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Harvesting maximal PV energy with fine grained energy distribution: An alternative to traditional PV systems in buildings

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ABSTRACT

The existing renewable technology in use, particularly solar PVs for homes and other buildings, is billed as a significant step towards providing more robust, secure and affordable electricity. However, unavailability of electricity buyback programs in many regions, and recent changes in buyback policies in some countries make solar costlier due to the need for extra storage in the system. To this end, we present our system called SMaRTI: Self-Managing Renewable Technology Integration. This system is mainly designed for places where the utility grid is available, but for various reasons any excess electrical energy cannot be put back onto the grid through buyback programs. In traditional hybrid or grid-tied PV systems with battery backup, the electrical energy from the PV and the grid are tied at the inverter output. However, in SMaRTI this tying up is carried out at multiple distribution points in the system, giving SMaRTI an opportunity to optimize the PV output more efficiently. By using SMaRTI, not only one can utilize up to 98% of electrical energy generated by PV system but also the cost of ownership is reduced by more than 40% over a ten years period.

1. Introduction

Buildings are the major consumer of energy, on average they consume about 40% of total energy output of a country [1]. Hence, it is important that renewable sources of power are available for them. Renewable energy technology is set to change the energy demand and supply situation in the world as it is clean and has a lower carbon footprint [2,3]. As the cost of renewable energy, especially solar photovoltaics (PV) has reduced immensely in recent years, there has been a surge in installation of solar PV around the globe. Although the cost of the solar panels has decreased, the overall installation and maintenance cost is still high due to batteries and their relatively short life span. As a result, the payback period of solar PV systems is long for most domestic and small commercial building owners [4]. One of the reasons for the long payback period is the unavailability of net metering and feed-in-tariffs by some utility companies that can help consumers to sell access energy generated during peak sun-hours [5,6].

Due to the unavailability of provision of net metering and feed-in tariffs, building owners have to buy huge battery banks to store access energy produced from renewable sources, which results in increase of the total ownership cost [7]. Even where feed-in tariffs are available, their rates are not often favorable to most building owners [8]. These battery backups waste a lot of electrical energy due to highly inefficient charging and discharging, especially during the night [9]. Due to this reason, consumers are hesitant to pay additional costs for inverters and short-lived battery backups [10].

There is also another interesting problem in the electrical distribution systems in some places. These places already have grid-tied meters installed. Electrical energy generated as distributed generation (DG) can be put back to the grid.[1] However, this two-way electrical energy flow cannot be used for net metering because the meters are configured to charge the consumer in both cases; when energy is supplied to the grid or supplied by the grid. Therefore, if one uses a grid-tied PV system and puts the excess electrical energy back to the grid, even then one is being charged. Historically, this type of metering was deliberately designed to stop the theft of energy and it is not possible to change these large number of meters in a short time.

In this paper, we discuss the design and development of a PV system that intelligently blends stand-alone and grid-tied system

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[1] Grid and Utility are used interchangeably in this paper.

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Table 1
Energy consumption of office appliances for working hours from 8 am to 5 pm.

Appliance	Quantity	Total power (kW)	Energy consumption (kWh) for 9 h (8 am–5 pm)
Fan	10	0.25	2.25
Computer PC	15	2.0	18
Laptop	10	0.5	4.5
Printer	1	0.3	2.7
Scanner	1	0.03	0.27
Water dispenser	2	1.2	10.8
Lights	20	0.6	5.4
Total		4.88 kW	43.92 kWh

in a way to exploit the electrical energy from PV during daytime with minimal battery requirement. We have named this system as SMaRTI (Self-Managing Renewable Technology Integration) and it mostly caters to small-scale commercial consumers and building owner that consume most of their electrical energy during daylight hours. Hence, this system is naturally suitable for tropical regions where sufficient daylight is available during normal working hours throughout the year, especially where it is available for 3.5–6 h a day [11]. SMaRTI uses simple power electronics and intelligent algorithm to provide a low-cost alternative to standard hybrid PV installations. Furthermore, the system proposed in this paper possesses the flexibility to integrate with most types of electrical wiring layouts seamlessly. Therefore, the system can be configured and optimized for virtually any building where electricity demands are high during the day time.

2. State of the art systems

A lot of research work has focused on the optimization of maximum solar energy utilization. This includes improvement of solar cells [12], better inverter design, extracting maximum power from PV modules through better charge controllers [13], efficient storage of solar energy using improved battery design [14], algorithmic improvements such as ant colony optimization, artificial immune system, genetic algorithm, game theory, optimal designing of PV systems [15–17] and so on to improve efficiency of overall PV system design [18–20]. Different types of Solar PV materials are also discussed in [21], such as building integrated photovoltaic thermal (BiPVT). Along with that, the indoor environment analysis has also been examined in [22], which demonstrates that the BiPVT systems can be used in a much more efficient and economical way. However, while all these approaches are improving the optimization of the PV systems, our approach is to maximize the electrical energy utilization of PV systems when feed-in tariff or net metering is not an option, but the grid is available all the time.

Our approach is to modify the PV system design by tying up electrical energy from grid and PV at many distribution points, rather than just at inverter output. Through our experiments, we show that this approach works better and to our knowledge, this methodology is not found in the literature.

There are usually four standard models of utilizing PV systems: off-grid PV systems with batteries, grid-tied PV systems with batteries, grid-tied PV systems without batteries and direct-coupled DC PV systems. Fig. 1 shows a typical hybrid solar PV system which is tied to the grid and uses batteries. Components needed for installation of such PV systems include PV modules, charge controllers, inverters, energy storage devices, a supplemental power source for days of high cloud cover [23–28].

Conventionally, to design a hybrid solar PV system, a few steps should be performed which include:

- Calculation of demand of power consumption.
- Optimization of power demands.
- Sizing of battery banks.
- Calculation of equivalent peak sun hours (EPSH).
- Sizing of solar PV system.

