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Published in: 2022 IEEE Global Humanitarian Technology Conference (GHTC), Santa Clara, CA, USA.
DOI: 10.1109/GHTC55712.2022.9911006
Published version: https://ieeexplore.ieee.org/document/9911006/

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The repurposing of nickel metal hydride hybrid electric vehicle batteries for solar energy storage applications in rural Pacific Island communities

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***Abstract*— With the transportation sector taking a significant proportion of global emissions, the production of hybrid electric vehicles has been increasing. These vehicles have begun to penetrate emerging economies that do not have battery recycling programs seen in developed economies. In Fiji, there are an estimated 15,000 spent Toyota Prius nickel metal hydride batteries in landfills that have a substantial environmental footprint that can be repurposed for off-grid rural solar applications. Using a sample of 62 used Prius modules, constant current tests were performed to characterize the modules and were sorted to develop packs suitable to deliver one day of the World Bank's Tier 2 electricity access. The packs can deliver the daily required 15.4Ah of power for rural households in Fiji and maintained Coulombic efficiencies between 85-95 percent. To pilot these systems, algorithms for a solar charge controller need to be developed using parameters determined in this study. Additionally, electrochemical impedance spectroscopy measurements should be made to create relationships between impedance, capacity, and state of health that will reduce the testing time to characterize modules. Utilizing these methodologies, a product life extension model can be implemented to reduce the batteries' environmental impact while providing cost-effective rural energy access.**

Keywords—battery repurposing, emerging economies, hybrid electric vehicle, nickel metal hydride, off-grid solar energy storage

I. INTRODUCTION

The growing severity of global climate change is radically transforming industries towards electrification. Within the transportation sector, hybrid electric vehicles (HEVs) have taken the largest proportion of these green vehicle alternatives of the global marketplace with many of the notable models produced by Toyota, such as the Prius. Although many electric and hybrid electric vehicles use lithium-ion batteries, the Prius predominantly uses the nickel metal hydride (NiMH) battery chemistry. With a growing number of these batteries reaching their end-of-life in vehicles, there is a substantial battery waste stream being developed.

Life cycle assessments of NiMH batteries show that the chemistry has a higher environmental and human health impact when compared to their lithium counterparts. However, production of this battery type for HEVs has continued due to their reliability, longevity, and resiliency in a wide spectrum of world climates. While the automotive market seeks to replace NiMH batteries with lighter, more energy-dense replacements, thousands of these HEV batteries will be set to retire in the upcoming years. In addition to supporting the electrification of vehicles, batteries have also continued to play a pivotal role in rural electrification, especially in emerging economies. Unfortunately, batteries continue to be the most expensive part of stand-alone solar home systems, especially with the cost reductions in solar panels. Reducing the cost of these batteries can improve the overall access to energy in these remote communities, improve resiliency, and encourage electricity demand growth.

Field Ready, a global NGO, observed in their work in Pacific Island Nations that there were an overwhelming number of used Toyota Priuses on Fiji, nearly half of their vehicles, in support of Fiji's Low Energy Development Strategy 2018-2050. Due to strict laws and inspections in Japan for older vehicles, many second-hand vehicles are exported out of the country throughout the Asia-Pacific region. Although Fiji has a high percentage of their populous connected to the main electricity grid, Fiji contains over 300 islands, with more than 100 being inhabited. On these remote islands and rural areas, energy access is often non-existent or is expensive and difficult. This study seeks to characterize Prius battery modules and analyze their applicability of use for solar homes in rural Fiji, as well as the implications of the environmental business model of reuse to the global hybrid electric vehicle marketplace.

II. NIMH HEV BATTERIES

A. HEV Industry

Market forecasts indicate that HEVs are predicted be a substantial part in the vehicle electrification, edging out all other alternative vehicle options, although gasoline-based vehicles will still have the highest market share [1]. Currently, Toyota is the largest producer of HEVs with over 44 individual hybrid electric vehicle models, passing 15 million HEV total global sales since their first HEV in 1997 [2]. The most notable HEV vehicle, the Toyota Prius has multiple new generations and other varieties such as the Prius Prime that all use a Panasonic NiMH

six-cell prismatic battery module. Other Toyota HEVs such as the Camry and Lexus also use these modules. As HEV production increases worldwide, NiMH battery waste streams are going to increase, and a resilient supply chain will have to develop in kind especially as they have a substantial environmental footprint that needs to be evaluated to reduce their environmental impact and maximize their use

B. Environmental Impacts

Life cycle assessments (LCAs) are a systematic approach to determine and evaluate the potential environmental impacts of a product throughout their entire life cycle. Several comparative life cycle analyses have been made comparing NiMH and li-ion batteries within vehicle applications to determine which chemistry has the highest environmental impact. These studies have all shown that there are significantly more environmental impacts caused by NiMH batteries than lithium-ion. The comparative LCA had a cradle-to-gate scope on the production of prismatic vehicle batteries, using a li-ion battery that had a capacity of 4Ah and a NiMH battery with a capacity of 4.5Ah with a functional unit of 1kg [9]. In every methodology, NiMH batteries had a higher environmental footprint as seen in Figure 1 with the CML midpoint and ReCiPe endpoint methods through SimaPro.

