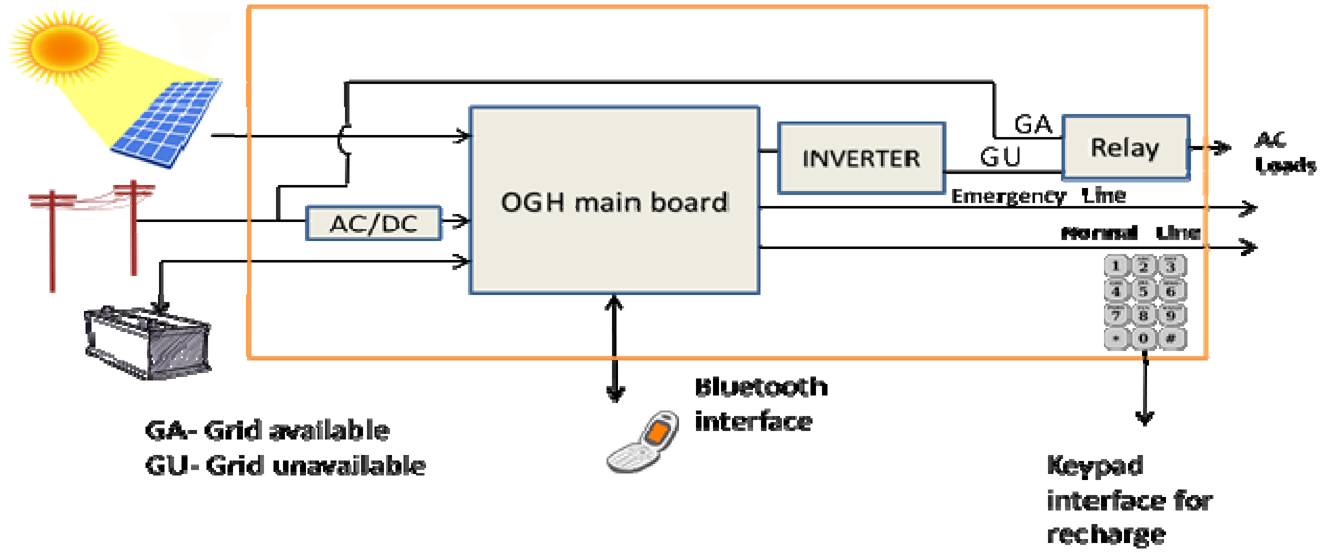

Fig. 2: OGH Block Diagram

The system works with maximum power point tracking (MPPT) algorithm for extracting the maximum output available from PV modules. OGH takes care of the fact that this system is designed for Off-grid and near Off-grid homes where powering

homes for longer duration even during the unavailability of Solar Power becomes crucial. For this purpose, the distribution of loads is carried on two lines in each home. The regular loads are fed through the Normal line while some low-power crucial loads are connected on an Emergency line. When neither Solar nor Grid power is available, the system continuously supplies power through the battery and continuously monitors the state of charge of this battery. Up to a certain threshold of this backup power, all loads on Normal line as well as Emergency line are supported. However, as the battery power falls below this threshold, the normal line is cut-off and only the loads on emergency line are supported. The emergency line is designed to continue to operate for another 48 hours after this state is reached.

Even though we recommend the use of DC load only, at times homes have some existing low power AC appliance which they would like to continue to use even when the grid-power is not available. As per the user request, it was decided to build a small inverter in the OGH to support up to 125W AC load with the total AC and DC load still confined to 500W. However, the system has an in-built intelligence to feed the AC loads directly through the Grid, when it is available and use the OGH-inverter only during load-shedding.

In addition, the OGH system provides pre-paid metering for billing and monitoring purposes. For a fixed duration of time or fixed number units, the system can be recharged. After the expiry of the due date or number of units charged, the system cuts-off the power to all the loads and generates alerts. The system is restored once the recharge is carried out either using a keypad interface or using a built-in Bluetooth.

Support for multiple types of loads, load segregation and prepaid metering are some of the advanced features that make OGH unique in contrast to other market products.

B. Policies and Deployments

Ministry of New and Renewable Energy (MNRE), Government of India defines systems to be deployed with subsidy / or for Government purchases [4]. The central schemes are implemented through State agencies like Tamil Nadu Energy Development Agency (TEDA). For defining the technical specifications of the systems, MNRE/TEDA largely get their inputs from the vendors. At the same time the availability of a particular technology in the market influences the normal policy formulation. Rarely a deep dive is undertaken for technical improvements and innovations. As mostly AC systems are prevalent in the market, they have been deployed in most of the Government funded schemes. Looking for proven systems and playing safe becomes a bottleneck for emergence of innovative ideas and technologies.