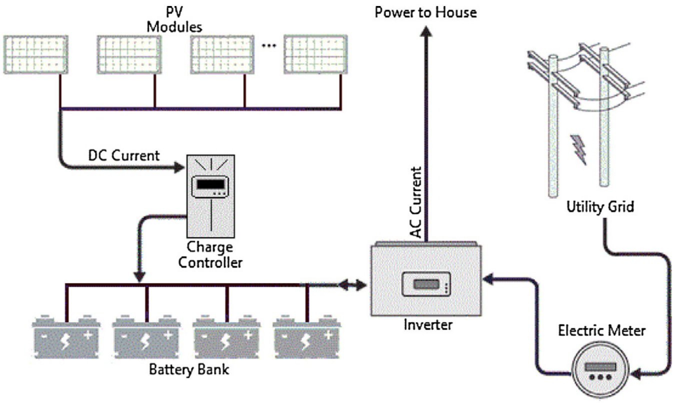

Fig. 1. A typical hyrbid solar PV system.

The average daily solar insolation in kWh/m^2 per day is measured in equivalent peak sun hours also referred to as EPSH. The EPSH value for a particular geographical place is used to approximate the average sun hours throughout the year. For example, 5.6 kWh/m^2 EPSH means that on average 5.6 h of solar energy will be available at 1 kWh/m^2 every day throughout the year [29,30].

To understand the motivation behind our paper we first discuss a case study where we install a solar system in a typical small office building. The first requirement we assess in installing this PV system is its sizing, which is based on the users' requirements. Here, all devices need to be available for nine working hours (8 am–5 pm) in a day on solar to the maximum extent while reverting to the Utility supply only as a backup. Following is the outline of electrical energy requirements of a small office building.

Table 1 provides an estimated value of watt hours needed per day for solar PV system at 43.92 kWh for a duration of 9 h. Given that we can only utilize an average of 5.2 h EPSH (Equivalent Peak Sun Hours) of solar energy in Lahore, Pakistan. A typical solar PV installation would only produce 20.96 kWh leaving us to cater for another 3.8 h of office timings. Keeping in view the inefficiencies of solar PV system as discussed later, we estimate that we need to store another 23 kWh of remaining energy on large storage batteries using extra solar PV panels. The summary of the cost of this solar PV installation is given in Table 2.

From calculations shown in Tables 1 and 2, the designed solar PV system generates about 44 electric units daily and saves $3200 annually. With an overall cost of $26,000 and savings of $3200 per year, the average payback period of this solar PV system is estimated to be nine years. These calculations are based on several aspects including the life of inverter and charge controllers which is roughly seven years and storage batteries that have 1.4 temperature derating factor with 50% depth of discharge [31–33]. We also

Table 2
Cost of PV system for given appliances in Table 1.

Solar PV estimation constraints	Units	Cost(US $)
Total power consumption hours required	9 h	
Solar PV peak watt (Wp) Required	10.701 kWp	$16,200[a]
Backup (watt-hours) required during no sunlight	22.965 kWh	
Battery bank required (Ah), maintenance cost included	5358 Ah at 12 V	$8000[b]
Other equipment (charge controller, inverter, wiring and installation charges)		$2450
Total cost		$26,250

[a] Cost of 1 W is $1.5.
[b] Cost of 100 Ah gel battery is $150.

take into account losses by maximum power point tracker (MPPT) controller at 10%, power electronics components losses also at 10% and wiring losses are 5%. In addition, we considered the overall efficiency loss per year is 0.7%.

In summary, to cater for the 23 kWh of energy, an extra 60% of capital cost is required to buy batteries, panels, high power inverter, wiring, etc. The cost of this over-provisioning in the system is considered a big prohibiting factor for end users to install renewable energy systems in their premises. Hence, the goal of this paper is to reduce this upfront capital and recurring maintenance cost to make the system more viable.

3. Motivation and problem statement

In the previous section, we discussed the details of deploying traditional solar PV systems with a practical case study and finding out that the upfront cost is a prohibitive factor. In this case study, first we observe that when more electrical energy is required than the EPSH can provide, the cost of solar PV system becomes high due to extra solar cells, battery backup, and associated equipment. Secondly, we can conclude that battery replacement cost increases the overall payback period of the PV system and consumers do not consider it to be a viable option, relying on relatively expensive electricity from the utility. Consumers do not realize that the upfront cost of deploying a solar PV system may be higher, but over a long time, PV system is still a cheaper option.

Although, PV system is the greener option, it is usually not considered for energizing buildings as common practice among the consumers. For example, take the case of an office building which requires most of its electricity during day time as shown in Table 1. This building requires 0.16 million units (in kWh) over a ten years period. If the electrical energy from the utility costs an average of $0.24 per kWh over this period,[2] then the total cost of electrical energy will be $38,474. For a traditional PV system, the upfront and maintenance cost is around $26,250. Over a ten year period, some 30% of electrical energy from the utility costs around $11,542. Thus, the cost per kWh over a ten year period is around $0.23. Using SMaRTI, the upfront and maintenance cost of the system is around $16,838. In ten years around 10% of electrical energy from the Utility costs $3,847. After adding all that up, a single kWh of electrical energy using SMaRTI costs around $0.13. In summary, over a ten year period utility costs $0.24, traditional PV costs $0.23 and SMaRTI costs around $0.13 for a single kWh on average. The details of these calculations including cost and savings after deploying SMaRTI are discussed in Table 3 and in subsequent sections.

