Life-cycle cost of PVBB systems, depending on their grid-tie type

Ulrich Bonne, Kailua-Kona, Hawaii

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SUMMARY -- The ownership (i.e. 20-year levelized life-cycle) cost of energy (in $/kW/month and in $/kWh) for three types of PVBB (Photo-Voltaic with Battery Backup) grid-tie or no-tie systems were analyzed and compared for varying PV sizes relative to the assumed-constant daily energy use load:

1. "On-grid with a NEM (Net Energy Metering) contract," with[4] and without battery back-up,
2. "On-grid without a NEM contract" and thus no permission to inject surplus kWh into the grid, but able to trickle-charge its batteries from grid energy when needed and
3. "Off-grid PVBB with an engine generator for secondary backup.

The above systems' CapEx are based on 2013 quotes for PV and battery backup installation costs, 20-year NEM contracts, and historical escalation rates of the Minimum Monthly Charge (MMC), retail fuel and electricity costs, see **Fig.1**. In addition, a conservative assumption was made that each day's kWh-energy generation, storage and use would be independent of adjacent days' generation and storage or grid-exchange as appropriate. This greatly simplified the computations.

To make meaningful cost comparisons between different PV grid-tie systems, representative data on PV outputs are needed. To be representative, we chose to average data of 3 full years of daily kWh production. The day-to-day variability then quantifies the credits a NEM system may get during sunny surplus days, vs. the equivalent loss to an on-grid system without a NEM contract, or the cost of engine-generator electricity needed during cloudy days by an off-grid system. Although the recorded PV output data (via Enphase) were obtained with a 2-kW PV system, the normalized cost data can be made to represent any size PVBB system, such as e.g. 4- or 6-kW systems. The next few bullets further characterize the grid-tie scenario, the main components and their principal costs:

• PV system installation w/o batteries	2.5 $/W after ~50% subsidies
• Battery system addition with electronics	1.0 $/Wh after ~50% subsidies (Li-ion or lead-acid)
• Active battery storage of peak or avg. PV	2.5 or 3.8 hours (peak PV = avg. PV x 1.5)
• PV output data monitored	kWh/day for a 2-kW system in Hawaii for 3-yrs[1]
• Capacity factor at the site in Kailua-Kona*	18.8% as per monitored data. *Elevation: ~400 ft.
• PV average energy output, Ea	9.04 kWh/day, and variability of +44 and -50%
• OpEx based on MMC and maintaining Ea	NEM grid-tie, 20-year contract
• 2013 base costs	MMC: 20 $/mo., Fuel: 4 $/gal, Electr.: 0.44 $/kWh
• Escalation or inflation in %/year	MMC: 2, Fuel: 5, Electr.: 7
• Engine generator efficiency & installed cost	18% & 1000 $ for 7 kW output, after 50% subsidy
• 20-year levelized costs of MMC	24.4 $/mo.,
• 20-year levelized costs of electricity	Electr.gen-set: 1.13 $/kWh and grid: 0.87 $/kWh

The comparative results will show that optimal oversizes for the above three grid-tie types of PVBBs were 100, 110 and 133% of the average daily energy consumption, respectively.

DISCUSSION – The next sections describe how we arrived at these results, step by step..

1. Trends and escalations -- According to DEBDT data (see **Fig. 1** below), the cost of oil for power generation has risen by an average of 5%/year from Jan 2006 to Jan 2013. Meanwhile, the average electricity rate in Hawaii has risen 8%/year and the average total electricity sales to residential customers decreased by 3%/year during that same period.[1]

2. Solar PV output variability -- My PV-micro-inverter daily output was recorded by Enphase since its installation in Nov. 2009. **Fig. 2** shows not only the strong variability from day to day, but that this peak-to-peak variability amounts to about ±50% around an average of 8.874 kWh/day. The low output value on day 393 was caused by an imposed shut-off during official inspection). The average annual peak-to-peak variability was only about +/-6% for the 3 years of data. Clearly, the +/-50% represents no small challenge – but the good news is that even on cloudy days the solar PV output is far from zero. In other words, if we design a PV system just large enough to cope with the "-50% days," a grid connection would only be needed during above-average load/PV-output days. That is why off-grid households use an on-site engine generator or "gen-set" as secondary backup. The 20-year levelized electricity cost calculates to be 1.12 $/kWh based on today's fuel price of 4 $/gal and 5%/year escalation – compared to 0.87 $/kWh for Hawaii Island's 0.44 $/kWh rate of today and a conservative 7%/y escalation. As shown in the next section, an off-grid solar PV system, oversized 40-50%, results in a levelized life-cycle cost of only 0.15 $/kWh, including present total subsidies of ~50%.

