Contribution of Batteries to the Economics of PV Systems

Ulrich Bonne, Kailua-Kona, HI, ulrichbonne@msn.com, http://energyfuturehawaii.org/, 12-Sept-2010

Problem -- Batteries are readily available for use as a means to even out the variable output of clean energy sources powered by sun, wind or ocean, and to provide power when the grid goes down, after a quick switch to “off-grid” operation.

But one wonders about the proper size of such a battery, which clearly would depend on home load, its relation to the energy output of a PV system, with or w/o an EV or PHEV, the day-to-day variability of available sun & PV energy and of loads; how battery size influences the annual NEM (Net Energy Metering) dollar balance with the utility or positively contributes to grid voltage stability, and last-not-least the economic benefits of permanent off- vs. on-grid operation of a PV system.

This analysis is our first involving recorded daily PV system output data over several months, and is part of an overall effort aimed at providing unbiased economics for home-owners, of different designs of solar PV systems[2-5], with or without battery-back-up (whether lead-acid, NMH or Li-based), on- or off-grid operation, with NEM or FIT[6,7] agreements. Such analyses are to enable economic comparisons between alternate options in terms of return on investment of installing and operating the considered systems as well as the cost of the provided electricity.

Inputs	
10.00	Battery size in kWh
85.00	Charge/disch. Eff. in %
20.00	Min. battery SoC in %
60.00	Day-time energy use in %
4.00	EV charge in kWh/day
0.40	Electricity cost in $/kWh
4.0	Miles/kWh; 24.84 mi/gal
4.00	Gasoline cost in $/gallon
Outputs	
16.00	EV Travel in miles/day
940.4	Gasoline savings in $/year
20.00	Min. daily SoC in kWh
31.51	NEM $ 12 Nov.’09 – 9 Sep.’10

Approach – The raw data for this analysis were provided by Enphase Co-recorded daily kWh outputs[1] of a 2-kW PV

