



PV-Battery Systems for Critical Loads During Emergencies

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HURRICANE MARIA STRUCK PUERTO RICO ON 20 SEPTEMBER 2017 and left large parts of the island without electricity for months. As Figure 1 shows, restoration in remote mountainous regions took considerably longer.

Long-term power outages can be lethal to individuals who rely on electrically powered medical devices or require medicines that must be refrigerated. Although the initial death toll of Hurricane Maria was 64, one study concluded that actual number of deaths caused by the hurricane is closer to 2,975 due to the lack of utilities, such as electricity. Researchers calculated this number by comparing the total medical-related deaths during 2017 with the average numbers in the past four years. Another study estimated the death toll at 4,645.

It is likely that remote areas were more severely affected because damaged roads not only prevented access to medical facilities but also hampered the regular delivery of medical supplies and fuel for portable generators. Communities were deprived of electricity and water, hospitals and clinics were inoperable, and communication and transportation were unavailable for months; 200 days after the hurricane, 160,000 people still lacked electricity. The devastating destruction from the hurricane is highlighted in Figure 2.

Small systems combining photovoltaic (PV) generation and battery energy storage could be deployed during such emergencies to help affected individuals cope until grid-supplied power is restored. However, very little reliable data are available on how such systems would actually be used to meet critical medical needs and, thus, on what their design requirements should be. To gather data on how emergency systems would actually work and provide some relief to a severely affected community, our group from the University of Washington in Seattle made three field trips to Jayuya, a remote small town in the mountainous center of Puerto Rico, to collect preliminary information about medical needs, install PV battery systems, and gather the data collected by these systems after several months of use. Figure 3 shows some photos highlighting the work.

Field Results

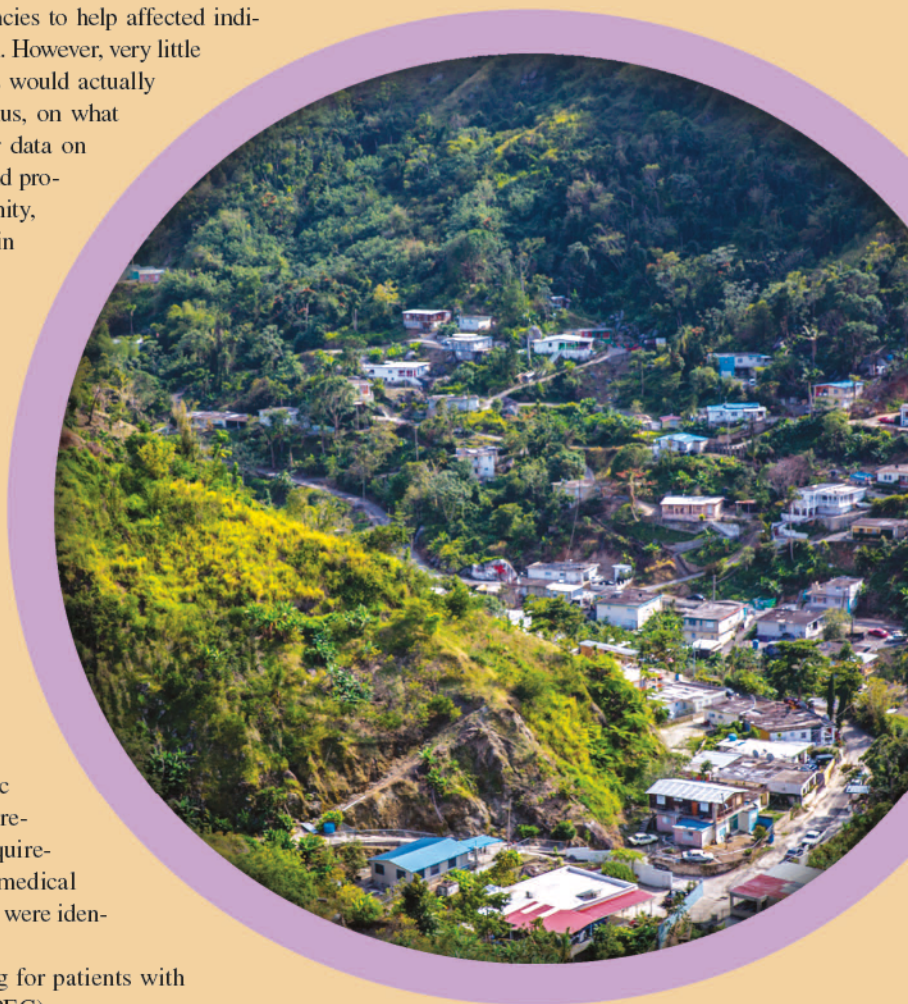
Figure 4 outlines the time line and purposes of the three field trips to Puerto Rico.