3. Cost comparison – We are now ready to compare the three types of PV-grid interaction systems outlined in the Summary, and presented in **Fig.3**:

a. "On-grid with a NEM contract," whereby surplus kWh are credited, to be used or lost within a year. Regular $/kWh billing is applied after that period if more kWh are used than produced. In Hawaii, payment of the MMC of ~20 $/month applies to on-grid systems, regardless of whether a NEM contract exists or not, as in the next case.
b. "On-grid without a NEM contract and thus no permission to inject surplus kWh into the grid," whereby no credit is provided for surplus energy (which is wasted, unless used by extra equipment such as for desalination and pumping water), but also no utility permit is required to install a PVBB system.
c. "Off-grid with a home diesel generator for secondary backup."

As recorded by the internet-tied Enphase micro-inverter monitoring system, we can see whether the daily kWh of PV output meets or exceeds the daily load of the household or business. For purposes of this comparison, we assumed that this load does not vary from day to day and equals the average PV output. For a 2-kW PV in Kona at ~400 feet elevation it would be about a constant 9 kWh/day. This would correspond to an average capacity factor of 9/(2*24)*100 = 18.8%, which is close to the often used Hawaii-wide average of 17%. To vary the relative PV oversize, we simply changed the nominal average load, summed over all new surplus and deficient outputs, and weighted them with the applicable tariffs, to obtain the normalized curves of **Fig. 3**.

To clarify the significance of these curves, we list a few more assumptions, besides those made in the Summary:

- The PV CapEx (Capital Expense) in $/W does not change. Actually, $/W decreases with increasing size, but the state subsidy cap compensates for that, so that the effective $/W change is so small that it was neglected and led us to work with a constant 2.5 $/W after subsidies for PVBB sizes between 1 and 5 kW.
- No cost of money was included in this analysis. A 10-year home equity line of credit (HELOC) at 3 or 5%/year would increase the PVBB CapEx, and the life-cycle electr. costs, by about 16 to 28 %
- The PV energy balance of energy produced, used and grid-exchanged is done daily, so that stored energy is not carried over to the next day, which is tantamount to implying that on average, the battery SOC at the start of each day is the same. This may happen to be close to a practical solution anyway, but greatly simplifies the computational programming, of not having to keep track of daily, annual or average deficit and surplus energies. It allows simply adding all the differences between the chosen average load and the daily PV output, as illustrated by **Fig. 2.** As a further simplification, we normalized those differences to units of kWh/month per kW of PV size.
- All three types of PVBB grid-tie life-cycle costs (LCC) were calculated with battery backup, except that (1) We also plotted a dashed-line curve to represent the NEM case without battery, to show that the difference in $/kW(of PV peak power)/month is less than 5 $/kW/mo, for the 100% load match; and (2) For the off-grid case we added $1000 for installing a 7-kW engine generator (unchanged for PVs between 1 and 6 kW).
- To convert on-grid LCC in $/kW/month to electricity cost in $/kWh, see Appendix 1.

As the chosen PV size relative to a load is decreased, see **Fig. 3**, the normalized LCC in $/kW/month increases because of higher expenses for the back-up electricity.

