Analysis of a Residential 5kW Grid-tied Photovoltaic System

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Abstract---**A grid-tied photovoltaic (*GTPV*) in conjunction with the proper energy storage system, have the potential to increase electrical power quality and reliability. This paper highlights the key dynamics behind GTPV energy storage sizing. Brief assessments on the merits of energy buffers for solar GTPV are presented. Also presented is an economical framework that may help policy makers assess all the benefits in order to manage the trade-offs intrinsic to renewable technologies. Study results showed that 245*Ah* and 2.5 *kAh* buffers were needed to produce 6 *kWh* per day for 30 minutes and 60 *kWh* per day for 5 hours, respectively. Results also revealed that the "*customer-generator*" GTPV system has cut the electricity bills significantly down, 36.45 percent, throughout the study year.**

Index terms— **Compensation, energy storage systems, Fallon, grid-tied photovoltaic (*GTPV*), renewable energy, variability**

I. INTRODUCTION

The sun is the basis of all forms of energy (*thermal or electrical*) in the solar system. It is a well-known fact that solar energy is the most abundant and cleanest renewable energy source available. Today's technology can harness solar energy for a variety of uses, ranging from domestic to a large-scale commercial use. Yet, solar photovoltaic (PV) makes up only a small portion of the US' power generation capacity, although it has grown significantly over the last two decades. Some entities, such as the Solar Energy Industries Association (SEIA), has reported that PV installations in the nation grew by 30 percent (1.4 GW) in 2014 and more than 12 times the amount installed five years ago, bringing the total amount of PV operating in the U.S as of year-end 2014 to 6.2 GW [1].

As the integration of PV increases, the grid operators face a variety of new challenges associated with variability and stochasticity of solar resources. Transmission constraints in conjunction with the non-capability of the conventional power plants to follow random renewable generations are the major drivers hindering a large-scale solar penetration [2]. Numerous experiments investigating the challenges and advantages of grid connected PV systems have been conducted in the past [2]–[7]. A grid-tied photovoltaic (GTPV) system has the potential to reduce the electrical power bill over the course of its lifetime for a "*customer-generator*" owner. In addition, any electricity surplus, exceeding the regular household usage goes back to the electric utility [8]. In most case, a check is issued by the latter to the home owner for compensation purposes. This paper proposes energy storage to address variability issues of a residential 5kW GTPV system. Additionally, technical feasibilities and economical compensations were investigated for a period of one year under Fallon, Nevada weather conditions.

II. CHARACTERISTICS OF THE GTPV SYSTEM

Typical grid-tied PV system consists of PV modules connected either in series and/or parallel to an inverter that converts DC electrical power to AC power. The output of the inverter is then tied to the electric grid. The system under investigation is a polycrystalline silicon (*p-Si*) technology, which was first introduced to the market in 1981. In contrast to monocrystalline solar panels, p-Si solar cells do not undergo the Czochralski process. Therefore, their process is not only simpler, but also much cheaper at the expense of a less efficiency, ranging from 13 to 16 %. The PV array used in this investigation has two strings of eleven modules. Each module is rated at 235W with a total of sixty cells per module. The roof pitch of the house was found to be 5:12, which yielded a tilt angle of 22.62 degrees. Some characteristics of the GTPV or "*customer-generation"* system are summarized the Table I.

TABLE I: CHARACTERISTICS OF THE GRID-TIED PV SYSTEM

Designations	**Specifications**
PV Brand	SHARP ND Q235Q2
Inverter Brand	Fronius IG 5100
PV Panel Efficiency	14.4%
Inverter Efficiency	95.2%
Panel Weight	19 kg
Panel Dimensions (m)	1.64·0.99314·0.046
Voc Panel	37.2 V
Isc Panel	8.59 A
Syst. Operating current (I_{mp})	7.81 A DC
Syst. Operating voltage (V_{mp})	331.1 V DC

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Accordingly, under Reno weather conditions and vicinity, each PV module output was increased by 7.1 V due to record-low temperatures. Therefore, the whole array's output might increase by 78.1 V since the system was designed to have 11 panels by 2 parallel strings. Thus, the array open circuit voltage with the effects of local temperature can be estimated as in (1).

$$V_{OC}(Array) = V_{mp} + 78.1\,V = 409.2\,V. \quad (1)$$

So, knowing the above electrical, as well as physical characteristics, the maximum open circuit voltage is found by

$$V_{OC} = V_{OC}(Array) \times 125\% = 511.5\,VDC. \quad (2)$$

In which, V_{OC} is the array open circuit voltage in *V DC*.