Besides vendors push to maximize subsidy and total sales and therefore suggest specifications which are non-optimal – for example over-specifications in terms of battery. As a result, either these schemes provide too little for a home (for example only one or two low-power lights), or become too expensive, never becoming commercially viable. They are deployed as long as subsidy exists. Developing an independent market-demand is rarely the end-goal. Continuing with such inefficient system configurations not only leads to wastage of public funds, but also makes it difficult for superior technologies to percolate in the market.

Once IITM came with this solar-DC technology, TN Energy Development Agency (TEDA) decided to break from this mold by piloting a few solar rooftop installations with innovative

Fig. 3: Some snap shots of OGH system deployment in completely Off Grid Tribal homes at Kundithal village, The Nilgiris, Tamil Nadu, India

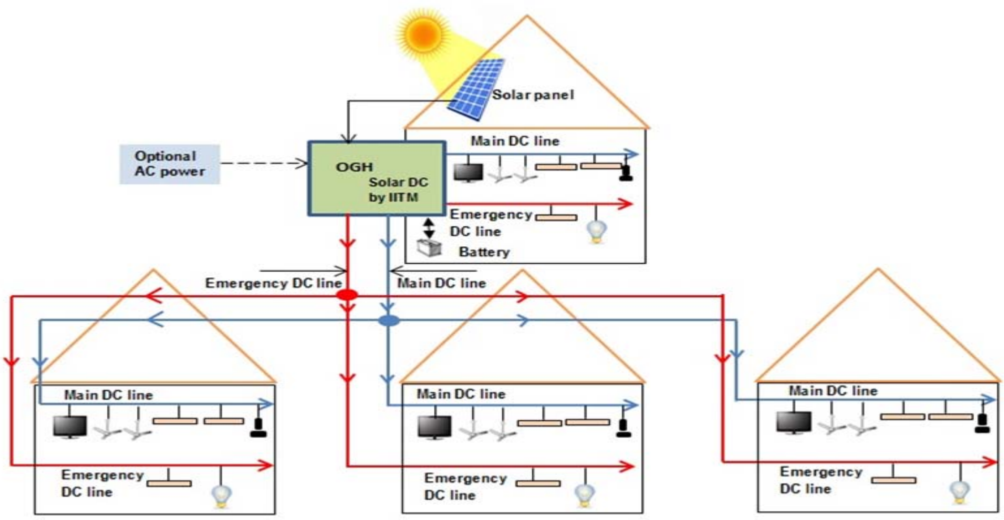

Fig. 4: Scenario depicting OGH Deployment in clusters

technologies in partnership with IITM. The hope is that, based on the learnings, governments could replicate it in mass scale.
The specifications for the systems deployed are as follows: 125 W PV panel, 800AH, 48V battery, one 18W LED tube-light, one 32W BLDC fan, one 5W LED bulb and one cell phone charger; this could be considered as the minimum need for a low-income household. Taken up by TEDA / IITM as a pilot project, this solution has been deployed at 20 homes in Kundithal, one of tribal villages in Gudalur, the Nilgiris District, Tamil Nadu.

Fig. 5: OGH deployment Sites

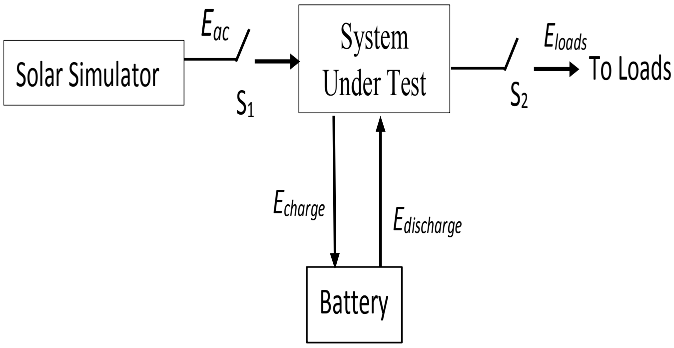

Fig.6: Measurement Set-up for OGH and HLS systems testing

This habitation never had electricity before. Some snap shots of this deployment are given in Fig.3. The villagers were overjoyed. One of the tribal women remarked: *"It is easier to cook with the light by our side. Earlier I couldn't place my utensils properly because of the dark, but now there is enough light for me to navigate through my cooking[1]."*

Apart from this, OGH system has also been deployed in 26 homes, one temple, one school and a community centre at Irrukam Island, Andhra Pradesh, India. Even at this place. people never had electricity at their homes and were thrilled to get DC devices working 24X7 in their homes. One of the beneficiaries expressed "*Our kids can now study in dark and we can carry our routine activities with much ease now[2]."* At places people are also asking for a TV. With solar panel of 250W and battery of 1800AH, we could add a 24" LED TV and a set-top box for DTH. This has been done at the community center at Irrukum Island.