Figure 3 shows that LCC rise in the order the grid-tie types are listed below for 2-kW PVs:

- Off-grid – despite exhibiting the highest LCC until the 100% match point (due to its high gen-set back-up electricity cost) but becomes the lowest after increasing the PVBB size by just ~15%, and further decreases LCC until about 133% of the match point size, because no MMC is due, and backup gen-set electricity is barely used. **LCC = 24 $/kW/month at R = 133% for a 2-kW PV.**
- On-grid NEM w/o battery backup – The present NEM contract (dashed-line curve) provides the lowest normalized LCC up to the average size match of R = 100% of PV output/load. Increasing the PV size and the "lost" or unpaid kWh increases the LCC beyond that point. **LCC = 22.6 $/kW/month at R = 100%**
- On-grid NEM with battery backup -- The future NEM-PV contract terms may smartly require controlling grid injection to be less than some fraction (maybe 60% as in Germany) of peak PV power, rather than mandating specific sizes of battery backup. **LCC = 27.8 $/kW/month at R = 100%**
- On-grid, no NEM – This type, which is also representative of plug-in solar appliances like SunPax[3], is next up in LCC. At the 100% match point, its LCC is ~20 to 25 $/kW/month higher than the 27 $/kW/month of the NEM type. However, by just increasing the PVBB size by 10 or 20%, their LCCs become practically identical, since the average unused surplus energy becomes small or negligible. **LCC ~ 28 $/kW/month, with R at 100 to 110%**

Remember that the above numbers are conservative, because we assumed that there would be no carry over of stored kWh from one day to the next

Figure 4 shows that all minimum life-cycle and kWh costs for on-grid 4-kW PV systems are reduced by 16-27% relative to 2-kW systems, while the costs for the off-grid system only dropped by 4.4 % (because no MMC is involved). Also included were plots of Self-Consumption (S) and Autonomy (A) in %, defined as ratios of energy (E in kWh) generated and/or consumed:

S = E(PV-consumed)/E(PV-total generated), and A = E(PV-consumed)/E(total consumed).

They reflect features of local PV output variability. If greater, S and A would be smaller at R =100%.

The greatest uncertainty of the points in **Figs. 3 and 4** are those near the 100% match area, as the PV output rises and the on-grid systems shift from being billed based on kWh use to MMC.

Example: Minimum costs of a 2-kW PVBB equipment to satisfy an average of 9 kWh/day can now be obtained by multiplying the LCC values of Fig. 3, for

these types of grid-ties	NEM,	(NEM w/o batt.),	no-NEM and	off-grid,	respectively,
a 20-year levelized LCC of	55.6	(43.2)	~59	47.8	$/month,
for PVBB/load sizes of	100	(100)	110	133	%,
with CapEx costs of	30.4	(20.8)	31.2	45.8	$/month, and
effective electr. costs* of	0.206	0.167	0.21	0.177	$/kWh. *See Appendix 1.

The CapEx costs for all would increase by factors of 1.159 or 1.276 if financed with 10-year loans at 3 or 5%/year interest, respectively, i.e. not an overwhelming increase.

RESULTS AND CONCLUSIONS -- The analysis of 3 full years worth of daily PV output data in Kailua-Kona, Hawaii, was based on 2.5 $/W and 1 $'Wh of installed PV and battery back-up after 50% total subsidies, respectively. No cost of money was included, but could be factored into the results below, for average, 20-year levelized LCC and kWh-costs for different grid-tie types of PV or PVBB systems:

PV output variability data reveal how much surplus or lack of PV energy is generated each day to meet an assumed fixed load. From a number of whole years of data (3 in our case) we can derive average annual or monthly kWh surplus and deficiencies. The type of grid-tie contract then determines whether we get a credit or loss for the surplus days, and the need for buying kWh from the grid or for generating our own. As PV size is increased and the ratio of daily PV energy output over average consumption increases, less energy is needed from the grid or on-site generator, but more energy is wasted if not injected into the grid. The average output for the 2-kW PV turned out to be 8.88 kWh/day or 3241 kWh/year, which corresponds to a capacity factor of 18.8%

Because we did not consider (1) **Energy management "tricks**" such as shifting loads to sunny days or not pumping water during cloudy days, nor (2) Carrying over stored electricity to the next day, -- the LCC and $/kWh rate results reported here are conservative, i.e. higher than actual, yet still significantly lower than many utility rates.