First Field Trip: Preliminary Needs Assessment

The goal of the first trip was to identify, based on interviews with patients and their families, the critical medical needs that require electric power at the household level and carry out a preliminary assessment of the power and energy requirements associated with these needs. The critical medical conditions and associated electrical devices that were identified during these interviews were

- ✓ feeding machines and electrical bedding for patients with percutaneous endoscopic gastrostomy (PEG)

A Case Study from Puerto Rico After Hurricane Maria



- ✓ nebulizers or oxygen concentrators for patients with asthma and/or chronic obstructive pulmonary disease (COPD)
- ✓ continuous positive airway pressure (CPAP) machines for patients with sleep apnea

- ✓ refrigeration for medicines, such as insulin for diabetic patients, and food for patients with special dietary requirements.

Dialysis and treatments for other acute medical needs were not included in this assessment because they are usually not carried out at home and patients with critical needs are frequently evacuated before or after emergencies. Interviews also revealed how individuals coped with the lack of electricity. PEG patients used gravity feeding instead of powered peristaltic pumps, which resulted in substantially faster feeding. Many diabetic patients kept their insulin cool either by using water and ice or moving their refrigerators to nearby businesses that had emergency generators; however, some stopped taking insulin out of fear that it had degraded. The local clinic was without power until a backup generator arrived, and they lost medicine requiring refrigeration as well as all vaccines.

Other loads common to all households were perceived as important but less critical: refrigeration for regular food, fans, lighting, TV, and washing machines (particularly important in households with bedridden patients). Cooking appliances do not appear on this list because most households in this part of Puerto Rico use gas for cooking.

Basic information about the critical loads was also gathered by reading manufacturers' labels and asking families

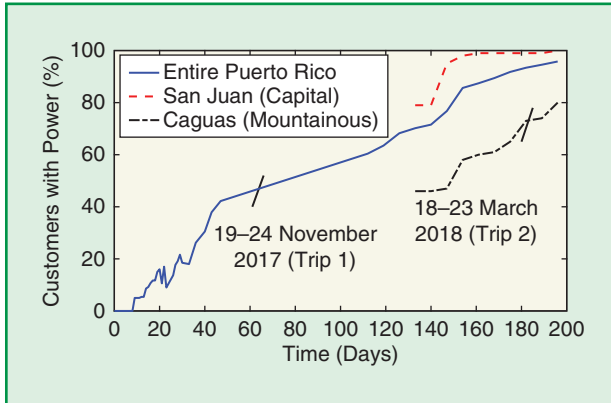


figure 1. The restoration of power to customers in Puerto Rico after Hurricane Maria, beginning on 20 September 2017. Note the significant difference between the San Juan urban area and the mountainous and directly hit region of Caguas.



figure 2. The devastation caused by Hurricane Maria in Puerto Rico. (Photos courtesy of the University of Washington, used with permission.)

how often each appliance was used and for how long. Table 1 summarizes time-of-use and duration data. Because there was no electricity during the first field trip, it was not possible to measure actual demands or load profiles, so the measured power values in Table 1 were obtained during the third trip. The maximum power drawn by the devices was used for sizing the inverter, whereas the entire load profile was required to size the PV and battery systems.

Diesel generators are commonly used in emergencies but were perceived as having the following drawbacks:

- ✓ Our interviews revealed that the condition of some asthma and COPD patients had worsened because of the exhaust gases (such as carbon monoxide) or the aerosolized soot particles produced by the diesel engines.
- ✓ Because of the noise, generators cannot be used at night to power the CPAP machines of sleep apnea patients.



figure 3. Some of the PV-battery systems installed in Puerto Rico by researchers at the University of Washington in Seattle. (Photos courtesy of the University of Washington, used with permission.)

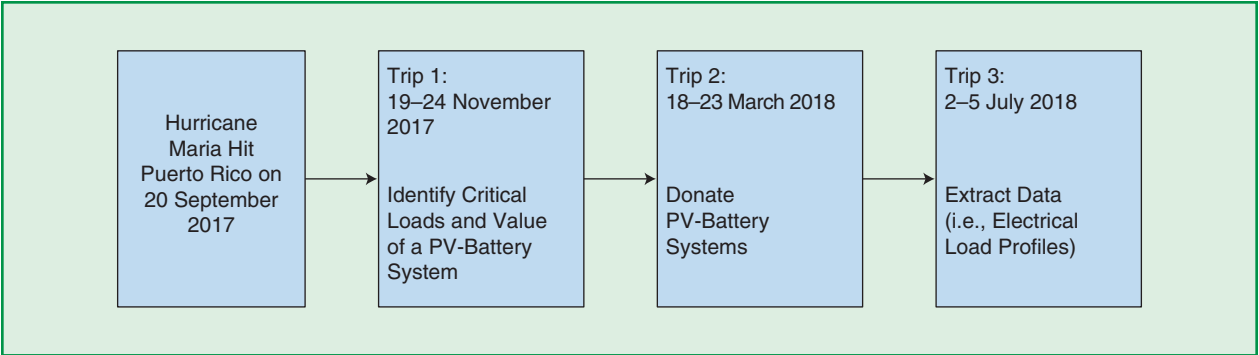


figure 4. The time line and purposes of the field trips.

table 1. The maximum and average measured power, time of use, and duration of critical electrical loads.