3.1. Operational issues with traditional solar PV systems

The higher cost of ownership for traditional solar PV system can be reduced in regions where buyback programs are available, but where buyback program is not available we are faced with some challenging operational issues with traditional PV systems and we need to address them. A traditional PV system is designed for usage throughout the year, as well as for maximum usage situations to make it workable for an upper bound of power consumption. Also, it has fill-in for the intermittent periods when cloud cover and other environmental factors such as fog reduce solar generation. For these reasons, PV system is over-designed to create a buffer even for the shortest winter days. However, on longer days during summer this extra PV provisioning is not utilized optimally and excess generation is lost.

Fig. 2 shows the solar insolation graph for a 4.88 kW PV system on a typical sunny day in July. The total electrical energy that can be produced by this PV system is 16 kWh as shown in Fig. 2a. But practically, only 13 kWh is harvested by a typical solar system with batteries which is about 80% of the ideal achievable electrical energy as shown in Fig. 2b. If we remove batteries, it can only harvest 11.5 kWh of electrical energy, presenting a further loss of about 30% of the electrical energy as shown in Fig. 2c.

Our proposed system is designed to harvest this otherwise lost electrical energy to the maximum possible extent. A typical MPPT inverter and charge controller charges batteries from both the utility as well as the electrical energy from solar. Since batteries are kept fully charged during the pre-dawn period by the utility in a traditional hybrid PV system, solar energy consumption does not start until some time after the sunlight is available.

Moving on from our discussion of a generic 4.88 kW system, we present a description of some practical issues with the solar installations currently deployed in Pakistan, and this goes for some other developing countries as well [36]. Note that there is no option available for net metering or feed-in tariff as policies are not implemented in Pakistan for smaller consumers of 10 kW or less.

Ideally, a system should rely on electrical energy from solar as the primary source to meet electrical energy requirements of the building. Any leftover electrical energy from the solar source can be used for battery charging. The role of the utility only becomes important in foggy or night-time scenarios, when solar power is not available. The utility keeps batteries charged for backup just like uninterruptible power supplies (UPS) to provide electricity during night time or when solar energy is not available. But practically, it does not happen which makes an interesting problem in the installation of PV system as explained in rest of the paper.

Fig. 3 shows detailed measurements of power consumption of an installed PV system of 4.88 kW. Red lines in the middle show 2.44 kW as a reference line for calculating the average consumption. Most of the time, the average power consumption is less than 2.44 kW and exceeds only a few times on a typical day. In addition to this, it can be notices that that how much electrical energy being utilize out of the total harvestable electrical energy from PV system in a month. In these graphs, we have drawn a 2.44 kW reference line to represent maximum practical energy that can be harvested from a 4.88 kW system. It is interesting to note that 90% of the electrical energy needs of this building during daytime can be fulfilled by a much smaller PV system. For example on Day 16, the utilization is not more than 60% of the total electrical energy that could be harvested, and 4.88 kW is an over-provision for this building.

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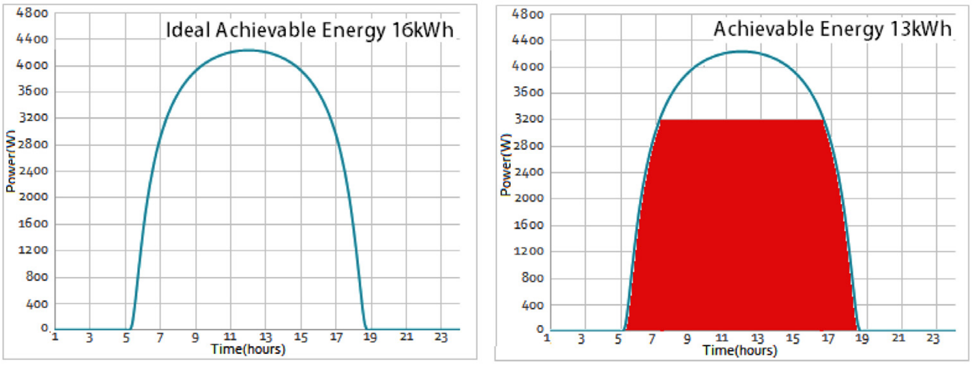
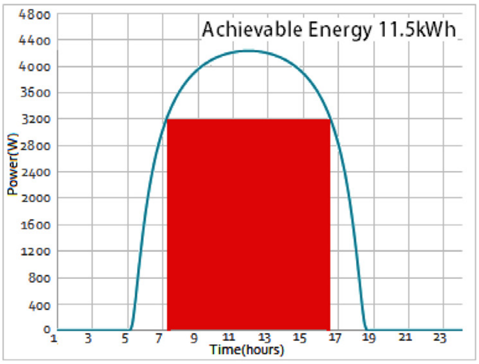
[2] We have assumed the cost of electricity at $0.16. After adding inflation of 8%, the average price of electricity for ten years is $0.24.



(a) Average solar ideal insolation. (b) Practical usage with batteries



(c) Practical usage without batteries.

Fig. 2. A comparison of usage of solar PV system with and without batteries.

In the zoomed view, a curve of the ideal achievable electrical energy is shown in orange color. The unshaded part of this graph is unutilized solar energy. Ideally, the system should charge the batteries from the shaded region. But practically, the total utilization of solar energy is not achieved because of a design of the inverters and charge controllers. In short, the building utilizes only 50% of the electrical energy from solar. This problem of unutilized solar energy is also discussed in [36].

In summary, we would like to make the case that the traditional solar PV systems such as hybrid PV are not very useful in places where buyback programs such as net metering or feed-in tariffs are not available. Hence, we propose SMaRTI, a system that is optimized for places where energy buyback programs are not available.

4. Design of SMaRTI

Hybrid PV systems couple PV with utility at the main point which is usually at the inverter output from where electricity is distributed to the whole building. The inverter distributes electricity to the whole building. We believe this is not a proper approach and we cannot perform certain optimizations in the system for maximum energy utilization. Therefore, we distribute this coupling

Table 3
Analysis of the cost of ownership of utility, traditional PV and SMaRTI systems over a ten year period. This table uses the same set of appliances as given in Tables 1 and 2.