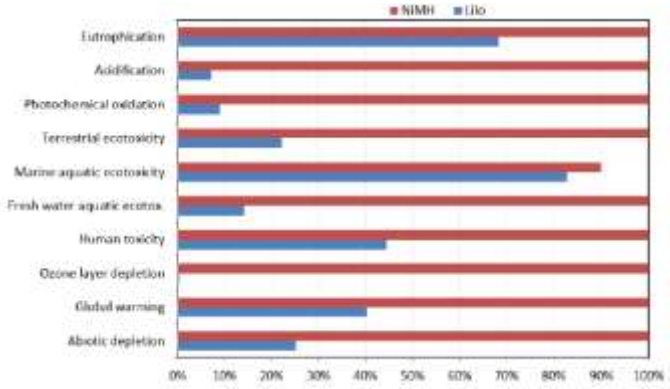


Fig 1. LCA outcome comparison using the CML midpoint method [9]

All these indicators reflect that the production and use of NiMH batteries in HEVs are detrimental to the environment and human health. However, there is a gap in the literature on HEV NiMH or li-ion environmental impacts within their end of life. It is important to consider that not all these batteries end up in recycling, but in landfills, as in the case of Fiji. Kilgo et al. investigated the metal leaching of li-ion, NiMH, and photovoltaic (PV) modules in simulated landfill leachates and municipal solid waste materials. The study looked to identify what the potential toxicity was from these products by observing leaching levels in correlation to the US Environmental Protection Agency's (EPA) toxicity characteristic leaching procedures (TCLP) and batch leaching tests with and without simulated municipal solid waste (SMSW) [3]. The results in showed that a NiMH power tool battery leaked significant amounts of arsenic above the regulatory limits for TCLP in the United States and cobalt and nickel surpassed limits set by California.

A National Renewable Energy Laboratory (NREL) Study reviewed the NiMH status for use in Electric Vehicles under environmental, health, and safety (EH&S) issues. They determined that environmental risk was small and fell under the leaching limits set by the US EPA. However, the battery leached concentrations above the standards set in California and European Union [4]. This aligns with more stringent European Union regulations on NiMH HEV batteries as set by European Direction 2000/53 [5].

C. Recycling

Due to the rising demand for battery materials, there is a consensus that the electric and hybrid vehicle industry must investigate into the increased and more efficient recycling of batteries for the recovery of rare materials. Toyota proclaims that they are required to make sure that their vehicles are 85% recyclable and 95% recoverable and have reached 90% hybrid battery recycling in Europe [5]. Although there is a consensus on the need to recycle and recover, many of these frameworks are established in developing economies such as Europe, North America, and parts of Asia. In other areas of the world, the market penetration of these vehicles, supply chain logistics, and recycling facilities, are not at the point where they can feasibly manage this issue.

One study used a LCA of these batteries to look at how recycling would impact the overall environmental impacts of various battery chemistries used in vehicles seen in Figure 2. The assumptions made in this study is that there is almost a 100% material recovery and the material recovery is of virgin quality [6]. If efficient recycling standards were implemented with a strategic battery supply chain, almost all environmental losses from production could be recuperated from NiMH batteries. Recycling NiMH HEV batteries decreases the overall environmental impact of the battery while avoiding landfill metal leaching that could occur if batteries are improperly disposed of.

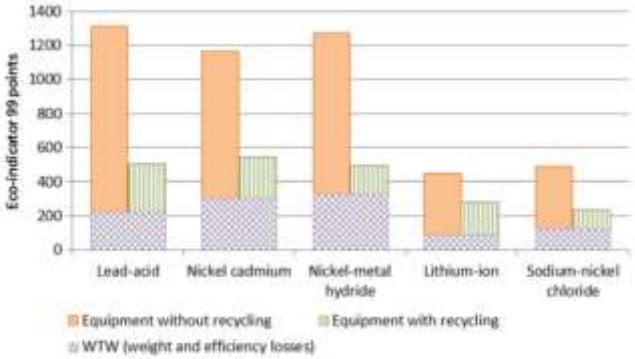


Fig 2. 1 Eco-Indicator results with and without recycling for different battery types assuming vehicle life distance of 180000km and 3000 cycles [16]

D. Sustainable Business Models

By applying relevant business models to the HEV battery waste industry, the environmental impact of these batteries will reduce and create a circular business advantage. Toyota has already begun to attempt to include more circular inputs through their design, with 'materials' being one of their four environmental sustainability focuses in support of the UN SDG 12: Responsible Consumption and Production [7]. One business model, pproduct-use extension works to provide additional llifecycle services that would resell, maintain, repair, or remanufacture to extend the lifespan of the product [8].