Device Name	Duration, Time of Use	Average Power	Maximum Power
PEG feeding machine	30 min, four times	<10 W	120 W (manufacturer)
Electrically actuated bed	30 s, ten times	18 W	53–65 W
Inflatable mattress	8–24 h	Lower than 10 W	<10 W
Nebulizers	5–25 min, two–four times	23–52 W	23–66 W
Oxygen concentrators	Up to 24 h	350 W	428 W
CPAP	9 h, 10 p.m.–7 a.m.	34 W	47 W
Refrigerator	8–24 h	136–352 W	140–392 W
Refrigerator (small)	8–24 h	20 W	97 W
TV	2–4 h, 3–9 p.m.	28–292 W	31–392 W

table 2. A summary of the various systems installed.

	PV Size (W)	Battery	MPPT	Inverter (kW)	Number of Installations
Type A	260	160 Ah (lead acid)	Yes	1	Six
Type B	100–200	80–100 Ah (lead acid)	No	1	Six
Type C	400	1.1 kWh (lithium ion)	Yes	1.1	Five
Type D	100	100 Ah (lead acid)	No	dc system	Four

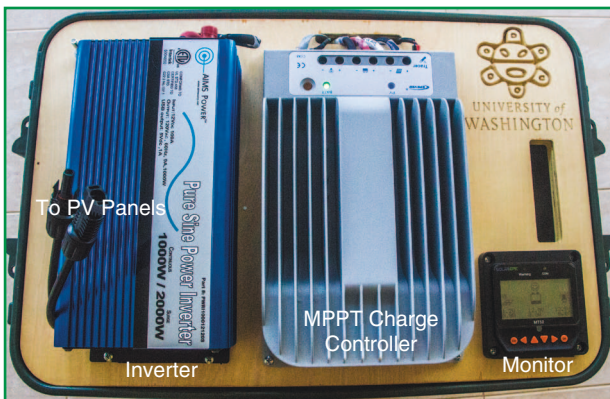


figure 5. The top view of a PV-battery system designed at the University of Washington. The batteries, data logger, and majority of the cables are inside the box.

- ✓ Reliable access to a supply of diesel fuel during an emergency can be difficult or impossible, particularly in a remote area.
- ✓ Using a generator can cost up to US\$10 per day. Over an extended period of time, this can be excessive for low-income households.
- ✓ Emergency diesel generators are often not designed for continuous use. Individuals would have to use them for periods of 2–6 h. For example, some households ran diesel generators up to 8 h per day (4 h in the morning and 4 h in the evening) to keep medicines cool. There were also many instances in which generators had broken because of overuse.

- ✓ Maintaining a generator (e.g., changing the oil) is challenging for some users because it requires time, knowledge, and money.

Second Field Trip: PV-Battery Systems Deployment

The goal of the second field trip was to install 17 stand-alone PV-battery systems of four different types and power ratings in households with individuals relying on electrically powered medical devices or medically related refrigeration needs. A summary of the installed systems is given in Table 2; four systems had been installed in the first trip. Because systems were not available for all households with critical medical needs, priority was given to those who lacked the resources to buy or obtain another source of electricity and those living in the more remote mountain areas.

Figure 5 shows a top view of a Type A system, which consists of an inverter, a maximum power point tracking (MPPT) solar-charge controller, a display monitor, lead-acid batteries, and data loggers to record the electrical load profiles, PV output, battery state of charge (SoC), and temperature. System Types A, B, and D were designed at the University of Washington, and system Type C was a commercially available system.

Because of budget and time restrictions, the systems were limited in capacity. Nevertheless, we anticipated that they would be able to meet at least some of the critical loads of individual households, either fully on their own or in tandem with diesel generators, if households were already using a generator.

Long-term power outages can be lethal to individuals who rely on electrically powered medical devices or require medicines that must be refrigerated.

Because these systems were sized from inaccurate load profiles based on the limited information collected during the first field trip, some of them were undersized. Although we encouraged the users to try not to discharge the batteries below recommended safety limits to maximize battery life, some batteries degraded prematurely because of excessive depth of discharge (DoD).

Third Field Trip: Data Collection and Analysis

The purpose of the third trip was to obtain the data collected by the data loggers in the installed PV-battery systems. Satisfaction surveys were also administered to gauge user experience and perceptions of solar energy as a form of emergency energy supply. These quantitative and qualitative data are analyzed in the next section.