Attribute	Utility		Traditional PV		SMaRTI	
	Utility	Solar	Utility	Solar	Utility	Solar
Electricity share	100%	0%	30%	70%	10%	90%
Avg. kWh usage (per day)	43.92	–	13	30.74	4.39	39.53
Total units consumed in ten years (kWh)	160,308	–	48,092	112,215	16,030	144,277
Batteries cost	–	–	–	$8000 (5358 Ah)	–	$1900 (1340 Ah)
Solar panel cost[a]	–	–	–	$16,200 (10,701 Wp)		$10,500 (7000 Wp)
SMaRTI related equipment cost	–	–	–	–	–	$300
Inverter and other equipment Cost	–	–	–	$2450	–	$2338
Total capital cost upfront	–	–	-	$25,996		$15,038
Maintenance cost over ten years	–	–	–	$254		$1800
System cost	–	–	–	$26,250	–	$16,838
Ten years electricity bill from utility	$38,474	–	$11,542		$3847	–
Total cost of ownership	$38,474	–	–	$37,792	–	$20,685
Per unit cost of each system	$0.24			$0.23		$0.13
Comparative savings in cost of ownership				−3%		−44%

[a] The kWp is the nominal power or kilowatt peak. PV modules are rated in kilowatt peak, which means peak power. This value specifies the output power achieved by a solar PV module under ideal solar irradiation; 1 kW/m^2. We require 10 kWp for a 4.88 kW system [34,35] in traditional solar PV system for a building in Tables 1 and 2. In SMaRTI, 7 kWp is needed for the same building because it utilizes the maximum electricity produced by solar PV modules and fulfills the shortfall using electricity from the utility. Note that the total electricity requirement in the building is kept constant for both systems.

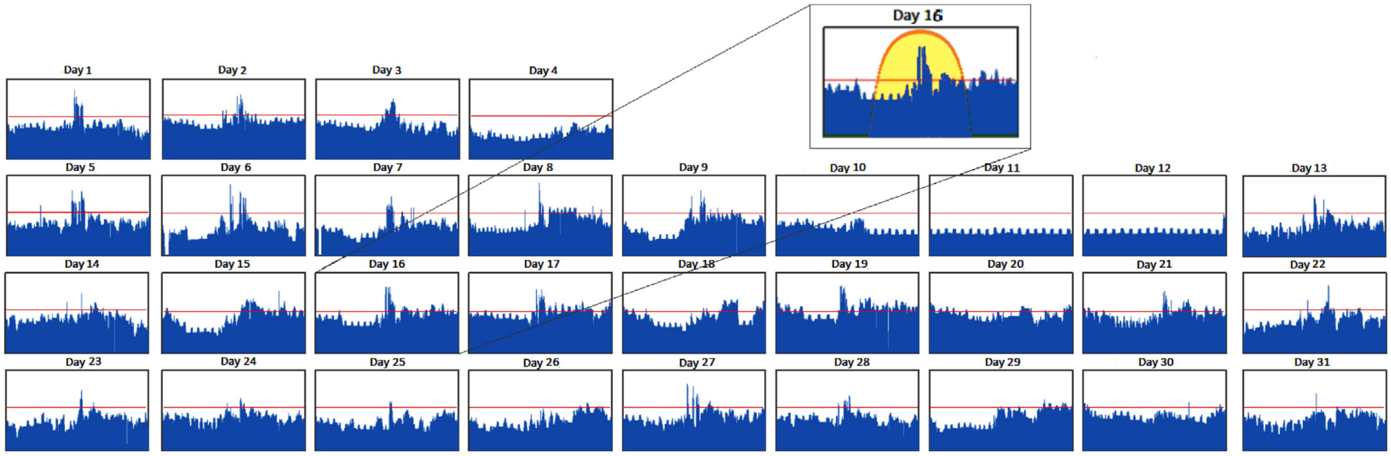


Fig. 3. Power consumption of a building during the whole month of August. All charts scale from 0 to 4.88 kW (average power over 7-min interval). Line in the mid of each chart shows the installation of proposed technique using a 2.44 kW solar power system.

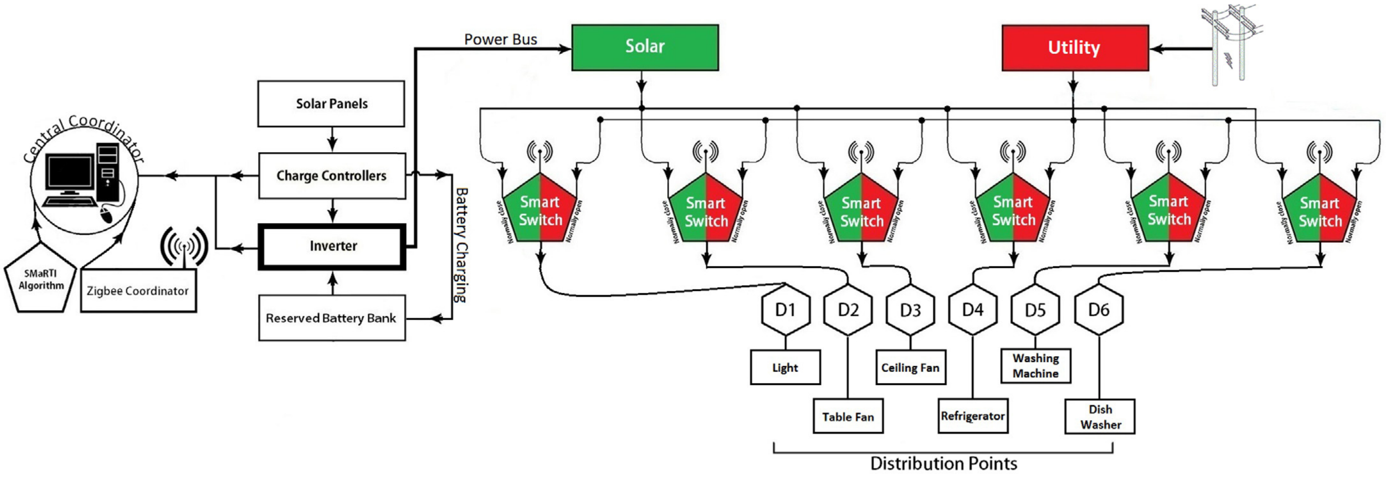


Fig. 4. Proposed solar PV system block diagram.

