

A Comparison of Batteries for the MECS Project

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Introduction

Three different batteries of different chemistries and different design have been purchased and tested for use with efficient electric cooking appliances. These are:

1. Lithium iron phosphate (LiFePO₄, also known as LFP).
2. Valve-Regulated Lead Acid (VRLA). These units were manufactured by Yuasa.
3. Lead-Carbon, which is like lead-acid but with reported higher tolerance to deep cycling. These units were manufactured by Leoch.

In the context of the MECS project, the batteries are required to operate cooking appliances. In off-grid applications they are needed to store solar PV electricity. In weak-grid or mini-grid applications, batteries are needed to store electricity for later use, when grid electricity is more expensive, insufficiently powerful, or unavailable.

All the batteries tested have a nominal capacity of 100Ah and a nominal voltage of 12V. In the case of lead-carbon, a single 100Ah battery was used. In the case of VRLA and LiFePO₄, two 50Ah batteries of each were used to make a total of 100Ah when connected in parallel. See Appendix for details of specific batteries.

Battery Characteristics Important to the MECS Project

Useful Energy Capacity

All three batteries have a nominal capacity of 100Ah and voltage of 12V, making an energy capacity of 1.2kWh. However, this reported capacity is available by slow discharge over 10 hours (C/10 rate).

Even in the most efficient cooking appliances available, the required capacity is at least 0.1kWh per litre of water or equivalent to be heated from ambient temperature to boiling point. Sometimes the energy required is significantly greater than this. A realistic useful energy capacity would be enough to heat 5 litres of water per day. With heat loss, thermal capacity of the cooking device and conversion losses, a useful energy capacity would be about 0.7 kWh per day.

Useful Power Rating

The nominal energy capacity of a battery is available under ideal conditions, in a new battery. The example discharge rate quoted above, C/10, would give the batteries an energy capacity of 1.2kWh. However, this discharge rate would provide a power of just 120W.

For the purposes of the MECS project, the ideal power rating would be over 1kW. The tested electric pressure cookers (EPCs) have power ratings of about 1kW. Most electric hotplates have power ratings of 1kW to 2kW. Given that the cost of a battery-electric cooking system is strongly driven by the power rating, an acceptable electric power is approximately 700W, or 500W at minimum.

The power available from a battery reduces as its charge is depleted. Therefore, under high-power discharge, the voltage collapses sooner than under low-power discharge, and the effective available energy is reduced at high power. Furthermore, batteries are degraded by total cycles used, by power draw and by depth of discharge.

In the design of an electric cooking system, there is compromise and trade-off between energy capacity, power rating, cost and longevity of the battery.

Internal Resistance

The internal resistance determines the voltage rise or drop at the battery terminals for a given current injected or drawn from the battery respectively. It is important in determining the energy lost within the battery itself when charging or discharging. In the experiments conducted to date, only the discharging internal resistance has been measured. The charging internal resistance is different and will be determined in later experiments.

Battery Testing

Experimental Setup

The three batteries were tested using solar home system 'power hubs' connected to electrical appliances as test loads. The test equipment is shown in Figure 1. In some experiments, the appliance was connected directly to the output of the inverter, but in others it was connected via a Variac auto-transformer to reduce the voltage and therefore reduce the load. The combination of Variac and appliance thereby became a variable resistor. The Acksen power recorders were validated by comparison with a Yokogawa power analyser in some experiments. The Yokogawa measured AC currents, AC voltages and phase angles, both upstream and downstream of the Variac, whereas the Acksen only measured apparent power. When the load was almost entirely resistive (phase angle = 1.0), the Acksen was found to agree with the Yokogawa to within 1% accuracy.

The hotplate (manufactured by Sabichi) had a nominal power rating of 1.5kW, but when connected to a power hub inverter, its maximum power was found to be closer to 1.3kW at a voltage of about 230V.