Analysis of Field Data

We choose to analyze the six households that received Type A PV-battery systems because they were the only systems equipped with data loggers that could record all of the necessary data. Systems in five other households recorded only the load profiles.

Energy Consumption and Generation

Figure 6 shows the total daily energy consumption and PV generation over 47 days for six households where Type A PV-battery systems were installed. The energy-use pattern for household 6 is similar to the PV generation pattern, which shows that users managed to consume the PV generation on the same day. This energy-consumption pattern contributed to keeping the battery in good condition. Another important

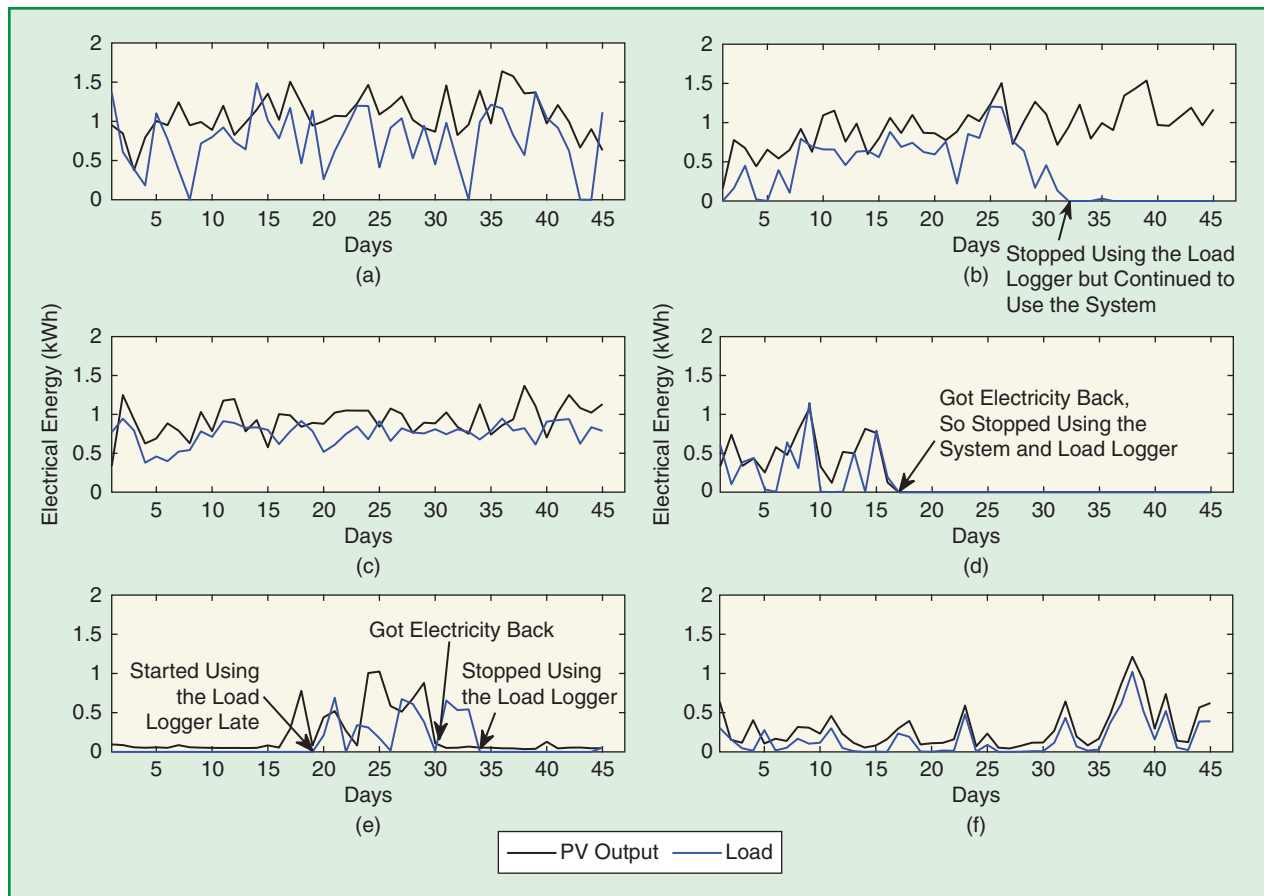


figure 6. The total daily load and PV output for six households over 47 days. Households (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, and (f) 6. The load was measured after the inverter.

The local clinic was without power until a backup generator arrived, and they lost medicine requiring refrigeration as well as all vaccines.

finding is that households 4 and 5 stopped using the systems after they regained grid power within one month after installation, whereas the other users continued to use the systems throughout the whole period.