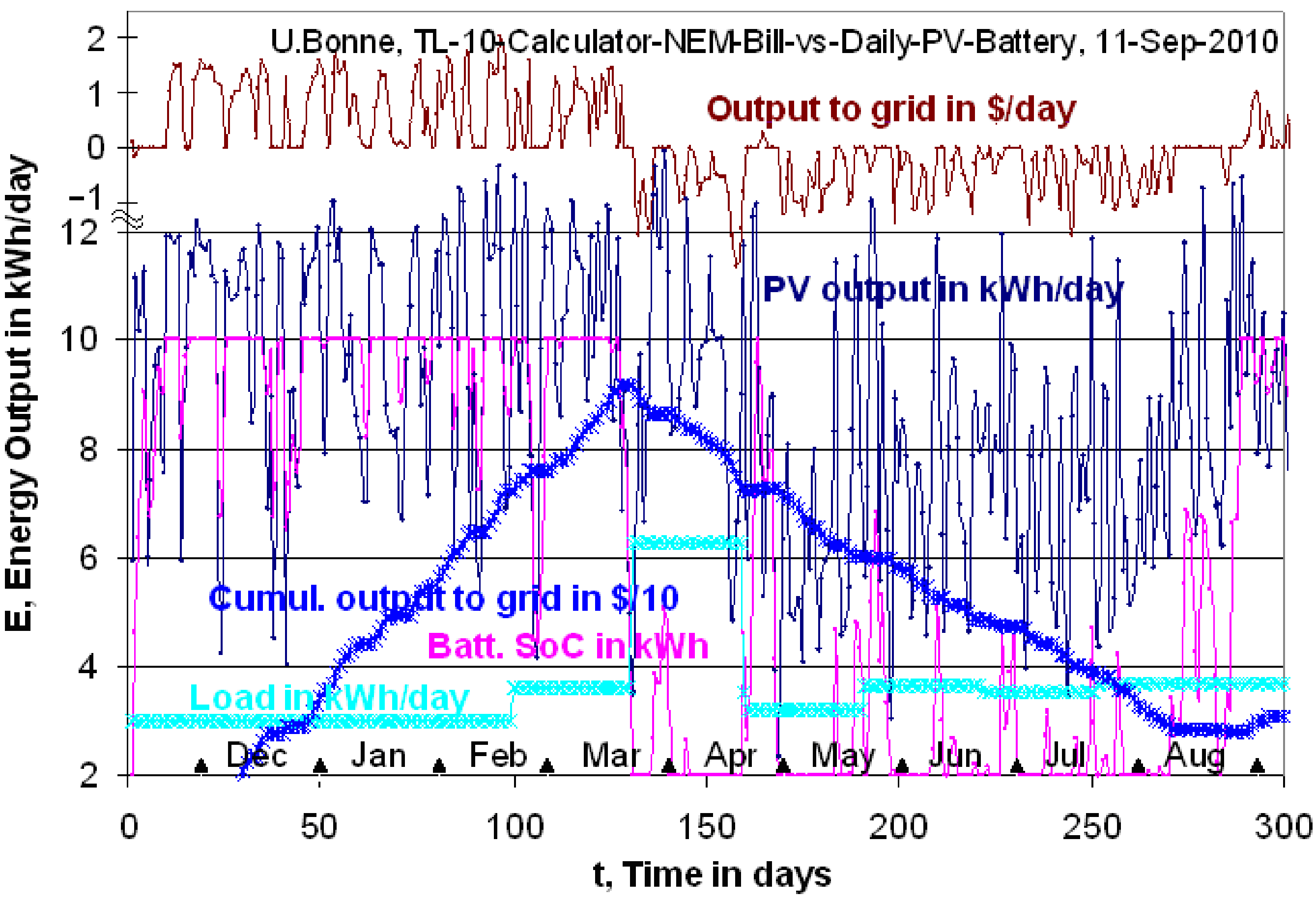

Fig. 1. Day-by-day solar PV system output, average monthly load and balance to grid.

system on our house[2], from Nov 2009 to now, and by HELCO's monthly metered home total (and net) electricity consumption. They were plotted in Fig.1, as indicated by the labeled blue and green curves. The higher consumption in April coincided with a month-long family visit of 4 more people than our usual 2 residents. One might recognize how the average trend of the daily PV output variability follows a lower frequency of seasonal change of solar elevation and angular incidence with the South-facing, about 20-degree roof slope.

The above data base was set up to help determine the effect of changes in battery size or load as represented e.g. by daily charges to different size EVs, on observable response of the system in terms of grid load variability and possible NEM bill or refund at the end of the first year the PV system has been in operation.

The battery system features and extra EV load data are spread-sheet inputs listed in the text box above right. The resulting daily battery SoC (State of Charge) is the pink trace in Fig.1. As shown, excess charge above the 10 kWh battery capacity are sent to the grid. Energy needed after the battery SoC has reached 20% is taken from the grid.

The net energy (NEM) output to grid in $/day and the cumulative outputs to the grid were then obtained and also plotted in Fig.1. The cumulative output appears to follow the seasonal output corresponding to the PV orientation.

As noted in the inputs, the battery charge/ discharge efficiency is temporarily represented by a simple number of 85% for each charge and discharge operation, i.e. 73.2% for a charge+discharge operation, and will later be upgraded to reflect its dependence on SoC[5].

Results and Conclusions – The collected data allowed the 2-kW PV system to be characterized by a 301-day average output of 8.83 kWh/day and thus a capacity factor of 18.4%, feeding into an average home load of only 3.64 kWh/day, which would have led to an electricity bill of $438 without the PV, but without the MMC worth $302 for the past 301 days. Because of the excess capacity, the analysis of the data was expanded to include the ability to simulate the economic benefits of adding a hypothetical battery and charges to a future EV (Electric Vehicle). The associated gasoline cost savings were obtained by assuming an equivalency of 23.84 kWh/gal, which corresponds to an overall vehicle energy efficiency ratio of 80/20 = 4 for EV/CV (Conventional Vehicle with IC engine).

First-off, we verified that the battery SoC system model provided overall sensible results, despite (1) the lack of minute-by-minute consideration of charges and discharges within each day, and (2) the still preliminary accounting of all battery features (self-discharge, efficiency dependence on SoC, energy for periodic cell balancing, etc). By running this model with just 10 months worth of daily data, we found that on:

1. **Off-grid operation** -- Our present 2-kW PV system would be able to meet the needs of the 3.6 kWh/day household, including the extra load of extended family visits, with a minimum battery of only 4.1 (or 10) kWh, without ever draining the battery below a SoC of 21% (67%) and therefore not needing an auxiliary generator if operating off-grid over the past 10 months. However, we would also be wasting $564 ($561) worth of electricity from the excess PV output over the 10 months, if priced at the present effective tariff of 0.40 $/kWh.
2. **Off-grid operation with EV** -- With the 10 kWh battery and off-grid, we could afford to charge a PHEV with 1.5 (or 2.1 if we had had no family guests in April) kWh/day, w/o going below a battery SoC of 20%, save $352 ($489) worth of gasoline but still waste $358 ($315) worth of electricity. Increasing battery size would only marginally increase EV charging capacity, e.g to 2.4 kWh/day with a 20 kWh battery, because the solar weather patterns appears to have periods lasting over 200 days. Another example: increasing the battery from 10 to 20 kWh, and using 100% daytime load, allows EV charging increase from 1.9 to 3.1 kWh/day, without SOCs below 20%, or 1.9 kWh/day with SoC always above 60%. Of course, a few extra days of low solar input can severely limit EV energy charging.
3. **On-grid operation with EV** -- Under the present NEM (Net Energy Metering) agreement and w/o an EV to charge, we are donating HELCO $564 ($561) worth of electricity (from the excess PV output after 10 months), and in addition are paying the Minimum Monthly Charge (MMC) of 22.16 $/month on the Big Island, equivalent to 266 $/year or $219 for 301 days. .But if we had am EV, we could afford to charge it with 5 kWh/day (to drive an average of 25 miles/day 9,100 miles/year), end up with an end-of-year NEM bill of little over $ 86*(365/301) = $104, save most