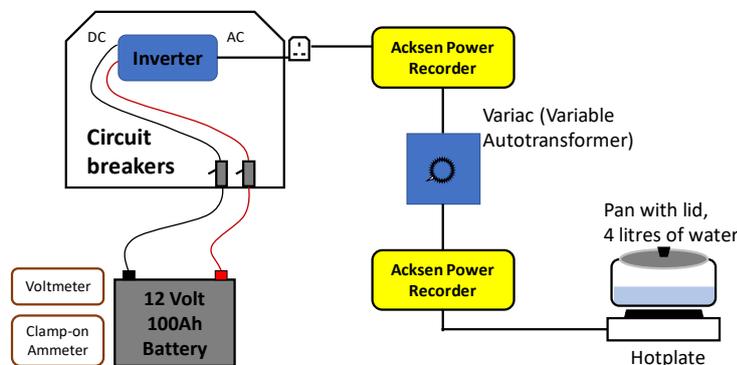


Figure 1. Experimental apparatus for battery testing

Battery Power Calibration with Hotplate power

For the hotplate to be a useful and quantitative measure of battery output power and cumulative energy output, its power consumption was calibrated by cross-reference to simultaneous measurements of the current and voltage at the battery terminals. This technique was also used, with the Yokogawa, to calculate the efficiency of the power hub (see separate report). The battery power as a function of hotplate power is shown in Figure 2.

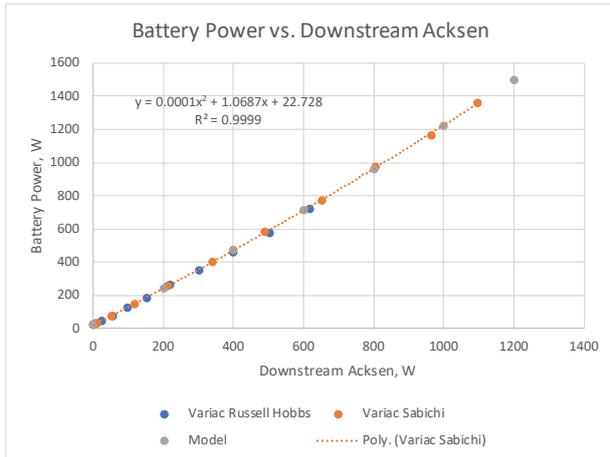


Figure 2. Battery output power vs. hotplate power

Test Procedure

1. The battery was first subjected to an increasing load by turning on the power hub inverter and setting the Variac to values between 0% and 100% in increments of 10%. This was done to measure the fully-charged power capability and the fully-charged internal resistance.
2. The battery was then discharged at the maximum load that did not trip the inverter. A fully charged battery was usually found to be capable of providing up to 1.3kW at 100% Variac setting. This sometimes temporarily tripped out the inverter in 'overload' fault. As the battery was depleted, the inverter again tripped out but this time due to low input voltage. The Variac was then progressively reduced in setting from 100% to 80%, 70%, 60% or even 50% each time the inverter tripped out. When the inverter quickly tripped out after each reduction in setting, it appeared that the battery was close to voltage collapse and considered almost flat.
3. Finally, the Variac was again set to value between 0% and 100% in increments of 10% until the inverter tripped out. This was done to measure the nearly-flat power capability and the nearly-flat internal resistance.

Test Results

The typical power output of a battery is shown in Figure 3. The power steps up during the first internal resistance test until the inverter trips out. The steady power endurance test for this battery, the YUASA VRLA, starts at 80% Variac setting, that being the maximum power delivered by the fully charged battery. The test continues to 70%, 60%, and 50% Variac settings. The final internal resistance test causes the inverter to trip out at a much lower power.

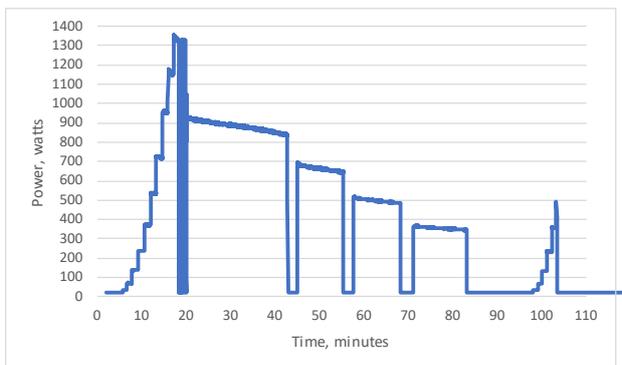


Figure 3. Battery power output profile during the test of the Yuasa VRLA batteries

The Acksen power recorder on the Variac output was used to measure the cumulative energy available from the battery.