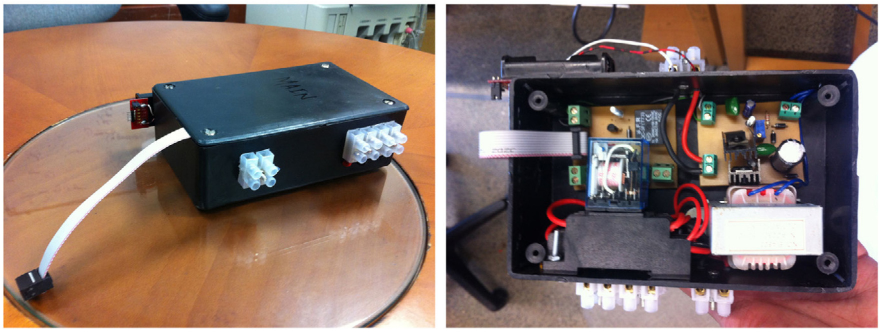
from one point to multiple distribution points (DP) in the building. In our proposed system, both the sources of power; PV and utility are provided to each DP individually and the decision to draw the electrical energy from either of the source is taken at the DP level. This approach also solves the problem of intermittent nature of solar insolation and its effects on energy use as presented in the Evaluation and Discussion sections.

The conceptual design of SMaRTI lies between the hybrid and off-grid PV systems as we take draw electrical energy from both PV and utility at a multiple DPs in the building and not just at inverter output only. Fig. 4 shows the overall architecture of our proposed system.

4.1. Smart switch and home area network

Smart switches are installed at different DPs in the building to control the flow of electrical energy from one of two sources; utility or PV. A single DP may have a single medium size load or multiple small loads with one smart switch. Other than controlling the flow of electrical energy from either of the two sources, a smart switch measures the instantaneous power of being used at all DPs and reports a central coordinator to switch between the sources of electricity and finally make the physical change over. Fig. 6 shows the main components of the smart switch. A smart switch consist of three main components. **Zigbee module for communication:** A Zigbee module in smart switch communicates with the coordinator node and receives signals to shift the electrical energy source of the DP. **Relay for switching purpose:** Both mechanical and solid state relays(SSR) can be used for the on/off changing overs of the DPs and to change over between the power sources. **Circuitry for measuring instantaneous power:** An electrical energy sensor for measuring instantaneous power and wirelessly communicating it to a central coordinator node. Reporting instantaneous power to the central coordinator node is performed every second. The power measurement is done by low-cost Hall-effect current sensor cheaply available in the market bringing the overall cost of the smart switch down to few dollars [37]. The final fabricated smart switch is shown in Fig. 5.

All the smart switches along with the central coordinator node, form a home area network (HAN). This central coordinator node receives power consumption information after each second from all the smart switches. Other than instantaneous power information from all the smart switches the central computer also receives live information of PV generation after every second using DC current measuring sensors attached to PV modules. Together, all these data values create the input set for the SMaRTI algorithm to run. The SMaRTI algorithm then decides how and when to make a change over at various DPs.



(a) Smart switch package. (b) Smart switch circuitry.

Fig. 5. A final fabricated model of smart switch.

4.2. SMaRTI algorithm

As mentioned earlier the SMaRTI algorithm is used for switching devices. The inputs to this algorithm are the instantaneous power consumption of the DPs, live PV output, and daily sunrise and sunset calculations based on time of the year and weather forecast.[3] The SMaRTI algorithm starts working at sunrise when all the DPs are drawing electricity from the utility. After sunrise, SmaRTI constantly checks for the PV output and as soon as the PV output matches with the power consumption of one of the DPs it switches the source of that specific DP from utility to PV. It continues to check for PV output, and as soon as the PV output is capable of accommodating another DP with a matching load, it is switched to PV. The decision of shifting a DP from PV to utility or vice versa is taken every 7 min. On a sunny day, most of the DPs are shifted to PV before midday. After midday, when the PV output starts to go down, SMaRTI begins to shift DPs back to utility and this process continues until sunset. After shifting all DPs back to utility, SMaRTI goes to sleep mode until next morning. Fig. 7 shows the working of SMaRTI on a building with six DPs (D1–D6). Section 5 discusses this figure and evaluation of SMaRTI in depth.