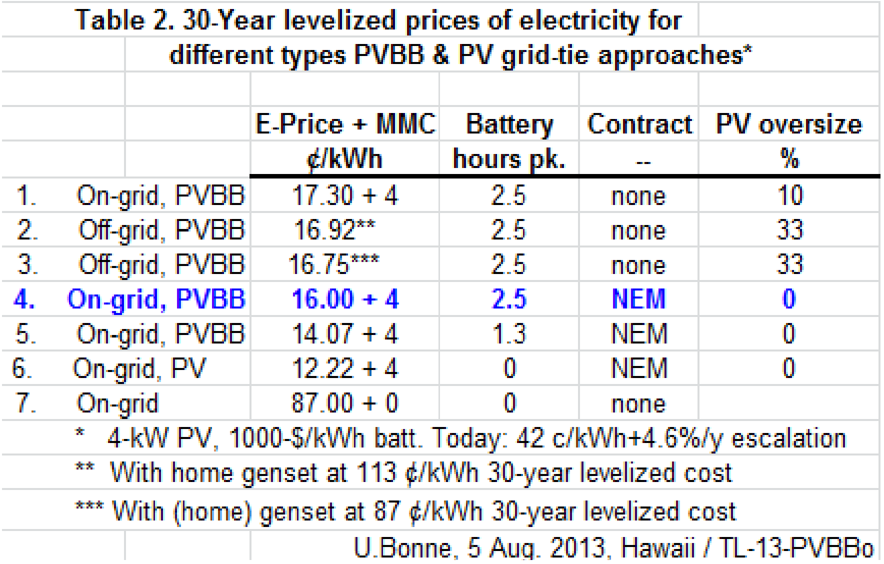

Table 2. 30-Year levelized prices of electricity for different types PVBB & PV grid-tie approaches*

		E-Price + MMC ¢/kWh	Battery hours pk.	Contract --	PV oversize %
1.	On-grid, PVBB	17.30 + 4	2.5	none	10
2.	Off-grid, PVBB	16.92**	2.5	none	33
3.	Off-grid, PVBB	16.75***	2.5	none	33
4.	**On-grid, PVBB**	**16.00 + 4**	**2.5**	**NEM**	**0**
5.	On-grid, PVBB	14.07 + 4	1.3	NEM	0
6.	On-grid, PV	12.22 + 4	0	NEM	0
7.	On-grid	87.00 + 0	0	none	

* 4-kW PV, 1000-$/kWh batt. Today: 42 c/kWh+4.6%/y escalation

** With home genset at 113 ¢/kWh 30-year levelized cost

*** With (home) genset at 87 ¢/kWh 30-year levelized cost

U.Bonne, 5 Aug. 2013, Hawaii / TL-13-PVBBo

- **The LCC or kWh costs** for the various systems do not change significantly as their PV size increases (lower CapEx balanced by lower capped subsidy percent), except for the diminishing relative contributions of the applicable MMC or gen-set capital cost (assumed to be constant, but zero for off-grid). The net result is that we get lower $/kWh rate as the PV size increases as indicated in Table 2. All provide uninterruptible power except for the NEM PV, #6.
- **The off-grid engine-generator** installed at $1000 (after 50% subsidy) adds 1000/20/12 = 4.17 $/month to the LCC, besides the 1.12 $/kWh operating cost of converting 4 $/gal fuel, with 5%/year escalation, when needed. However its 20-year levelized LCC and kWh costs are 7% lower than a regular NEM system with battery, but higher by 14% than a NEM system w/o battery. Each additional $1000 (after subsidies) adds 0.8 ¢/kWh to the 20-year levelized cost of electricity. Another example: For a gen-set cost of $3800, rather than $1000 after subsidies, the added electricity cost would be ~1.3, 2.2 or 4.3 cents/kWh more for a 6, 4 or 2-kW off-grid PVBB system.