With older hybrids produced in the 2000s and early 2010s, many of these vehicles had or are having their batteries start to underperform. This has created another industry in developed economies of battery *reconditioners* or *refurbishers.* These reconditioners and refurbishers take old hybrid vehicles and disassemble their batteries, testing them, swapping out components, retesting them, and delivering them back to the vehicle owner. However, these refurbishers do not work on repurposing the batteries, another potential for these batteries.

Toyota has one publicized instance of battery repurposing for an off-grid solar energy system which is at Lamar Buffalo Ranch in Yellowstone National Park. Using 208 old Toyota Camry batteries in 2016, Toyota installed a 85kWh energy storage backup on site, "the first of its kind to use recovered hybrid vehicle batteries for commercial energy storage" [9]. In a conversation with personnel at the ranch, the system is currently nonoperational as the power electronics used to maintain the batteries failed. These electronics have not been replaced and the batteries self-discharged due to not being charged in a long time.

The reuse of NiMH HEV batteries can have a substantial environmental benefit in scenarios like the one installed at the Lamar Buffalo Ranch. A study by Tohoku University in Japan looked at a fleet based LCA under three scenarios: non-recycling (landfill), recycling, and reuse & recycling [10]. This study mentions that the NiMH collection rate in Japan is low, although it is the largest HEV market worldwide. For example, in 2018, 28,443 HEVs and 7124 waste batteries were collected by appropriate routes while 150,000 vehicles were exported to developing countries [10]. Tohoku University's study used a research scope of manufacturing, transportation, collection, landfill, reuse, and recycling. The reuse scenario assumed for the repurposing or remanufacturing of the NiMH batteries back into 'new' NiMH HEV batteries, with a recycler grading batteries into 'recoverable' or 'unrecoverable'. These scenarios are summarized in Figure 3.

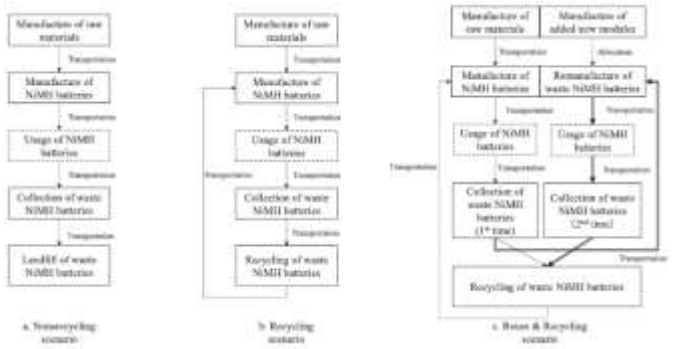


Fig 3 Research scope of the three studied scenarios by Tohoku University. [20]

Under IDEA, the categories of resource depletion, climate change, occupied landfill volume, and non-renewable energy demand are all summarized in Table 1. The reuse & recycling scenario has the most beneficial environmental impact with low the lowest score in each category. This shows the impact that moving towards a sustainable business practice can have on the environment.

TABLE 1 ENVIRONMENTAL IMPACT OF NIMH BATTERIES UNDER EACH SCENARIO. MODIFIED FROM [11].

Scenarios	Environ. Impact	GHG Release in kg of CO_2	Resource Depletion (kg-Sb)	Non-Renewable Energy (MJ)	Landfill Volume (m^3)
Non-Recycling	Negative	343	1.13	5160	0.052
Recycling	Negative	517	1.403	7366	0.013
	Positive	-150	-0.9	-2000	-0.002
	Net	367	0.503	5366	0.011
Reuse & Recycling	Negative	713	1.96	10149	0.018
	Positive	-450	-2.2	-6500	-0.015
	Net	263	-0.24	3649	0.003

E. Prius Module Repurposing

Nickel metal hydride batteries are known to be extremely resilient batteries, operating in a wide temperature range, with reconditioning/refurbishing potential. There have been several studies looking at the repurposing of NiMH batteries of various types from household batteries, phone batteries, and HEV batteries.

Prius batteries are known to be able to be used for extensive periods of time if kept within a narrow state of charge (SOC). Through a DOE study on a 2010 Toyota Prius, it was seen that after 160,000 miles of controlled testing, the measured capacity of the Prius batteries dropped from 6.09Ah to 4.94Ah, a decrease of only 19% [11]. With this potential remaining capacity, Prius batteries can be prime candidates for reuse.

Taking into consideration these different aging parameters, a failure analysis was performed by Peter Leijin and Jonathon Scott from AECS and the University of Waikato. This research showed that in a Prius pack with every module in series, all the modules perform at the capacity of the worst module. An example was shown through a vehicle that had 38, 2400mAh modules driving in electric vehicle mode that could drive 2.6km [12]. However, when one of those modules was replaced with one of half capacity (1200mAh), the vehicle could only drive 1.3km [12]. Leijin and Scott conducted coulomb counting tests on each module for four different donated HEV battery packs seen in Figure 4. Through these battery samples, while some Prius battery packs aged linearly, some batteries had modules that had extremely varying capacities.