Algorithm 1. SMaRTI algorithm.

```
Input: Solar PV generation, power consumption of DPs, weather
       sheet
Output: Intelligently utilizing the solar PV power generation up to
        maximal level
initialization;
update currentTime;
while (1) do
    if $currentTime > sunset \| currentTime < sunrise$ then
        run all DPs on Utility;
    else if $solar\ PV\ generation = 0$ then
        run all DPs on utility;
    else if $solar\ PV\ generation > sum\ of\ power\ consumptions\ of\ all\ DPs$ then
        run all DPs on solar;
    else
        run PV Optimization Algorithm
    end
end
```

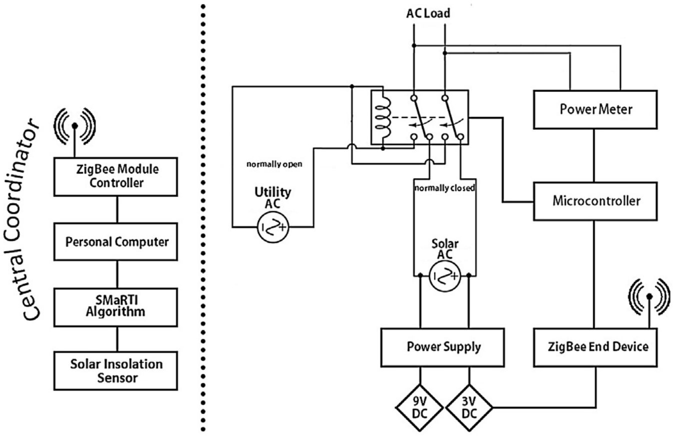


Fig. 6. Smart switch block diagram.

PV optimization algorithm: As the power profile of DPs may vary during the day we develop a PV optimization algorithm to optimally utilize the electrical energy from PV based on the power profile of the DPs at any given point in time. This algorithm is invoked as part of SMaRTI and is invoked to make the decision of moving the source of electricity of DPs. This algorithm is similar to

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[3] AccuWeather Inc. http://www.accuweather.com/downloads.asp (retrieved October 2015)

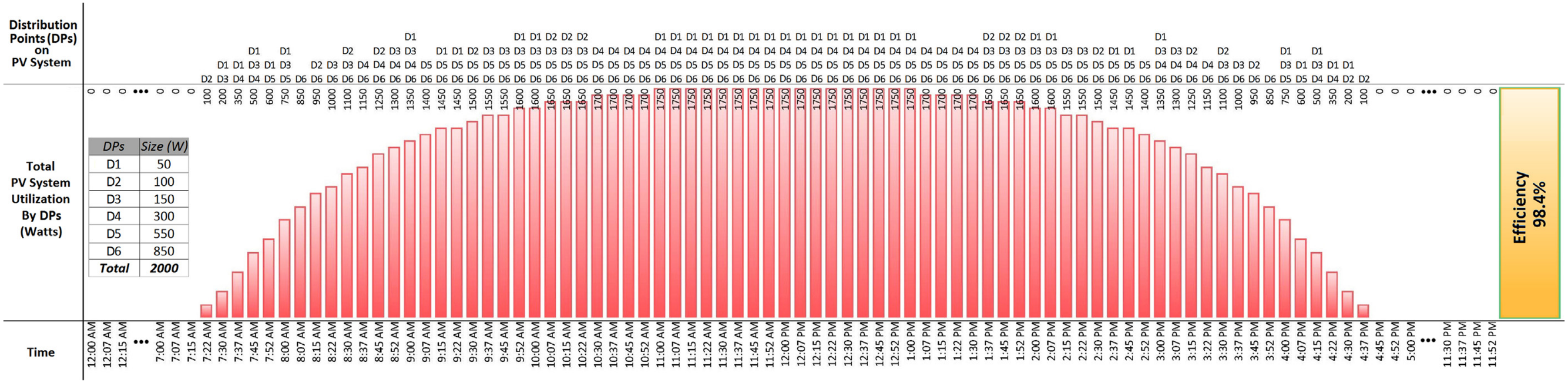

Fig. 7. Solar PV utilization using six distribution points (DPs).

the 0-1 knapsack problem. Following is the objective function of DPs of this algorithm.

maximize

$$U = \sum_{i=1}^{n} p_i x_i, \tag{1}$$

subject to

$$\sum_{i=1}^{n} s_i x_i \leq c,\ i \in N = \{1, \ldots, n\}, \tag{2}$$

where

c = total solar power available at specific time
s_i = size/combination of DPs i
p_i = power(W) of DP i
$x_i = \begin{cases} 1 & \text{if DP } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$

If we increase the number of DPs, the load on individual DP will decrease, resulting a better control and efficiency. This is because when power consumption of each DP is less, more area under the ideal insolation curve can be utilized. But on the other hand, the cost of the whole system will also increase because we need more and more DPs. Algorithm 2 explains the design of PV optimization algorithm.

Algorithm 2. PV optimization algorithm.

```
Input: DP[n]
Output: Fitting DPs according to available solar PV generation
initialization;
var adder = 0, i = 0;
while (i <n || adder <total solar PV generation) do ;   /* From eq (1) */
    if DP[i] <total solar PV generation then ;          /* From eq (2) */
        Switch DP[i] to solar;
        Adder += DP[i];
    end
    i++;
end
```

5. Evaluation

The evaluation of our proposes system is done three stages and is described as follows. For our first evaluation, we have used SMaRTI on a test building with 2–3 kW electricity requirements. For these energy requirements, vendors would suggest a system with peak ideal capacity of 4.88 kW, but we have done this with 2.44 kW solar PV system. First of all, Fig. 7 shows that we have divided the load of our test buildings into 6 DPs with varying loads of 50-850 W. For illustration purpose, we decided to run decision making cycles of power sources every 7 min. This time can be increased or decreased from thirty seconds to an hour. Of course, the lesser the duration of the time period, the better the utilization will be. But decreasing the time can harm appliances and reduce the life of smart switches. Practically, switching happens so fast that most running loads do not notice.

For one day experiment that starts before dawn when all DPs draw electrical energy from the utility at dawn. The system starts shifting the DPs to PV using smart switches when the sun is available. First shift happens, at 7:00 AM when D2 needs 100 W of power is shifted to PV power. At 7:30 AM, sufficient electrical energy is available for both D1 and D3 with combined power requirements of 150 W. At this point, D2 is changed over to the utility and D1 and D3 are put on PV. At around 10:00 AM the maximum number of DPs are shifted to PV, and stays until about 1:00 PM. After 1:00 PM, PV output starts to go down and DPs are shifted back to utility depending on the PV energy available at that particular time. In the end, by using SMaRTI 98% of the energy is utilized as compared to the traditional approach which is around 50–60%.