REFERENCES

[1] U. Bonne, "Study of a Newly Installed Home Solar PV System: Actual and Calculated Outputs " Friends of NELHA Website, 6 Dec 2009, http://www.energyfuturehawaii.org/learn-more/7-renewable-energy-a-energy-efficiency/119-study-of-a-newly-installed-home-solar-pv-system-actual-and-calculated-performance.html

[2] DEBDT data on fuel and electricity cost escalations and decrease in electricity sales: http://www.hawaiienergy.com/10/hawaii-residential-electric-cost-and-oil-cost-per-kwh and http://www.hawaiienergy.com/12/hawaii-residential-kwh-per-day, respectively

[3] Jonathan R.Cole, "The Solar Option," http://www.lightontheearth.org. SunPax is a PVBB "appli-ance" which plugs into any building outlet, and only uses the grid for trickle-charging its batteries when needed, does not require a utility permit or contract, yet provides uninterruptible power.

[4] U.Bonne, "Unlimited home and business generation of solar Photo-Voltaic energy with Battery Backup (PVBB)," Resolution Draft for consideration by the Governor of Hawaii and the Public Utilities Commission, 24 May 2013

APPENDIX

1. **Convert LCC in $/kW/month into cost of electricity, Ce, in $/kWh** – The conversion from one to the other of these quantities is easy, after having arrived at values for $/kW/month:

   $$Ce = Lcc / (4.5*30 \text{ days/month}) = 0.206 \text{ \$/kWh},$$

   for Lcc = 27.8 (see **Fig. 3** for 100% match between PV and its load), where 4.5 kWh/day is the average output of 1-kW PV system operating with a capacity factor of 18.8%, which is also the daily average load.

2. **Power spikes from distributed from generation of renewable energy (solar & wind) – Figure 5** may serve as illustration of the RE generation spikes a utility is challenged with. In this case, the RE-generated power spikes in Germany's E.ON utility territory (measured at the battery facility of Falkenhagen, Germany), reach up to 3x the level of the grid-provided consumption power. During

the period from 2008 to 2010 the RE power spike height and density have noticeably increased, indicating the need for more storage.

3. Acronyms and Symbols

A	Autonomy (of an RE installation) = E(PV-consumed)/E(total consumed)
CapEx	Capital Expenses
E, Ea	Energy, Energy average
FIT	Feed-In Tariff, an electricity accounting contract, whereby a qualified user can sell surplus PV electricity to the utility at a discount (presently between 20 and 30 c/kWh)
kW	kilowatt, a unit of power or of energy per unit time or of energy charge rate
kWh	kilowatthour, a unit of energy used or charged into a battery; 1 kWh = 1000 Wh
LCC	Life-Cycle Cost
MMC	Minimum Monthly Charge, a fee charged by utilities to pay for grid expenses
NEM	Net Energy Metering, an electricity accounting contract, whereby the user gets credited for surplus kWh, which can be “redeemed” within a year at the same $/kWh rate
OpEx	Operating Expenses
PV	Photo-Voltaic solar energy system
PVBB	Photo-Voltaic solar energy system with Battery Backup
RE	Renewable Energy
S	Self-consumption = E(PV-consumed)/E(PV-total generated)
SOC	State OF (battery) Charge
TOU	Time of Use