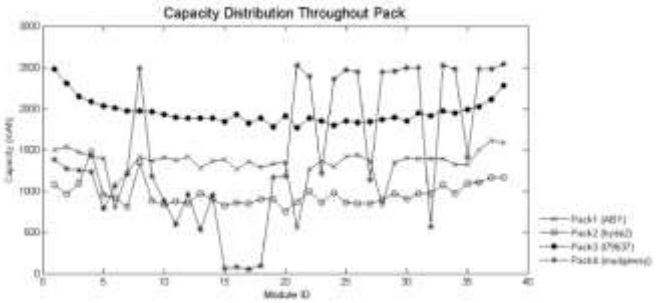


Fig 4 Capacity distribution within four Prius packs, Modified from [13]

It is important that when these NiMH batteries are repurposed for these solutions that they are disassembled and have their modules tested for their SOH to match them to other modules that are in a similar state through constant current cycling or EIS. This testing must occur with proper equipment with harnesses for the batteries. Through these practices, a new circular supply chain and business model can be created for used NiMH HEV batteries that will reduce resource depletion and extend the use of these batteries. One application of these batteries would be to complement them with solar energy to provide off-grid power in communities that do not have access to reliable electricity. This business model is especially appropriate in Fiji that is continuing to receive used Priuses from Japan and have an ever-increasing NiMH battery waste stream that are ending in landfills or warehouses. Additionally, Fiji has a substantial number of islands that are not connected to the national electric grid and need a resilient option for solar energy storage to encourage development while maintaining environmental sustainability.

NiMH Solar Home Systems

A. Off-Grid Solar Market and Costs

The United Nations reports that the growth in the renewable energy sector has been due to the expansion of wind and solar power in connection with expanded policy support and cost reductions [13]. Within emerging markets in lower income countries, solar home systems are installed based off a variety of financing schemes. Some systems are paid for outright either by the user or through donations while others are pay-as-you go (energy as a service) or pay-to-own (loan). However, these systems can be a large monthly expensive for users with low incomes and can have electricity service cut with missed payments. A basic solar PV system will consist of a solar panel, battery, charge controller, and lights. Additionally, there will be other costs for wiring and labor/installation. A cost breakdown is seen in the Figure 5 developed by IRENA, summarizing cost component shares for small scale solar systems (<1kW) in Africa from 2012-2015 [14]. The x-axis represents different surveyed solar home systems.

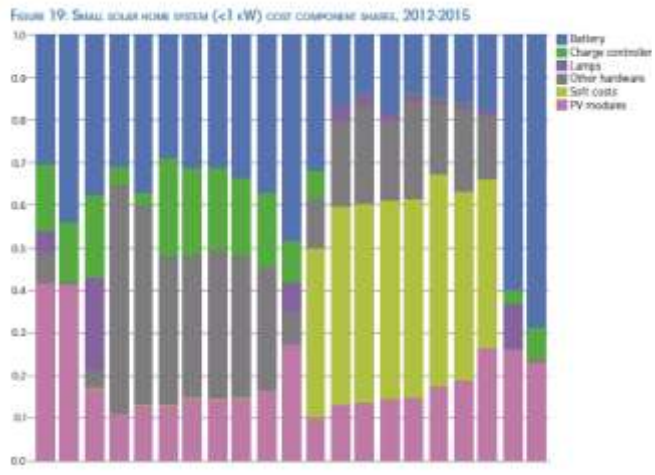


Fig 5. Small scale solar home system (<1kW) cost component shares, 2012-2015 [15]

It can be seen in these systems that the battery took 14 – 69% of the total cost of the small-scale PV systems but were also the most variable cost depending on the battery sizing, how many days of battery back-up for the system, etc. The battery is most commonly the largest cost of a system at 29%, while the average cost of the solar panels is 20%. Throughout all of these off-grid solar home evaluations, nickel-based batteries (NiMH or Nickel-Cadmium) are not included by world energy agencies and organizations. These battery types have not been used within off-grid solar home systems and do not have the extensive range of products available such as solar charge controllers that are common for lithium or lead batteries.

B. NiMH Solar Charge Controllers

The solar charge controller is a vital component within any off-grid solar system. The solar charge controller works to maintain a solar system by managing the flow of electricity between the electrical components. Although NiMH batteries could be connected in a series of 10 to fit within a standard 12V solar home system, there are several complications to their use. One of these issues is connecting batteries in parallel.

