DESIGN FOR REUSE, REMANUFACTURING, RECOVERY, AND RECYCLING IN PUERTO RICO

Yue Li,[1] S. Jackson Smith,[1] Dan J. Donnelly III,[1] Jonathan Doan,[2] Eugene S. Smotkin[*,1,3,4]

1. Department of Chemistry & Chemical Biology, Northeastern University, Boston, MA 02115, USA
2. A3 Global, 300 Schell Ln Suites 309/310, Phoenixville, PA 19460, USA
3. Affiliate Faculty of the Department of Chemical Engineering, Northeastern University, Boston, MA 02115, USA
4. Technology and Education Center for Renewable Energy, San Juan, Puerto Rico, 00901

Abstract

Puerto Rico has an abundance of nickel–metal hydride (NiMH) batteries approaching the end of their service life as traction batteries. We have demonstrated that these batteries can be repurposed as stationary energy storage systems when operated at substantially lower C-rates. Data derived from Prius battery modules illustrate the thermodynamic advantage of operating at reduced discharge power: lowering the C-rate from 7 C to 0.1 C increases the available non-expansion work by 73%. To validate this concept, we reconfigured 39 Toyota modules for use in a low-income home in Utuado, Puerto Rico, where typical household energy storage requirements are 5 kWh or less. The reconfigured battery pack was integrated with solar panels to provide a sustainable power source. This work presents both the thermodynamic framework and a schematic for a holistic circular battery economy—one that engages low-income families directly in the processes of reuse, remanufacturing, recovery, and recycling to establish a sustainable energy lifecycle for Puerto Rico. From a thermodynamic standpoint, we extend the application of Peukert's law to predict mid-point (average) voltages and amp-hour capacities, enabling projection of the total available non-expansion work as C-rates are reduced. This extended Peukert-law methodology is also applicable to lithium-ion (Li-ion) and lithium-iron-phosphate (LFP) battery systems.

Introduction and Motivation

Puerto Rico's electric grid continues to suffer from systemic fragility and frequent outages, with large-scale blackouts affecting millions of customers including low-income families who have no backup power options. At the same time, the island has an abundance of hybrid electric vehicle (HEV) batteries, such as Toyota Prius nickel-metal hydride (NiMH) batteries, approaching the end of their service life as traction batteries. A Prius pack (battery) has 28 prismatic NiMH modules connected in series. A module is a sealed, monolithic unit that incorporates six 1.2 V NiMH cells permanently connected in series, resulting in a nominal module voltage of 7.2 V and a nominal pack voltage of approximately 200 V. The rapidly expanding battery aftermarket, together with growing concern over the fate of end-of-life (EOL) battery modules drives the need to maximize cradle-to-grave lifetimes and to develop second-life applications across all battery uses. Second-life refers to any use of a battery module or pack after completion of its first service life, without specifying the application. This paper focuses on second-life battery modules for the automobile aftermarket and repurposing for residential energy storage in marginalized Puerto Rican households.

Figure 1 illustrates a typical open-loop HEV module economy. Battery packs are dismantled to the module level

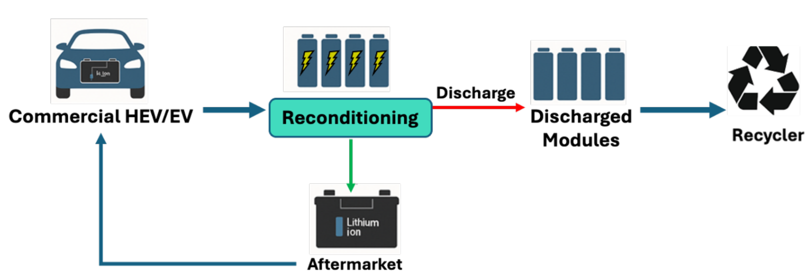

Figure 1. Open loop HEV/EV battery economy.

for reconditioning. Evaluated reconditioned modules are reused in the aftermarket, repurposed for residential back up power or discharged for delivery to recycling facilities, where they are crushed and shredded to a black mass. The black mass can contain recoverable critical metals that can be returned to the battery manufacturing supply line. The introduction of a repurposing infrastructure within Puerto Rico's module lifecycle enhances opportunities for a fully circular economy (*vide infra*).

Economic context underscores the circular-economy challenge: a new Toyota hybrid module costs roughly $70, a reconditioned module sells for about $30, and EOL modules delivered to a recycler fetch about $2 per module. These large price differences define the practical incentives and constraints that shape decisions among aftermarket, repurposing, and recycling. Recovering value through reconditioning and second-life applications is substantially more cost-effective than immediate disposal, while also reducing material waste and extending the useful life of critical battery materials.