Battery test results compared

The voltage-current characteristics of all three batteries are compared in Figure 4. The YUASA VRLA battery has the lowest starting voltage, and dips lowest during the initial power test. The lithium-iron-phosphate battery has the highest voltage, and its voltage remains highest even just before voltage collapse at the end of the final test.

All batteries suffer a drop in voltage at the terminals as they are discharged, firstly due to a drop in the open-circuit voltage. Hence the voltages are reduced when almost flat, even at zero current. The lithium-iron-phosphate battery has a drop in open-circuit voltage of just 0.7V whereas the others drop by well over 1V.

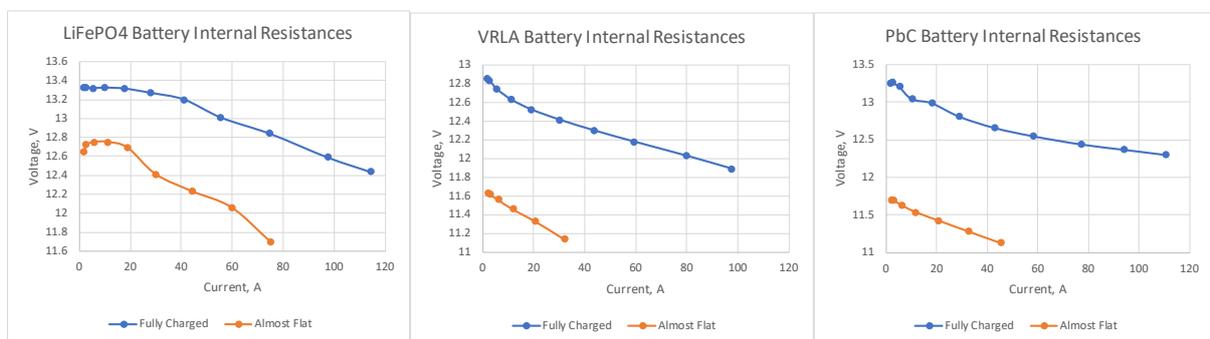


Figure 4. Current-voltage characteristics of three battery types when fully charged and when mostly discharged.

The second reason for a drop in battery terminal voltage is internal resistance. Using the central portions of each test, a linear trendline can be plotted. The gradient of this trendline indicates the internal resistance, Figure 5. The lithium-iron-phosphate and lead-acid batteries have very similar internal resistances, but the lead-carbon battery has a lower resistance, both at the beginning and end of the discharge test.

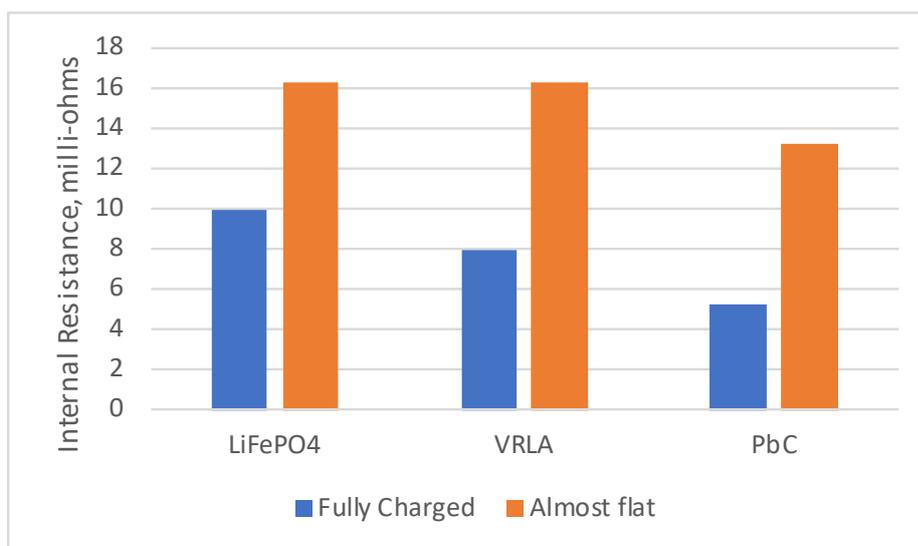


Figure 5. Internal resistances of the batteries

The total energy extracted from the batteries and final continuous power before voltage collapse are plotted in Figure 6.