NiMH batteries do not have a documented set cut-off voltage for their full SOC but are in a general range between 1.4 to 1.6V [15]. The general way that NiMH batteries are detected at the full (100%) SOC is a negative dV/dt, a drop in voltage overtime. Extra energy being put into the battery is directly converted into heat and pressure of the nickel cell. . This becomes an issue when NiMH batteries are put in parallel with each other. The final end-of-charge (EOC) voltage of these batteries can depend on their SOH. If one battery starts to exhibit their –dV/dt before another in parallel, the other battery will attempt to balance their voltages by discharging itself into the full battery. This results in the further overcharging of the battery, further increasing the temperature and pressurization of the battery until it is eventually destroyed.

Different studies showed various ways to determine the EOC for series NiMH through solar charging by using voltage, temperature, and conductance characteristics. Each of these characteristics could be applied to Prius modules as well. However, most of these algorithms were developed for 10-cell series NiMH systems to match a 12V system like lead-acid batteries and use wide-spread commercial solar panels. However, as Prius modules have 6 cells each, two modules should be connected in series to create a nominal battery pack voltage of 14.4V. These batteries also have a set capacity which would require more batteries in parallel for a larger load. New charge controllers must be developed for these battery packs that could adopt similar charging algorithms described above.

A. Voltage Limit Algorithms

In the battery test performed by the US DOE on the 2010 Toyota Prius HEV, the vehicle battery was tested to the life of 160,000 miles . From the static capacity test, the following results were developed that features the maximum cell voltage (V_{max}) and minimum cell voltage for the NiMH battery for a 1-C rate, different than the manufactured specified 1/3 C-rate. It can be seen in Table 2 that in the beginning-of-test (BOT), the maximum cell voltage was 1.5V, 9V per module. However, at the end-of-test (EOT) the V_{max} dropped to 1.46V, 8.76V per module. This shows that as the cells degrade from their use, the

maximum obtainable cell voltage will continue to drop. For each vehicle, it is unknown what SOH each module is and what maximum cell voltages they have. This comes back to the issue that if this V_{max} differs for two parallel modules, thermal runaway may occur as one battery reaches a full SOC before the other.

TABLE 2 HYBRID PULSE POWER CHARACTERIZATION TEST RESULTS

	10s Discharge Power Capability (kW)	1s Discharge Power Capability (kW)	10s Charge Power Capability (kW)	1s Charge Power Capability (kW)	Maximum Cell Voltage (V)	Minimum Cell Voltage (V)
BOT	19.6	26.4	16.3	23.0	1.50	1.00
EOT	17.1	25.1	22.2	27.1	1.46	1.00
Difference	2.5 (13%)	1.3 (4.9%)	-5.9 (-36%)	-4.1 (-18%)	—	—

This gives one option to set a solar charge controller at a voltage level that does not reach the V_{maz} of any cell, reducing the risk of thermal runaway and overcharging any battery module. For example, if a voltage of 1.40V per cell is chosen, in a two-series Prius module solar battery pack, a maximum voltage of 16.8V is obtained, 8.4V per module. This reduction in overall voltage can give a larger possibility of increasing MPPT and PWM controllers efficiency on standard 12V solar panels. However, the reduction of this voltage also coincides with a reduction of capacity as each pack will never reach its full SOC. To increase the efficiency, solar charge controllers can also have a different voltage setpoint depending on the SOH of the battery. These characteristics and algorithms need to be observed at different C-rates to determine what cut-off voltage is the best for the batteries to be applied to the charge controller.

C. Solar Design

In coordination with Field Ready, a discussion took place to identify suitable locations to pilot the solar home systems with used Prius batteries in Fiji. Their team identified Dama Village in Bua Province located on the northern island of Vanua Levu that has around 40 households [16]. Entering the coordinates of Dama Village, the solar insolation data for the site can be retrieved using Global Solar Atlas. When considering this solar design, the worst month is designed around to ensure resilient energy access throughout the year. This results in a $PV_{out, Feb}$ of 3.758 kWh/m^2 per day which will be used for the designing of solar systems and battery sizing calculations in Dama Village.

The load profile determination for each household would be an extensive and resource demanding process. Therefore, one way to design around this is to utilize a load profile that represents a certain level of energy access. Several organizations have developed matrixes for tiers of energy access, including the the World Bank in conjunction with the Energy Sector Management Assistance Program (ESMAP) seen in Table 3. The Tier 2 load comprises of services such as electrical lighting, air circulation, televisions, and phone charging along with other low-powered electronics such as radios. Lighting use in this scenario can go beyond simple task lighting directed towards education, cooking, security, etc. This tier also has a minimum availability requirement of four hours during the day and two hours at night, a combined minimum of six hours of use. This study considered the minimum power capacity requirements for Tier 2 of 200Wh and assumed that the overall growth rate is negligible.