In a similar manner, the system's short circuit current, I_{SC}, can be determined by

$$I_{SC} = I_{SC}(panel) \times 1.25^2 = 13.42A\,DC. \quad (3)$$

Where, 125% ·125% is commonly referred to as the 156% factor in the PV industry. Following the same above judgment, the total system current can be easily computed (*15.7 A*). In addition, the maximum inverter's *AC* output current can be calculated by

$$I_{Inverter} = 21.3 \times 125\% NEC = 26.6A\,AC. \quad (4)$$

III. CHALLENGES AND BARRIERS OF GTPV SYSTEM

Although grid-tied PV has the potential to reducing load at nearby substations, a higher penetration could lead to a counter-intuitive behavior, such as creating excess load at the substation. Therefore, it would cause electrical power to flow in opposite direction, i.e., from substation to the transmission grid, which puts the whole system in a new state it was not planned to handle. Thus, the consequences might be devastating, ranging from voltage swing to other stresses on electric equipment [2].

The most evident obstacle to renewable energy installations and in some instances its penetration to the grid, has a lot to do with price competitiveness. In many cases, barriers to intensifying renewable energy are rather regulatory than technical. Therefore, a large scale deployment of PV systems is within states', counties' or other local agencies' control. Some specific barriers include, but not limited to: 1) utility rate structures, which have potentially been a barrier to increased deployment of renewable technologies; 2) lack of in-depth knowledge of interconnection standards, such as the "*IEEE 1547*"; 3) barriers in environmental permitting; and, 4) lack of sufficient transmission lines. Most of the prospective renewable resources are located in remote places that lack set or economical access to transmission lines.

IV. FACTORS INFLUENCING BUFFERS

As reported in [9], many factors need to be considered in the course of sizing energy storage systems. Toward that end, the most important and essential characteristics are treated here. They are: 1) the anticipated daily kWh of energy consumption and 2) the number of hours or days of autonomy.

Hence, irrespective of the type of battery technology utilized on the "*customer-generator*" PV systems, the bigger battery capacity would achieve more efficiently a net positive aspect. But on the economic standpoint, the larger energy storage system will become more expensive. So, the engineering solution to that upfront cost resides in re-utilizing electric vehicles' (*EV*) used batteries. Therefore, with respect to the fast growth in the EV automobile's industry, benefit of that is taken toward minimization of the important initial charge of the storage system. As a result, this paper proposes that second-life EV batteries be cheaply purchased and added as an alternative to favor an increasing penetration onto the distribution grid (*Fallon, NV*) of more "*customer-generation*" PV units. A direct consequence of that is the short-term solar transitory phenomena will be resolved, as well as the electrical power availability and consistency would be tremendously improved.

V. BUFFER SIZING SCENARIOS

The types of batteries recommended for a typical usage in conjunction with solar PV system are mainly of deep cycle batteries. The deep cycle batteries are explicitly designed to withstand discharge at a very low energy state, say 20%, and to be rapidly recharged in a relatively short amount of time. Consequently, as already stated above, the energy storage system (*ESS*) should be large enough to accumulate adequate amount of energy to drive home appliances at night or during cloudy days.

A. Smoothing the "Customer-generator's" Output

Without any exception from the fundamental Engineering rules, there are some assumptions that have to be set forth as guide lines to this study.

The average energy production under Fallon weather conditions was 8,880 kWh/year. Therefore, the daily kWh production can be estimated as 25 kWh. It is worth pointing out that, the average sunlight hours in Reno and vicinity is 5.8 hours/day. As a result, the customer future battery bank can charge and then discharge a continuous amount of power to the grid for a period of 5.8 hours on a daily basis. So, the daily power generation, *P*, by the GTPV system is given by

$$P = \frac{E}{t} = \frac{25kWh}{5.8Hours} = 4.32kW. \quad (5)$$

The battery discharge time, t_b, is deliberately set up to be 30 min. Hence, the equivalent amount of energy (*E*) required to smooth out the "*customer-generator's*" transient due to cloud coverage for a period of fractions of seconds to a maximum of 30 minutes, just to be conservative, is determined by

$$E = P \cdot t_b = 4.32kW \cdot \frac{1}{2}\ h = 2.16k\ kWh. \qquad (6)$$

Assume 12% of combined loss such as charging, discharging, and wiring from inverter to load as reported in [10]. Additionally, the inverter, Fronius IG 5100, efficiency was found to be 95.2%. Also, a depth of discharge (DOD) of 60% (*assumption*) is factored in since the innovative buffer system will only be utilized occasionally to cope with power fluctuations. So, the load on the battery is determined by

$$Battery\ Load\ 1 = \frac{2.16kWh}{0.88 \cdot 0.952 \cdot 0.6} \approx 3.60kWh. \qquad (7)$$

In which, "*Battery Load 1"* stands for the actual battery capacity.