The second stage is evaluation of this system over the twelve month period. We run simulations on all typical days of the months for a year by using fine-grained DPs. Fig. 8 shows the DPs results for sample days for twelve months. It can be observed from this graph that the system can utilize about 96-98% of electrical energy with six DPs throughout the year.

In the third stage of evaluation, instead of using vendor-suggested PV system of 4.88 kW, we practically implemented a 2.44 kW PV system as proposed by our methodology. The main objective was to empirically confirm that a 2.44 kW solar PV system would be enough for this building. We monitored the working of this system for over one year using eGauge real-time power monitoring and reporting system[4]. The results of this yearlong experiment were analyzed and Fig. 9 shows the results summarized for one sample week only. In this figure, the area under blue line indicates the electrical energy from utility where as the area under the green line shows electrical energy from PV. Furthermore, the red line shows maximum electrical energy that PV system can produce. It is clear from the figure that only for about 10% of the time during the daytime hours the system shifts some of the load to the utility. Table 3 shows that SMaRTI based solar PV system uses electrical energy from PV 90% of the time where as in traditional solar PV systems 70%. Also, the cost of our SMaRTI based solar PV system is much less than the traditional solar PV system.

6. Discussion

In our proposed PV model, two major questions require some discussion. Firstly, not all days are sunny days and are there a backup plan that provides electricity during low solar energy hours? Secondly, what would be an efficient way to distribute the total load among DPs and how many total DPS should be installed?

To solve the first problem of ephemeral solar outages due to clouds etc., we need a minimal battery backup that would give a 10–15 min buffer. Only if the PV output is constantly decreasing

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[4] Live reporting site for SmaRTI based solar PV system. http://egauge7568.egaug.es/ (accessed online on April 7, 2017)

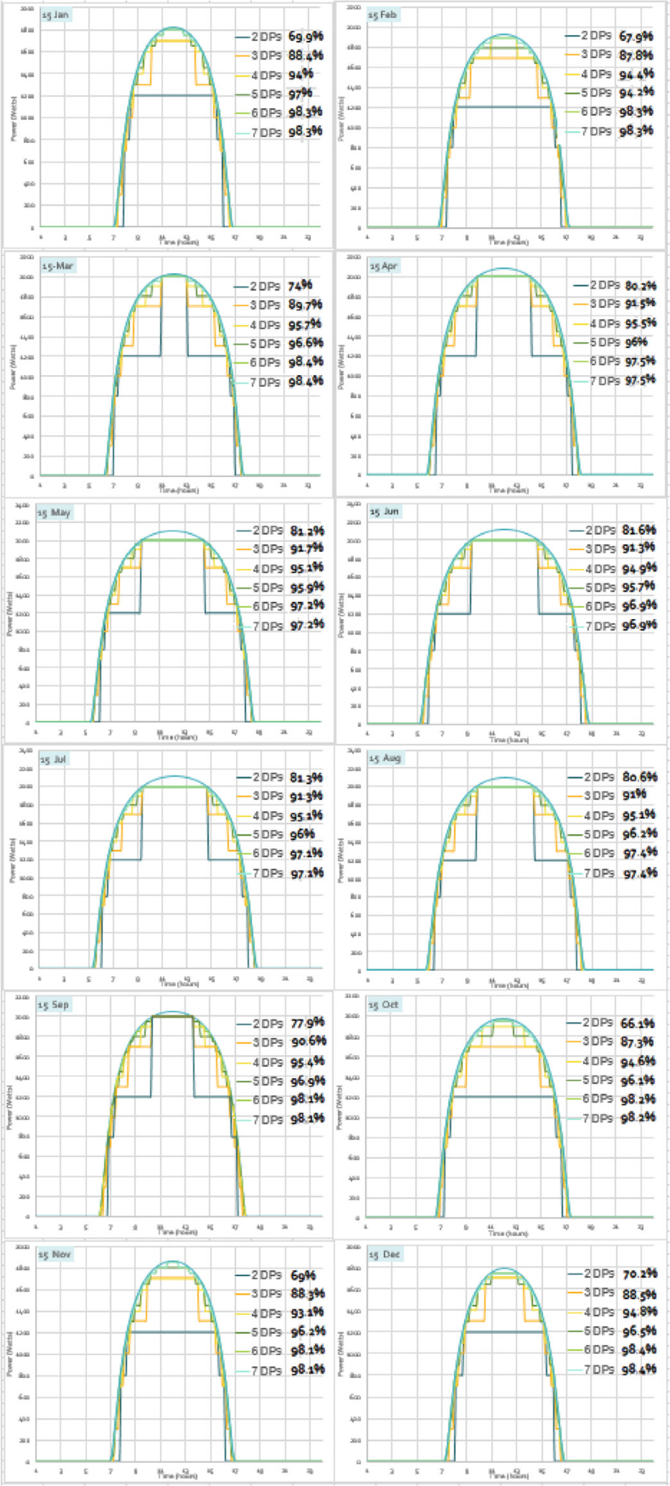

Fig. 8. 12 random days of year showing efficiency with different number of distributions points (DPs).

for longer times, the SMaRTI algorithm will switch some of the DPs back to the utility and will continue to do so if the PV output reduces further as given in Algorithm 1. With a 15 min battery backup included, the system will try to utilize PV to the maximum at any given time and any remaining load will be shifted to the utility.

For the second question, the number of DPs to be included in the design depends on many factors. The first limiting factor is the cost that the consumer wishes to spend on DPs with a smart switch. Hence, the more the DPs, the number of smart switches shall be needed. For a SMaRTI algorithm to run, the minimum requirement in our system as mentioned earlier is at least two DPs with smart switches.