of the cumulative MMC of 266 $/year and save $1175 worth of gas. This looks like a good deal. But, to no surprise to the experts, the above benefits are available with or without a battery, because the grid is assuming the battery "energy storage" function for free over many months.

4. **Battery benefits** – Besides continuity of power during occasional grid power outages, the two benefits of battery power are: a. Mitigating grid instability due to variable solar or wind power, and b. Ability to shift home and EV loads to off-peak grid times.
   (a) Having multiple PV -generators on the grid mitigates the individual system output variability of the hour-to-hour variability, but not the day-night or day-day variability.
   (b) If the utility were to establish variable time-of-day or grid-load-dependent tariffs, having a battery at home would help steer grid loads to low-tariff times, which shall be explored later
5. **Time-of-day loading** – Increasing the day-time use of home appliances and EV charging from 60% to a hypothetical 100% has a strong effect. It decreases the NEM bill from $ 86 to (a hypothetical annual balance of) - $ 14 for the 5 kWh/day EV and 10 kWh battery example. This trend clearly reflects the decreasing battery charge-and-discharge losses as more loads are shifted to day-time loads. (Low off-peak, night-time utility tariffs will be explored separately later)

In conclusion, while batteries are of course indispensable for **off-grid** operation, they are most effective if home and EV loads can be shifted largely to day-time hours, to avoid battery charge-discharge losses, especially with lead-acid batteries. Because PV excess capacity is needed to achieve power reliability, some energy dumping results, which in part balances the lack of MMCs with an off-grid system.

Battery back-up is not economically attractive for **on-grid** operation, except for having emergency power during grid outages and unless the utility implements tariff differentiation based on time-of-day or on instant grid-load level, which could either be communicated via the small changes in line voltage of via wireless signals..

Future Work – The above analysis should be refined by:

- Including some load variability within each day and from day-to-day
- Allowing a choice of using grid energy during low-cost, off-peak, night-time utility tariffs, possibly associated with future FIT (Feed-in-Tariff) regulations

References

[1] Enphase Energy Inc, http://enphaseenergy.com/products/products/envoy.cfm

[2] U. Bonne, "Study of a Newly Installed Home Solar PV System: Actual and Calculated Outputs," Kailua-Kona, HI, 6 Dec. 2009, posted on this "Friends of NELHA" website,

[3] U. Bonne, "Green Energy ROI and Electricity Cost Calculator," which outputs savings and ROI, and cost of renewable electricity generation or conservation; this free Calculator includes tax credits, bank loans, generator power, MMC, etc, on the "Friends of NELHA" website: http://www.energyfuturehawaii.org/solarCalc.php. Last updated: 9 Sept 2010

[4] William D. Brooks, AIA, LEED AP, "An Energy-Neutral Residence in Oahu, Hawaii," Kailua, Oahu, HI, 25 August 2010, on "Friends of NELHA" (FON) website http://www.energyfuturehawaii.org/files/Bill-Brooks-Energy-Neutral-Residence-2010.doc

[5] U. Bonne, "Lead-Acid Battery State of Charge as a Function of Output Voltage and Temperature," Kailua-Kona, HI, 9 Sept. 2010, on "Friends of NELHA" (FON) website http://www.energyfuturehawaii.org/files/PB-10-Battery-SoC-vs-V-T.doc

[6] U. Bonne, "Proposed Hawaii FIT Rates Discourages Installation of PV Systems below 3 kW," 30 August 2010, Kailua-Kona, HI, on Friends of NELHA (FON) website http://www.energyfuturehawaii.org/files/PB-10-FIT-HI-Economics.pdf

[7] Hawaii PUC, Document Management System, http://dms.puc.hawaii.gov/dms/ enter "2008-0273" in Docket Quick Link search box; then click on "Documents" in the middle toolbar; when the new screen opens after some waiting, with a list of over 400 documents. Scroll down to the date and title of the desired document

[8] Same as [4]. This MSWord document contains an active Excel spreadsheet at http://www.energyfuturehawaii.org/files/Bill-Brooks-Energy-Neutral-Residence-2010.doc