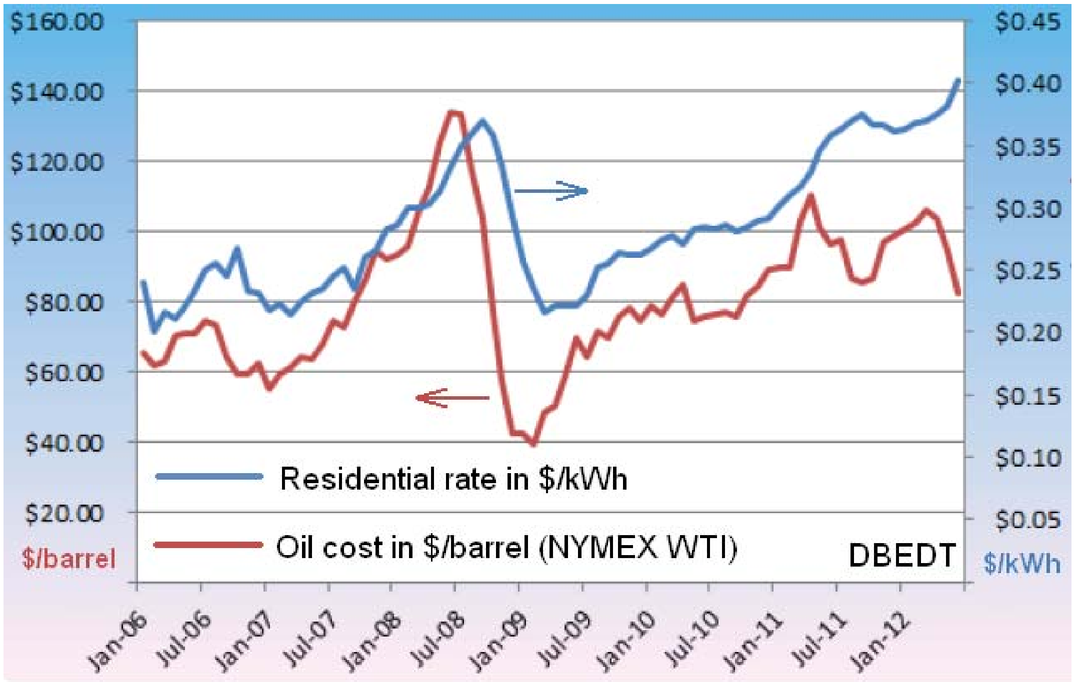

Fig. 1. Hawaii’s costs of fuel oil and average residential electricity.

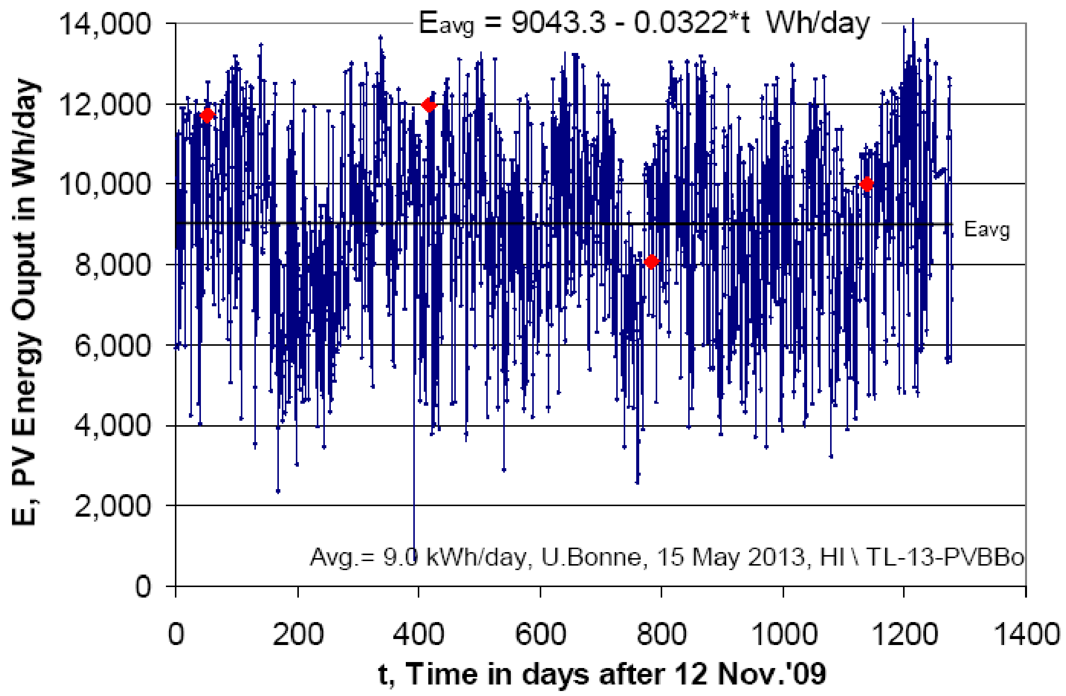

Fig. 2. Total daily output of a 2-kW PV for more than 3 years. The red dots mark Jan. 1st of each year