TABLE 3 MULTI-TIER MATRIX FOR MEASURING ACCESS TO HOUSEHOLD ELECTRICITY [17]



PRIUS MODULE CHARACTERIZATION

In this study, a random sample of 62 modules donated by two hybrid vehicle battery refurbishers in the United States were characterized. These modules could have come from any vehicle that used the same NiMH Panasonic battery such as the Prius or Prius Prime. These modules did not meet the refurbishers minimum requirements for reuse in HEV applications and were destined to be recycled. This study has four goals. First, identify the donated module capacities and observe common traits that identify module suitability. Second, test a variety of chargers to observe their applicability for properly charging and discharging the NiMH batteries. Next, build battery packs with the specifications required for an ESMAP Tier 2 load. Lastly, test the thermal performance of these batteries under charging conditions.

A. Module Analaysis

Each NiMH module has a nominal voltage of 7.2V, a combination of six, series-connected individual cells. These individual prismatic cells can be seen clearly on the module in Figure 4. The modules have small bumps that press up against each other to reduce volumetric expansion and allow air flow to cool the batteries when charging. Each battery pack combines these modules in series and has an end cap and four supporting rods that pressurize the NiMH batteries seen in Figure 6.

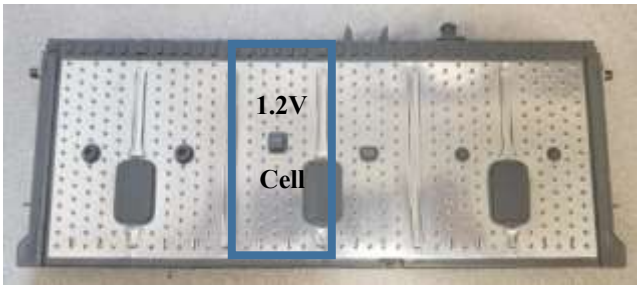


Fig 6 Prius module with outlined cell

The first tests were made on individual modules to measure their capacity drop from the manufactured capacity of 6.5Ah or 6500mAh. Through these studies, several initial assumptions were made. From the preliminary testing of a few modules, it was assumed that the Prius modules had roughly half of their remaining capacity, 3250mAh. This capacity was used to determine the initial charging and discharging current rate

B. Methodology

A cell voltage of 1.4V is assumed to be under this V_{max} of our used modules and a module V_{max} of 8.4V was used as a cut-off charging voltage. Using a requirement from the battery of 222Wh, accounting for system efficiency loss, a required battery capacity of 15.43Ah for one day of energy storage. The average power demand would be 37.03W. A constant current discharge at 0.5 A was used for the initial testing. And a constant current at 1.0A was used for the charging cycle.

The equipment used to conduct the charge/discharge cycling of these batteries were separated into enthusiast, hobbyist chargers and lab-grade chargers. These enthusiast chargers are typically used for remote control (RC) applications. Several refurbishers and Prius owners use these chargers to cycle the batteries and determine their capacity. If these chargers show equivalent performance to more expensive alternatives, they can be used to characterize Prius modules quickly and simply by Field Ready in Fiji to keep manufacturing costs down. The lab-grade chargers used for the module testing were the Agilent E631A Triple Output DC Power Supplies that have a maximum charging current of 1.0A. The electronic loads used to discharge the batteries were the 6063B DC Electronic Load. Lastly, a Centronics Corporation BMS-4000 Battery Maintenance System was used that could charge, discharge, and cycle the battery.

C. Module Testing

To avoid module swelling during charging, all modules were assembled using the original Prius Prime battery enclosure and labeled from 1 to 62 seen in Figure 7. An automated approach for data collection was developed through using a GPIB to USB cable, paired with the Keysight Benchvue software. This experimental set-up is shown in Figure 8 for the module charging cycle with the Agilent E3631A. However, not all equipment had GPIB capabilities. The only ones that were able to be used were the Agilent E3631As, HP/Agilent 6063Bs, and Agilent 33401As. All other equipment used had their data recorded manually through 5-minute intervals. The Keysight Benchvue software was able to control the different equipment and record data points at an interval of 0.5 seconds or 1 second depending on the equipment.



Fig 7 Assembled modules for cycling



Fig 6 Experimental setup

All 62 modules were tested with 1-3 charge discharge cycles. While the enthusiast battery chargers gave the mAh charged or discharged on an LCD screen, the mAh had to be calculated for the other equipment. This was calculated through Equation 1 using the time to charge in hours and the constant current used.

$$Capacity\ (mAh) = time\ (hours) * current\ (A) * 1000 \quad (1)$$

Several trends were noticed from the cycling measurements. First, the modules showed a standard charging and discharging curve for their chemistry that showed a steep drop off around 7V. NiMH batteries have a quality of keeping a very stable discharging voltage. Through its use, this discharging curve becomes more linear which can also be seen in the US DOE tests on the 2010 Prius Battery. Next, any module that recorded an initial OCV of under 6.889V had a much lower Coulombic efficiency than modules above that voltage. The Coulombic efficiency was calculated by dividing the discharging mAh by the charging mAh. Removing these 15 modules from the calculation, the average Coulombic efficiency of these modules was 95%. This left 47 modules that had a high Coulombic efficiency, indicating modules that would perform well.