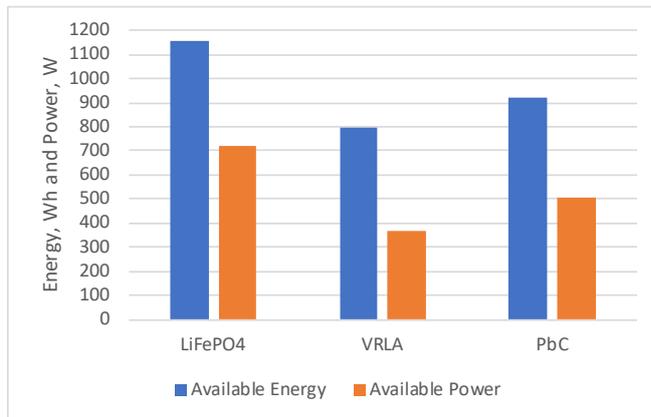


Figure 6. Available energy extracted during the test and power drawn before voltage collapse

Discussion

Based on the tests above, the lithium-iron-phosphate battery appears better than either of the lead-based chemistries. Only the lithium-iron-phosphate can deliver 700 watts until it is almost flat, and it is the only one to come close to delivering its nominal capacity at C/2 discharge rate.

However, the power and energy delivery of these nearly new batteries, in their nearly new condition is not the only consideration when choosing a battery for an electric cooking system. Cost, degradation rate (useful cycle life) in real world use and local availability are equally important. Table 1 compares these design considerations. The reported cycle life was supplied by manufacturers. Generally, the greater the Depth of Discharge (DoD) the shorter the life expectancy so the reported values may not reflect real situations.

Table 1. Summary table comparing battery chemistries

Battery type	Measured energy output from 1.2kWh battery (Wh)	Measured power from 1.2kWh battery (W)	Reported cycle life (DoD not clear)	Operating temperature range	Purchase cost per kWh See Appendix
LiFePO4	1160	718	2000 [1]	-20C to 60C [2]	£640
VRLA	795	365	1000 [3]	-15C to 40C [3]	£130
PbC	923	504	2500 [4]	-40C to 60C [5]	£210

Conclusions

Of the three battery chemistries tested, the lithium-iron-phosphate (LiFePO4) is clearly superior to the lead-acid and lead-carbon. It maintains a higher open-circuit voltage and can deliver much more energy at high power. Its energy delivery before voltage collapse is almost the nominal capacity of 1.2kWh. LiFePO4 is the only battery chemistry to deliver up to 700W continuously, the required power rating for electric cooking, at a nominal capacity of 1.2kWh.

The lead-carbon battery can deliver up to 500W continuously until voltage collapse, the minimum level of power required for electric cooking.

The valve-regulated lead-acid (VRLA) battery has poorer performance and is unsuitable.

Appendix

Battery	Unit purchase cost VAT not included (2019)	Cost per Wh
LI50-12, 12V 50AH LITHIUM IRON... (600Wh) https://www.batterymasters.co.uk/lithium-phosphate-batteries/li50-12-12v-50ah-lithium-iron-phosphate-lifepo4-high-capacity-deep-cycle-battery-charger-included.html	£385.60	64p
PLH+C100 pure lead carbon battery(1.2kWh) https://batterystore.co.uk/plh-c100-pure-lead-carbon-series-battery.html	£250	21p
Ultamax NPG50-12V 50AH (600W) https://www.batterymasters.co.uk/ultramax-npg50-12-12v-50ah-as-40ah-45ah-emergency-light-lighting-gel-battery.html	£77.78	13p

References

- [1] Li50-12, 12v 50Ah Lithium Iron Phosphate, LiFePO4 High Capacity Deep Cycle Battery
<https://www.batterymasters.co.uk/lithium-phosphate-batteries/li50-12-12v-50ah-lithium-iron-phosphate-lifepo4-high-capacity-deep-cycle-battery-charger-included.html>
- [2] Lithium Iron Phosphate Battery
<https://www.batteryspace.com/prod-specs/9055.pdf>
- [3] Gel Battery Technical Manual
https://files.elv.com/service/manuals_hw/71974_Blei_Gel_Akku_UMenglich.pdf
- [4] PLH+C100 - 12v 100Ah Pure Lead Carbon Series Battery
<https://batterystore.co.uk/leoch-plh-c100-leisure-battery/>
- [5] Pure Lead Carbon Technology
<https://batterystore.co.uk/content/SpecSheets/Leoch/Leisure/PLH/PLHC-100.pdf>