Load Profiles

Figure 7 illustrates the load profiles for the days with the highest energy consumption for eight households. The

load measured corresponds to different devices specific to each household connected at each moment. For example, household 1 used the system to power a refrigerator (~150 W) from 7 a.m. to 3 p.m., an entertainment system (~375 W) for periods of an hour at a time, and a nebulizer (23–52 W) a few times a day for 45 min. Households 1–6 used most of their devices during the day when there was sun to maximize battery life. Nevertheless, they used the battery when

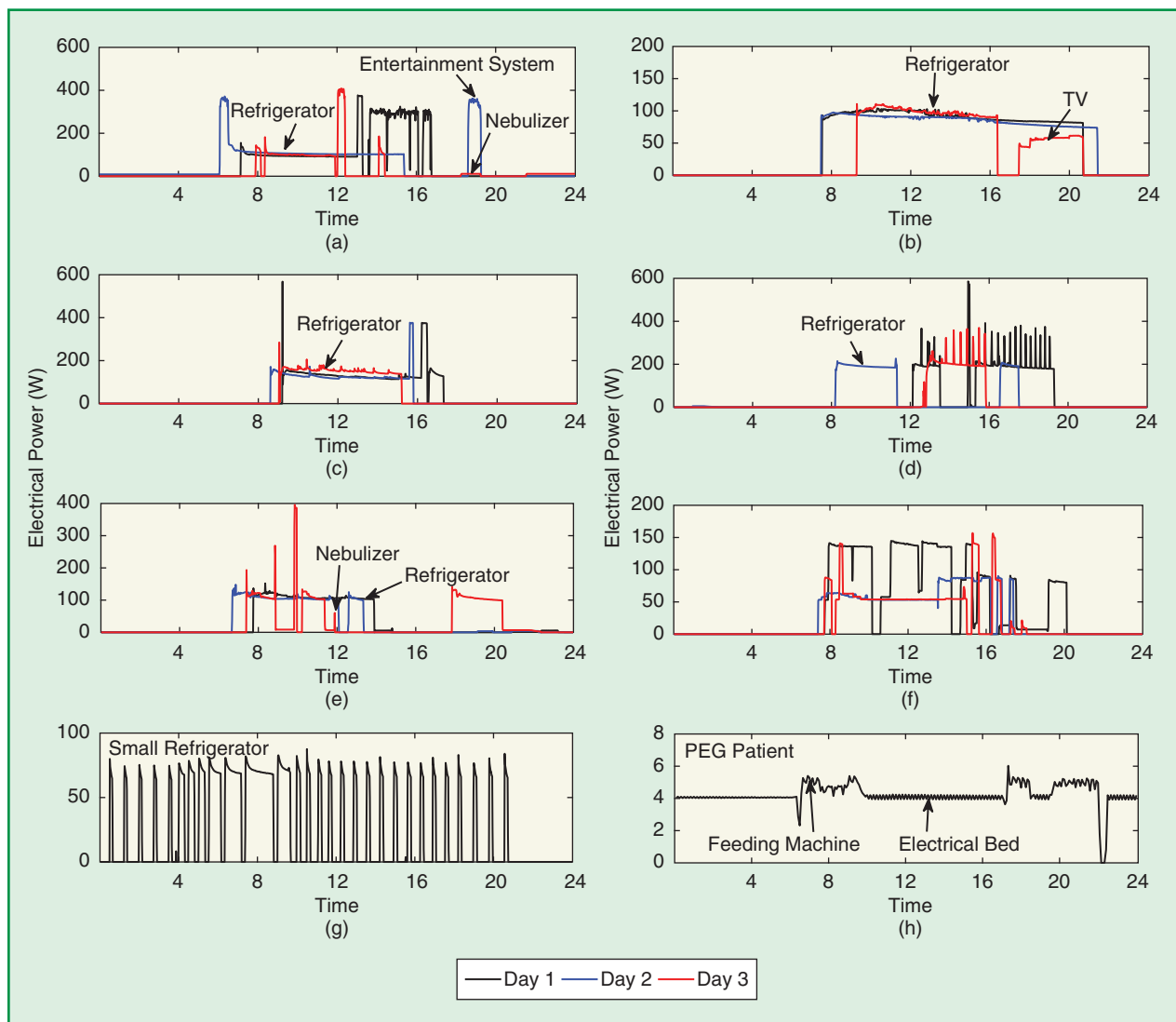


figure 7. The electrical load profiles of eight different households over one to three days. Households (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, and (h) 8. The load profiles consist of all of the critical devices; however, we were able to identify some of these devices through interviews, as noted in the figure.

Because battery use in emergency situations is likely to be poorly controlled, it is important to collect data about charge/discharge cycles so that information can inform the design of longer-life systems.

consumption was greater than PV generation, thereby increasing battery degradation. The PV systems given to households 1–6 are rated at only 260 W.