D. Battery Determination

The modules that had been tested were sorted from low to high capacities seen in Figure 8. The best performing modules featured capacities of 1800mAh or higher. Two packs were built using the best cells as denoted by the large rectangles surrounding modules. Optimally, all modules would be at the same capacity and this difference will decrease with a larger sample size.

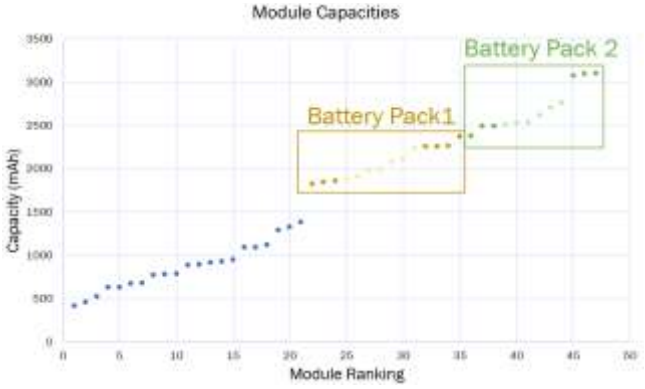


Fig 8 Sorted module capacities and developed battery packs

These two packs were labeled as Battery Pack 1: 2s7p (2 series, 7 parallel, 14 modules) and Battery Pack 2: 2s6p (2 series, 6 parallel, 12 modules). These packs were built by putting the worst and best modules together in parallel. This would work to average the capacities between each series to reduce the overall capacity lost. Further algorithms can be developed to optimize which modules should be put in which series. For Pack 1 this leaves an overall capacity of 14.180Ah at 14.4V with 0.485Ah of lost capacity. For Pack 2 this leaves an overall capacity of 15.649Ah with 0.976Ah of lost capacity.

Only Pack 2 met the 15.43Ah requirement for Tier 2 electricity use with Pack 1 having 91.9% of the capacity. However, in solar home systems, a battery pack with a 2-3 day back up is vital for proper functionality. This reduces the chance that when there are multiple days that have under average irradiation that users still have access to electricity. This is even more important for Fijian communities that need to have access to electricity during Tropical Cyclones to get access to the news or have lighting for safety. Ideally, these battery packs would be expanded to two or three times their size but with the limit in the number of modules that were available for testing, a one-day battery pack size is being used for this study.

E. Battery Testing

These batteries were then reassembled into the Prius battery casing to ensure proper pressure and charging curves seen in Figure 9. The original copper bus bars were cleaned bolted onto the modules with M4 washers and nuts to create the two battery packs. The batteries were then cycled to observe the experimental capacity of the batteries as compared to the calculated capacity. Dividing the 37.03W average power demand by the 14.4V system voltage, a required discharging current of 2.572A was calculated. On the charging side, the $PV_{out,\ Feb}$ of 3.758kWh/m^2 per day was used. The daily energy usage, 222.22Wh, is divided by the system voltage and 3.758 kWh/m^2 per day to give an average charging current of 4.106A.

While the 6063B Electronic Loads were still suitable to discharge the batteries as they have a max current of 10A, the E3631A Power Supplies could not be used due to their 1A limitation. Instead, a Sorensen DC2150-20E and Xantrex XFR 150-18 DC Power Supplies were used. One difference between the individual module cycling and the battery pack cycling was that the discharge cut-off voltage per module was changed from 6.0V to 6.5V. This was to reduce the severity of the voltage drop as the battery reached a 0% SOC and protect the battery. This reduction of DOD also will increase the cycle life of the battery.



Fig 9 Assembled battery packs and bolted bus bars

Table 4.4 shows three charge and discharge cycles that were performed on these battery packs. The first observation is that by the end of the three cycles, Pack 1 outperformed Pack 2, which is the opposite of what was predicted. Within the first charge cycle, the packs operated as expected but had a capacity that was less than what was needed by the sized battery system. These systems both performed at nearly 100% Coulombic efficiency.

TABLE 4 BATTERY PACK CYCLING TEST RESULTS

		CC (A)	Cut-off Voltage (V)	Battery Pack 1	Battery Pack 2
	Discharge	2.57	13.0	11.2 Ah	13.1 Ah
Cycle 1	**Charge**	4.10	16.8	13.7 Ah	14.3 Ah
	Discharge	2.57	13.0	13.8 Ah	14.3 Ah
Base Case	**Coulombic Eff.**			100.7%	99.4%
Cycle 2	**Charge**	4.10	17.0	23.6 Ah	21.3 Ah
Voltage	**Discharge**	2.57	13.0	**20.0 Ah**	**18.2 Ah**
Increase	**Coulombic Eff.**			84.5%	85.1%
Cycle 3	**Charge**	8.20	17.2	20.0 Ah	18.6 Ah
Current	**Discharge**	5.14	13.0	**17.9 Ah**	**17.1 Ah**
Increase	**Coulombic Eff.**			89.8%	91.6%

The cut-off charging voltage was increased in Cycle 2 by 0.2V to 17.0V to store more charge in the battery to reach the required daily Ah. Both packs charged up to 17.0V but it took considerably longer to gain the 0.2V as compared to charge cycle 1. The discharge shows that the Coulombic efficiency of these cells also reduced substantially. A final charge cycle was created that doubled the charging and discharging current of the battery packs along with a higher cut-off charging voltage. This cycle was used to increase the capacity of the modules and observe temperature increases. The higher rates of charge will result in a faster increase in temperature, allowing for the possible detection of underperforming cells in a module using a Fluke Thermal Imager.