Unlike photovoltaic modules, which are less affected by the ambient temperature, battery's lifetime and capacity are drastically reduced by temperature. The annual low temperature in Fallon is found to be 37.1°F [11]. Therefore, the latter was considered as the battery bank's ambient average low temperature. The derate battery bank's factor (*multiplier*) accounting for that is approximately 1.30 [12]. So, the "*Battery Load 1"* including the effects of temperature is estimated by

$$Battery\ Load = Battery\ Load_{Previous} \cdot Multiplier$$

$$= 3.60kWh \cdot 1.30 = 4.70kWh. \qquad (8)$$

To have an alternative perspective of the above calculated capacity, a division by the assumed battery nominal voltage, 24V, is necessary to find the actual battery bank.

$$Battery\ Load\ 1 = 4.70kWh \cdot \frac{1000}{24V} = 196Ah. \qquad (9)$$

In order to avoid deep discharge, the control algorithm should prevent the batteries from delivering more than 80% of their nominal capacity. So, the factor accounting for this strategy is 1.25 [13] as can be seen in (10). In other words, if 20% of their capacity remains, the charge controller will automatically shut off the energy supply. This technique will not only preserve the life span of the batteries, but also save on frequent maintenance.

$$Actual\ Load = 196Ah \cdot 1.25 = 245Ah. \qquad (10)$$

Consequently, the real battery size to smooth out the selected "*customer-generator's"* transients is 245*Ah*.

As a final step, the theoretical energy capacity, E_{SMOOTH}, of the battery bank deemed ready to deal with any intermittent power supply for periods long as 30min is determined by (11).

$$E_{SMOOTH} = Ah \cdot V = 245Ah \cdot 24V = 5.90kWh. \qquad (11)$$

It is worth noting that, one of the objectives of this study was to investigate ways to increase the number of GTPV arrays on the municipality of Fallon's electric distribution system. With that respect, 245*Ah* were needed to produce approximately 6*kWh* per day with at most 30 minutes of storage. Hence, the appropriate batteries, regardless of the technology, can smoothly fit in by connecting them either in series and/or in parallel.

B. Sizing to Load Shift

All the above technical assumptions apply strictly to this section. The only exception to that is the battery discharge time, t_c, which is set equal to the local on-peak time of five (*5*) hours. Therefore, for simplicity purposes, the self-repetitive calculations are skipped.

The total amount of energy to be shifted, E_{SHIFT}, is computed using

$$E_{SHIFT} = E_{SMOOTH} \cdot \frac{t_C}{t_b} = 6kWh \cdot \frac{5h}{0.5} = 60kWh. \qquad (12)$$

The equivalent load on the battery bank in *Ah* is as shown in (13), where, "*Battery Load 2"* denotes the load on the battery bank.

$$Battery\ Load\ 2 = 60kWh \cdot \frac{1000}{24} = 2{,}500Ah. \qquad (13)$$

In other words, 2500*Ah* were needed to produce approximately 60*kWh* per day with 5 hours of storage, which is also equivalent to the amount of inexpensive energy to be shifted from off-peak to on-peak. Obviously, during off-peak, the energy storage system will either be charging cheap power or remain idle.

VI. RESULTS AND ANALYSIS

Energy storage system (*ESS*) is often described as one of the key features of a high PV penetration. So, the ESS' ability of deferring load, on one hand, and enhancing power transient, on the other hand, can greatly reduce the challenges brought by PV integration. This novel scheme enables the grid to be better off having enough dispersed storage and generation reserves at consumer side, thus shaving off the sporadic peak loads. In a simple term, the GTPV with the proper ESS is now a dependable power system, which eliminates all worries about electrical energy fluctuations and failures within the right amount of time. As technically demonstrated in Sec. V, the 5kW GTPV system under study requires a total battery bank of 2,745 *Ah* not only to smooth out the solar transients, but also have the ability of shifting less expensive energy over time from off-peak to on-peak where the electricity price is much higher.