The days with the highest consumption from Figure 7 are used to construct the critical load percentages shown in Table 3. For households 1 and 2, the critical loads represent 17.2 and 15.4%, respectively, of the average daily load before the hurricane. This information was obtained from electricity bills dated before the hurricane. Unfortunately, it was not possible to obtain the loads before the hurricane for some households. These percentages can be used to create critical load profiles for other households in the future when designing microgrid systems for resilience.

Battery Degradation

Repeatedly discharging lead-acid batteries below a recommended SoC progressively degrades their energy capacity. Because battery use in emergency situations is likely to be poorly controlled, it is important to collect data about charge/discharge cycles so that information can inform the design of longer-life systems. All recipients of PV-battery systems were instructed to operate the battery within safe limits. As Figure 8(a) shows, households 5 and 6 used the systems such that the DoD of the battery rarely exceeded 50%. On the other hand, most of the discharge cycles of the batteries in households 1–3 exceeded a 50% DoD. This may

be inevitable, because critical needs might not occur during the daylight hours when PV generation is sufficient. We were able to confirm during the third field trip that the lead-acid battery of household 6 was still in excellent condition, but the residents of household 2 said that their battery was not performing as well as it did originally.

Because a battery's temperature also affects its useful life, the data loggers recorded battery temperature. As Figure 8(b) shows, even though Puerto Rico has a tropical climate, the battery temperatures generally remained within the expected limit of 20–25 °C, with the exception of the battery of household 5, where the temperature increased up to 30 °C. A possible explanation is that the household 5 is at a lower elevation than the others.

Survey

As shown in Table 4, all 15 households interviewed said that they would prefer a solar system over a diesel or gas generator for their energy needs. Among those, 14 said that they are

table 3. Critical and normal energy consumption for six households.

Household	Critical Load (kWh/day)	Load Before Hurricane (kWh/day)	Critical Load Percentage (%)	Cost of Generator Fuel (US\$/day)
1	1.5	8.67	17.2	10
2	1.2	7.77	15.4	7
3	1.2	—	—	10
4	1.1	—	—	—
5	0.7	7.5	9.2	—
6	1	—	—	—

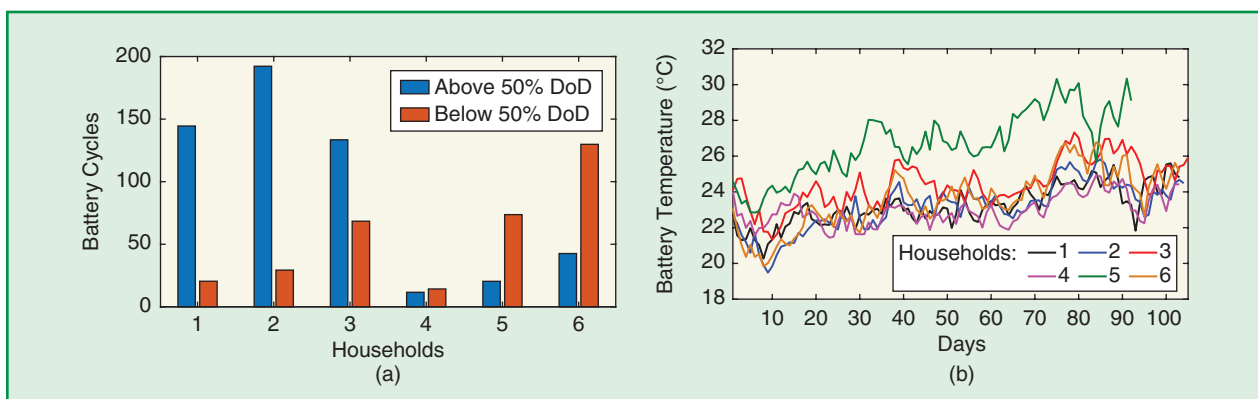


figure 8. The battery operation for six households over 105 days: (a) the number of battery cycles above and below 50% DoD and (b) the average daily battery temperature.

TV was critical to most families because it was a distraction from their current difficulties, was a source of entertainment, and provided information crucial to their well-being.

more comfortable using a PV-battery system. The household that answered “same” is household 4, in which electricity was restored within 18 days (Figure 6). Eleven households had used a generator before, and nine of the 11 that were actively using or had previously used a diesel/gas generator mentioned that the PV-battery system improved their health. One household was unfortunately provided with a defective commercial solar generator system that quickly broke down. They were given a replacement for use in future emergencies, but they gave our survey a low rating based on their experience.