OGH system supports home loads ranging from 100W to 500W. This system is deployed for a single home as well as for small cluster of homes when load requirement is less, subject to the maximum cumulative support load of 500W. The scenario of clustered approach of OGH deployment is shown in Fig. 4. This scenario was followed for both the deployments at The Nilgiris and Irrukum Island. The deployment sites are as highlighted in Fig.5

TEDA is also working with IITM to obtain a detailed feedback from the users on the functioning of the 100,000+ solar home lights systems provided over last 2 years. Systems with additional options with fans, cell phone chargers, TV etc. are being piloted so as to get a comparative evaluation for modifying the policy.

IV. COMPARISONS AND DISCUSSIONS

For comparison of OGH with existing systems, two HLS systems widely deployed by TEDA were tested. HLS system 1(HLS1) is typically deployed with 45W AC load while HLS system 2 (HLS2) is deployed with 27W DC load. HLS1 involves multiple AC-DC and DC-AC conversions and hence leading to high losses while DC HLS2 is relatively less efficient. Both of these systems charge the batteries which are in turn used to power the homes, making these systems work Offline. In contrast OGH is an Online Solar power system where the Solar power is directly used to feed the loads. For the deployments carried out at two places discussed in preceding section, the DC load provided per home, consisting of one ceiling fan, one tube-light, one bulb and one cell-phone charger, is about 65W; if the similar AC appliances were deployed, the load would work closer to 125W. This would push up the size of panels and batteries, if adequate storage is provided. So all the HLS systems deployed in Tamil Nadu have much smaller loads; fans could not be deployed (which are a necessity due to the extreme hot climate of Tamil Nadu) and only lights are deployed. Even with the higher loads of OGH, it supports better battery backup than other two HLS at full load. Further we have seen that OGH battery lasts double the time when we operate the BLDC fan at lowest speed and operate tube-light at the lowest intensity. This tuning of the loads does not give much reduction in energy consumption in normal AC fans and is generally not provided in normal lights installed with other HLS systems.

Though OGH provides several enhanced features over the existing HLS systems, major advantage of OGH system is its improved energy efficiency. End to end efficiency of a system is measured using the set-up shown in Fig. 5. The power generated by the solar panel is first stored in a battery (in this case Lead Acid battery). The stored power later drives the load. The system under test is first made to charge the battery from a fixed state of charge (SOC) to a certain higher SOC and then discharged till the time it attains the same fixed SOC. During charging of battery, the switch S_1 is closed and switch S_2 is open. Under this test condition, the energy consumed to charge the battery, E_{charge}, is measured. discharged through battery, $E_{discharge}$ is measured. From this setup, battery efficiency, η_{bat} is calculated as:

[1,2] Translated from Tamil in English

Then for discharging the battery, swtich S_2 is closed and switch S_1 is open. This makes sure that the load is powered only through battery. The energy

$$\eta_{bat} = \frac{E_{discharge}}{E_{charge}}$$

The system efficiency is measured as

$$\eta_{sys} = \eta_{MPPT} * \eta_{charge} * \eta_{discharge}$$

where η_{MPPT} is MPPT efficiency, η_{charge} is battery charging efficiency and $\eta_{discharge}$ is battery discharging efficiency.
Then, End to end Efficiency, η_{end}, for each system is calculated as:

$$\eta_{end} = \eta_{sys} * \eta_{\mathrm{bat}}$$

which is also equal to the ratio of energy delivered to the load, E_{loads}, to the energy expected to be generated by PV panel of a given rating, $E_{expeccted}$.

In practice, some of the solar-panel generated power could drive the load directly rather than going through the battery (when load is used in presence of sunlight). So the final values of end to end energy efficiency will be somewhat higher than the ones given in this paper. However the above definition is used to get a comparative measurement.

Calculated with this set-up, the first version of OGH gave 83% efficiency while with the improved design, it gives an efficiency of 88% (including 7% loss in battery). Two other available systems deployed by TEDA were examined, HLS1 gives an efficiency of 49% and HLS2 gives an efficiency of 65%.

Due to lower losses in OGH and efficient loads, the solar PV requirement to drive same loads would be reduced by a factor close to 2.5 as compared to a typical solar-AC system, deployed in off-grid homes. Similarly the battery sizing required to provide same amount of power would get reduced nearly by a factor of 2. The distinct features of OGH that make it technically efficient and economically better than other systems are:

1. Better Energy efficiency of the system as a whole
2. Better battery backup
3. Cost effectiveness

To conclude, use of DC power-lines at homes and use of DC appliances provide much higher efficiency as compared to the AC lines and appliances. Use of this could reduce demand on the grid. At the same time, it enables connecting solar panels and batteries directly to DC line avoiding convertor losses. This makes solar panel attractive and impact the supply side, as more and more homes start using it. The solar-DC system thus not only help bridge supply-demand gap, but also has the potential of making the nation Green. The OGH system design is dedicated to this objective.

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