The primary purpose of the GTPV is to supply all the electrical power that the customer needs or to partially replace the utility's supply. The monthly energy generated by the "*customer-generator"* is plotted against the utility's supply, which is his actual load, as illustrated by Fig. 1. Hence, as shown in Fig. 1, the customer has higher energy usage during winter (*November, December, and January*) than he truly produced. A direct economic consequence of that is, his monthly net pay, as shown in Fig. 2, were the highest in winter after the monetary compensation has been done by the local utility (*41.56%, 67.04%, and 66.50% of the electric bill, in that order*). In contrast to that, in the summer months (*May, June, and July*), the customer's net bills were the lowest, 8.03%, 14.88%, and 12.20% of the utility bill, respectively. Overall, the entire year, s/he only paid 36.45 percent of his bill. The study also reveals that because of the location of the city of Fallon (*39.4728º N, 118.7789º W*), the houses in general require more heating than cooling, as local temperatures tend to be chilly during winter months. In a nutshell, the GTPV owner was better off summer than winter months, as already stated above, and the rest of the year due to the abundance of sun shine and longer days. For example in May, s/he paid only $6.88, which was insignificant compared to a typical household's summer load in the US.

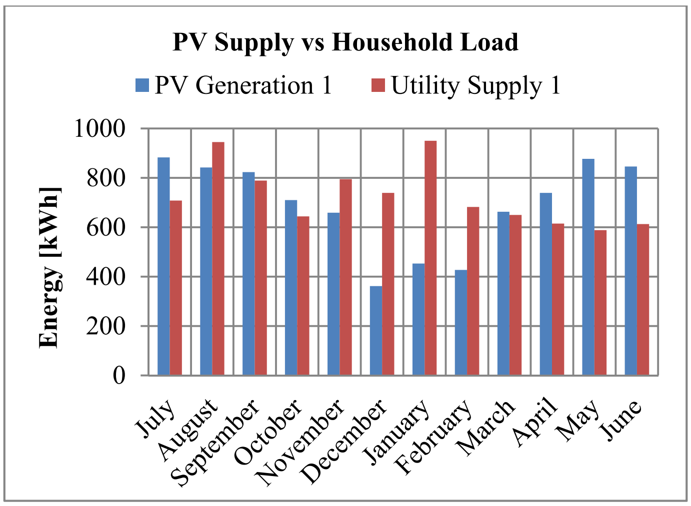

Figure 1 — Comparison between customer-generation and actual load.

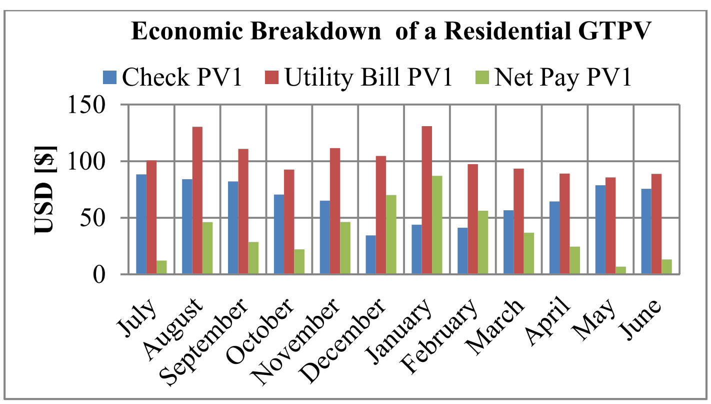

Figure 2 — Compensation between utility and GTPV owner.

VII. CONCLUSION

Increasing levels of GTPV systems creates significant challenges to grid operators due to transmission constraints. Energy storage systems (*ESS*) are often presented as a way of mitigating the issues of power congestion and other generation limits. ESS releases value from existing power infrastructure, liberating spinning reserve capacity and enabling PV systems to produce new revenue streams, improving reliability and resiliency of the power system by meeting peak power demands. A local 5kW GTPV system was concisely analyzed. In order to foster more the acceptance of GTPV, a buffer system was proposed and sized accordingly to not only smooth the power transients, but also defer the less valuable energy to a time when it is mostly needed. Finally, the study reveals that the customer was able to cut significantly down his net bill to a minimum of $6.88 for May.

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