Simulation Results and Discussion

A linear optimization method was used to minimize PV-battery system costs that are able to supply critical loads for a year considering PV and demand variations. Battery degradation cost over the lifetime of these systems was considered when choosing the optimal design. We consider the following scenarios:

- ✓ Case A involves household 1’s critical load profile as illustrated in Figure 7(a) and includes an efficiently managed refrigerator, a nebulizer, and an entertainment system.
- ✓ Case B represents a household with a PEG patient and a small refrigerator. The critical load profile is a combination of Figure 7(g) and (h).
- ✓ Case C is a household with a sleep apnea patient. The critical loads include the CPAP machine, a refrigerator, and a small TV. The critical load profile for this scenario was created using the data in Table 1.
- ✓ Case D has the largest critical load, which consists of a continuously running oxygen concentrator, a refrigerator, and a large TV.

An interesting finding was that TV was critical to most families because it was a distraction from their current difficulties, was a source of entertainment, and provided information crucial to their well-being.

PV output data for the optimizations are from the National Renewable Energy Laboratory’s PVwatts calculator. Lead-acid

batteries are assumed to last 200 cycles when the DoD is above 50% and 500 cycles when the DoD is below 50%.

Table 5 summarizes the operation of different combinations of battery and PV ratings for each case. In particular, it shows how much energy would be produced and consumed and how many charge/discharge cycles the battery would undergo in one, three, five, and ten years. The last four columns indicate the cost of each PV battery combination (capital cost), including battery replacement costs (maintenance cost), for a lifetime of one, three, five, and ten years. The cost of a system depends more on the number of battery replacements needed than on duration of the system. In some cases, the cost is the same for initial installations of larger batteries versus smaller ones that need replacing because of more frequent, deeper DoD operations.

The systems designed for cases A, B, and C provide some guidelines regarding the sizing of PV-battery systems for emergencies. Figure 9(a) shows how the optimal battery capacity decreases as the PV rating increases for case A’s system. Because we are interested only in the minimum battery capacity required to provide continuous power to critical loads, extra PV generation is curtailed to avoid having to increase the battery size. Figure 9(b) shows that, because the unit cost of batteries (US\$192/kWh for lead-acid batteries and US\$800/kWh for lithium-ion batteries) is much higher than the per-unit cost of PV generation (US\$1.5/W), the cost of the system decreases with decreasing battery size, even though the required PV rating increases.

Using lead-acid batteries leads to the lowest cost systems for cases A, B, and C for up to a three-year system life because, although lithium-ion batteries can be discharged completely and therefore have a smaller rating, their cost is still much higher. In particular, a system that lets lead-acid batteries discharge completely to meet critical loads is the least expensive solution for a one-year system life because such a system is effectively sized to minimize the number of battery cycles. When the expected system lifetime increases, limiting the lead-acid battery to 50% DoD is more economical because it reduces the required number of battery replacements.

On the other hand, case D requires such a large system that it would probably be economically

table 4. A summary of survey results.

	Solar	Generator	Same
Do you prefer solar or generator?	100% (15)	0%	0%
Which are you most comfortable using?	93% (14)	0%	6.7% (one)
	Yes	No	
Did you have a generator before?	11	Four	—
If yes, did solar improve your health?	82% (nine)	9% (one)	9% (one)

table 5. A comparison of various PV battery system designs.

Battery Type and DoD	Battery Size (Ah) at 12 V	PV Size (Wp)	Total PV (kWh), One Year	Total Load (kWh), One Year	Battery Cycles (n)				Cost (US\$)			
					One Year	Three Years	Five Years	Ten Years	One Year	Three Years	Five Years	Ten Years
Case A: Refrigerator, nebulizer, and TV												
Lithium ion (100% DoD)	100	800	1,291	484	78	235	392	783	2,150, r = 0	2,150, r = 0	2,150, r = 0	2,150, r = 0
Lead acid (100% DoD)	170	600	968		63	188	313	626	1,291, r = 0	1,291, r = 0	1,682, r = 1	2,464, r = 3
Lead acid (50% DoD)	260	700	1,130		36	107	178	356	1,648, r = 0	1,648, r = 0	1,648, r = 0	1,648, r = 0
Case B: PEG patient and small refrigerator												
Lithium ion (100% DoD)	60	300	484	197	166	497	828	1,655	1,020, r = 0	1,020, r = 0	1,020, r = 0	1,020, r = 0
Lead acid (100% DoD)	120	200	323		92	275	458	916	576, r = 0	852, r = 1	1,128, r = 2	1,680, r = 4
Lead acid (50% DoD)	120	300	484		88	263	438	876	726, r = 0	726, r = 0	726, r = 0	1,002, r = 1
Case C: CPAP, refrigerator, and small TV												
Lithium ion (100% DoD)	120	700	1,130	459	245	735	1,225	2,450	2,190, r = 0	2,190, r = 0	2,190, r = 0	2,190, r = 0
Lead acid (100% DoD)	270	500	807		117	351	585	1,170	1,371, r = 0	1,992, r = 1	2,613, r = 2	4,476, r = 5
Lead acid (50% DoD)	290	700	1,130		108	324	540	1,080	1,717, r = 0	1,717, r = 0	2,384, r = 1	3,051, r = 2
Case D: Oxygen concentrator, refrigerator, and TV												
Lithium ion (100% DoD)	950	4,900	7,907	3,594	219	656	1,093	2,185	5,900, r = 0	5,900, r = 0	5,900, r = 0	5,900, r = 0
Lead acid (100% DoD)	2,070	3,800	6,132		108	324	540	1,080	r = 0	r = 1	r = 2	r = 5
Lead acid (50% DoD)	1,980	5,500	8,875		110	331	552	1,103	r = 0	r = 0	r = 1	r = 2
The cost consists of only the PV and batteries, and r is the number of battery replacements. Wp is the nameplate value, which is a measure of watts at peak production.												