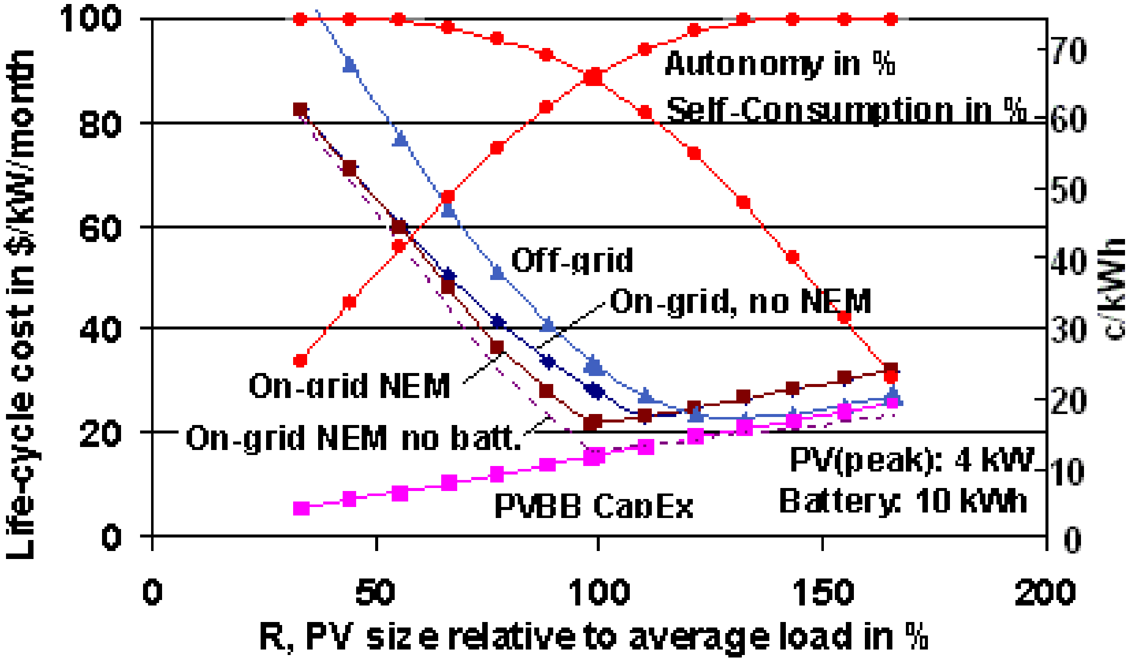

Fig. 3. Ownership cost of PVBB systems vs. size / load ratio. The dashed curve represents a PV system w/o battery backup. CapEx values for 4-kW PV and 10-kWh battery at 100% size match to load.