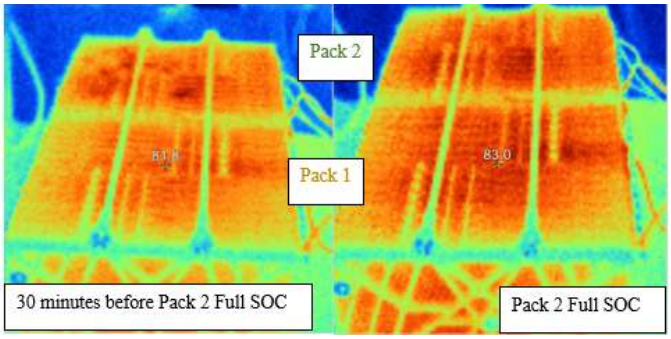


Fig 10 Fluke thermo-images of the battery packs charging.

The two images in Figure 10 show additional observations. Pack 2 is at the top of the picture, the two un-used modules as a thermal barrier at the center of the assembly, and then Pack 1. The right image is when Pack 2 hit the cut-off voltage of 17.2V, and the picture on the left occurred thirty minutes before. These two packs both had a peak temperature of 83.9°F, although Pack 2 heated up quicker. In the image on the left there are several cells within the modules that heated up very quickly and look to be affecting the temperature of the cells around them as seen at the full SOC. This will affect the capacity of the cells around

them. This could be further explored by removing these modules with underperforming cells and replacing them with another.

Discussion

It is proposed that the batteries used for these solar systems should be swapped every 2-5 years depending on further research and analysis. This process would disassemble the batteries, recharacterize them, and match them, and reassemble new battery packs. Battery swapping can be avoided if it is shown that the Prius battery modules do not degrade substantially at the solar home application with the low current or DOD. This offers another potential of these batteries for a new sustainable business model: energy as a service. This involves users paying per kWh of energy used and having all maintenance and electronics serviced by an entity. IRENA establishes that this business model is an innovation that can help Tier 1 to Tier 3 energy consumers gain access to renewable energy [18]. In sub-Saharan Africa between 2013 and 2018, this model gave affordable solar power to more than 8 million people with a cost of around 0.25 to 0.5 USD per day [18].

Although this study focuses on small scale battery solutions for solar home systems, there is the potential to use these batteries at a larger scale for micro girds or grid storage. Microgrids can operate as stand-alone grids for a community with centralized power generation, energy storage, and transmission lines. These microgrids can be especially useful for larger, clustered rural communities or for extremely remote communities in hard-to-reach Pacific Islands.

Conclusions and Recomendations

Through this study it was determined that used hybrid electric vehicle nickel metal hydride batteries have a large potential to be reused for low power applications such as solar home systems. These batteries have a higher environmental impact than other battery chemistries and there should be an increased focus to incorporate a battery supply chain in countries that do not have the recycling infrastructure that is required to process the batteries. This can culminate in a circular business strategy that ensures the maximum use of these batteries to reduce their overall environmental footprint per kWh. Although the donated modules showed that Tier 2 power was possible, there is a large amount of additional work that needs to be done to be able to implement this technology. One of the essential pieces of work that needs to be completed is the development of an appropriate solar charge controller.

Some additional future research that can be looked at is the further characterization of the batteries. Three is a need to consider additional parameters other than capacity for the SOH of these batteries. These parameters such as internal resistance and resting voltage drop can be evaluated to better match modules. These voltage drops can be determined by charging the modules up to a certain voltage and observing how much that voltage reduces over a 24-hour timeframe. One way to cover this issue is through EIS measurements. Gaining a larger sample size of batteries is critical to observe relationships of these batteries between EIS frequency, internal resistance, capacity, etc.

Overall, there are promising indications that show that NiMH Prius batteries can be reused for energy storage applications after their vehicle use. With the large quantity of packs to retire in the coming decades, combining academic and industry efforts can allow for the product-life extension of the modules in support of the UN Sustainable Development Goals. Two further efforts need to be made for the repurposing. First develop charge controllers to implement the piloting of the system with remote monitoring capabilities to observe real-world performance. Second, work on EIS characterizations to correlate battery usage characteristics and specifications with proper module sorting algorithms that will reduce the testing time of the batteries for wide-spread adoption.

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