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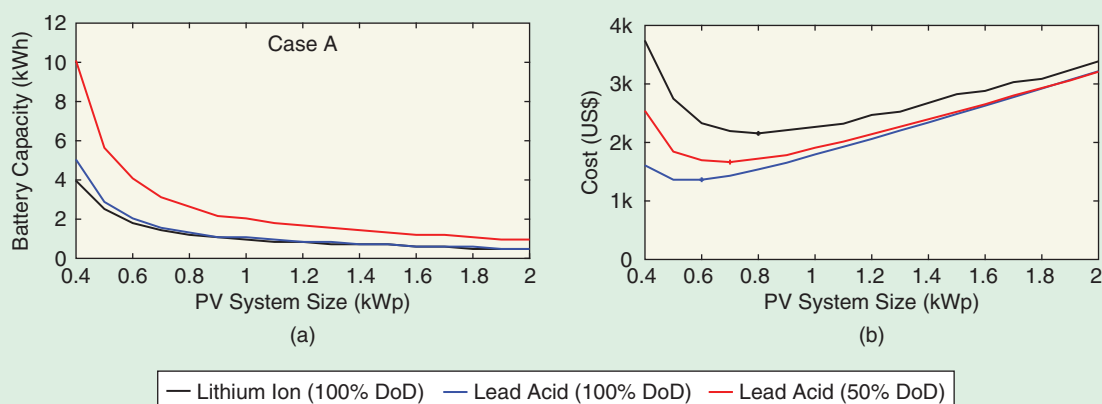


figure 9. (a) The minimum battery capacity required to power critical loads over a year for case A as a function of the PV rating. (b) The total system cost as a function of the PV rating.

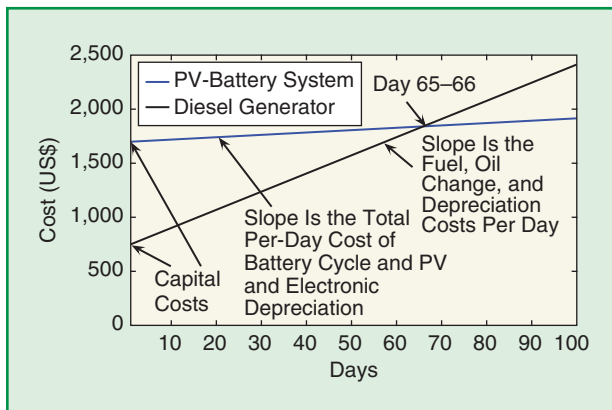


figure 10. A comparison of the cost of using a diesel generator versus a PV battery system during an emergency for case A.

beneficial to install a grid-connected system and operate it for nonemergencies as well. In this case, lithium-ion batteries would be less expensive because their cost is lower at larger ratings. The cost of the system in case D is based on a US\$0.75/W for PV and US\$195/kWh for lithium-ion batteries. Although lithium-ion batteries are currently more expensive than lead-acid ones, they are more convenient because they are smaller and lighter. They are easier for a user to move around the house to connect to various critical loads and also easier to deploy after a natural disaster.

Figure 10 compares the total cost of using a diesel generator and PV-battery system as a function of the duration of a power outage for case A (i.e., household 1). The capital cost of a generator is lower than for a PV-battery system. However, the ongoing costs of fuel, oil changes, and depreciation rise rapidly. On the other hand, the ongoing cost of running a PV-battery system largely depends on battery degradation because the PV panels and the other electronics are expected to last ten–15 years. These results suggest that any place likely to experience more than 66 days of power outages (cumulative over multiple events) would benefit from a PV-battery system. Longer usage loads (e.g., CPAP, air mattress, or oxygen concentrator) may inevitably need PV-battery systems or, at the very least, batteries that can be charged with a generator during its use because small diesel/gas generators are noisy when used at night and are often not designed for continuous use.

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For Further Reading

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