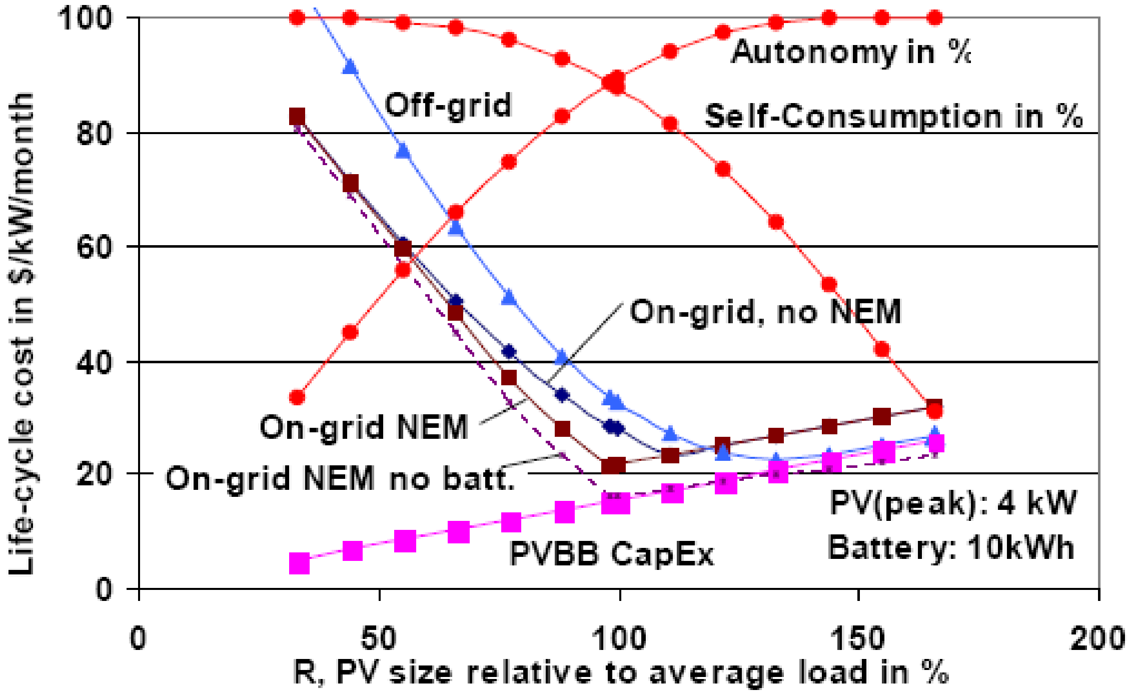

Fig. 4. Ownership cost of 4-kW PVBB systems vs. size / load ratio. The dashed curve represents a PV system w/o battery backup.

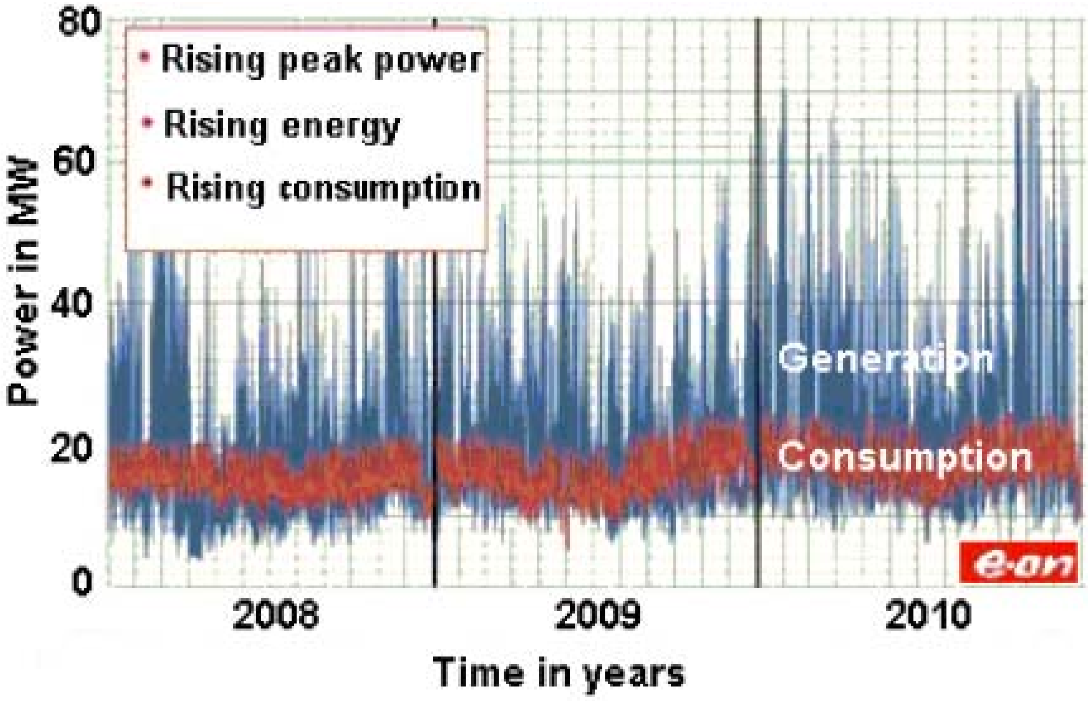

Fig. 5. Illustration of a utility's challenge to manage grid stability in the face of the ~3x larger and rising renewable power spikes & energy, relative to the level of consumption. (E.ON utility data at Falkenhagen, Germany)