The second factor is how many changes are required in the existing electrical layout of the building. Some buildings have all electrical connections from the mains distribution board. In this case, we can setup one DP, for example, for devices that need to be switched on all the time like a refrigerator, water dispenser, etc. and another DP we may have for devices that are there in the system, but their use is unpredictable and so on and so forth.

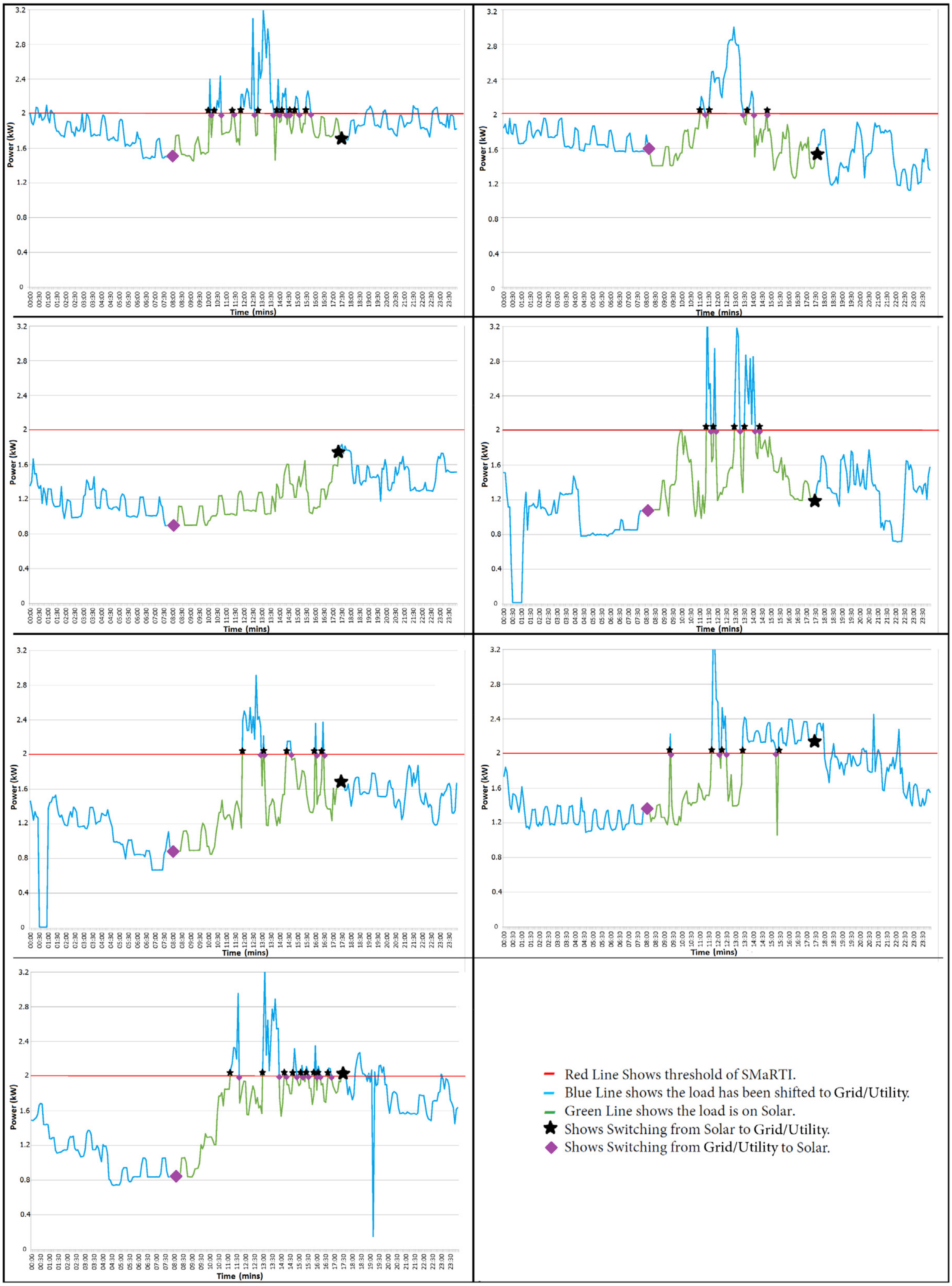

Fig. 9. One week power consumption details using SMaRTI based solar PV system.

7. Conclusion and future work

SMaRTI system proposed in this paper is maximizing electrical energy utilization from PV while keeping the upfront and maintenance cost to a minimum. The primary consumers of such a system are owners of almost every building where the electricity needs are greater during the daylight hours. This includes education institutions, small-scale commercial establishments, daycare centers, workshops, offices, etc. In its current form, our approach is mostly feasible for countries and regions between the tropics. This is because the assumption of our system is that the electrical energy from PV is available throughout the year during 8 am–5 pm working hours.

However, in our approach, we took many assumptions that necessitate further work in this area. Our assumption is that the DP load profiles are within a reasonable range. This is not true in many systems because power profiles vary a lot at times and further work is needed to handle such power profiles. Varying PV output because of extended periods of clouds and fog are also not discussed in this paper and needs to be researched further. One area where we can further reduce the cost of the system is the hardware of smart switches. At this time we are using Zigbee-based wireless smart switches. However, if all the switches are installed on the main distribution box of the building, as is the case in many traditional buildings, then a wireless system is not needed, and a wired system of smart switches will reduce the cost of HAN. Another area of interesting research is an extension of SMaRTI to a neighborhood. In such a case the algorithm needs to be scalable if this extends to an entire neighborhood. Besides scalability the fairness and privacy issues of electrical energy sharing in a neighborhood also needs further work.

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