The thermodynamic basis of a circular battery economy is that battery modules no longer meeting automotive aftermarket power requirements can still deliver substantial usable energy when operated at lower power. This makes their repurpose for low-power residential applications fundamentally viable. Our extension of the Peukert law translates this thermodynamic advantage into practice. By relating capacity and average working voltage to discharge rate, the extended framework enables accurate projection of low-C-rate energy availability from high-current characterization data, eliminating the need for time-intensive low-power testing while still providing reliable specifications for repurposed use.

Review of Related Work

HEV battery economy in Puerto Rico

Circular economy frameworks for energy storage emphasize design-for-circularity principles that prioritize value retention across the battery life cycle as well as EOL recycling.[1] In Puerto Rico, a circular economy for HEV battery modules remains more aspiration than reality. There are no facilities dedicated to module reconditioning to enable remanufacturing of batteries for the aftermarket or repurposing. Local recycling of EOL batteries are managed through authorized service channels and exported off-island for proper processing under federal hazardous waste regulations.[2] Regulatory frameworks have not yet established specific mechanisms for HEV modules repurposing and closed-loop material recovery.[3]

This work defines "break points" that determine how reconditioned traction battery modules can be reused or directly recycled. Other researchers have combined degradation modeling with life-cycle assessment or techno-economic analysis, and supply-chain analysis estimate capacity thresholds below which second-life use no longer provides environmental or economic benefit. For example Bobba et al. showed that aging, transport, and repackaging can offset reuse gains.[3] Neubauer et al. showed that if a battery's remaining capacity or cycle life is too low to cover refurbishment and replacement costs, reuse is no longer profitable and recycling becomes the better option.[4] Heymans et al. found similar break points for residential storage, where high power demand, low utilization, or high installation and balance-of-system costs can eliminate both cost savings and emissions benefits, making repurposing unattractive.[5]

This work seeks to augment conventional aftermarket decision breakpoints with criteria relevant to backup-power applications for populations experiencing extreme poverty, such as maintaining refrigeration to prevent food loss, ceiling fans and lighting. According to the U.S. Energy Information Administration, electricity customers in Puerto Rico experienced an average of 19 service interruptions in 2024, including 14 unrelated to major weather events and 5 associated with such events, and approximately 27 hours of total outage time per year between 2021 and 2024, underscoring the comparatively high frequency of power disruptions on the island.[6] It gets worse in underserved neighborhoods. Within a systems framework to be discussed later, thermodynamic and Peukert-type limits provide important inputs, and detailed electrochemical characterization such as the methods developed in this work supports decisions on whether modules should be used for remanufacturing of aftermarket battery packs or for battery packs designed for low cost back-up power batteries.

Prior research has demonstrated that second-life HEV traction battery modules, which still retain 70-80% of their nominal capacity, can be repurposed for energy storage systems such as residential, commercial, or grid-support applications, extending the economic and environmental value of battery modules beyond their first life.[4] Although small-scale projects, such as Rivian's proposal to deploy second-life battery modules in a solar-plus-microgrid system in Adjuntas, Puerto Rico have demonstrated potential applications for community energy resilience,[7] no large-scale commercial programs currently exist to repurpose EOL battery modules for energy storage in Puerto Rico. Current expansion of battery energy storage systems in Puerto Rico primarily relies on new batteries rather than second-life ones, including projects totaling hundreds of megawatt-hours designed to support renewable energy integration and grid reliability.[8] Therefore, while second-life applications are conceptually recognized and technically feasible, structured repurposing pathways are not yet established locally in Puerto Rico.

Thermodynamics

The viability of repurposing reconditioned Toyota Prius NiMH modules with capacities as low as 3.5 Ah (rated at 3.25 A) for lower-power applications is supported by fundamental thermodynamic principles, as described in Bard and Faulkner, Electrochemical Methods.[9] At constant temperature, the enthalpy per equivalent, ΔH, is fixed and can be expressed as the sum of the maximum non-expansion work, ΔG, and the thermal dissipation, TΔS (eq. 1):

$$\Delta H = \Delta G + T\Delta S \tag{1}$$

At constant temperature, where ΔH is constant, the maximum non-expansion work (ΔG) increases at the expense of thermal dissipation (TΔS) as the discharge C-rate is reduced. We demonstrated this when Toyota Prius modules were "downshifted" from vehicle traction to the power requirements of the household in Utuado, Puerto Rico shown in Figure 2. Following Hurricane María, a prototype pack, 13 parallel strings of 3 modules each (22 V), was installed.[10] The Prius data (Fig. 2) capture the thermodynamic advantage of this transition: reducing the discharge rate from 7 C to 0.1 C increased the available non-expansion work by 73%.[11]

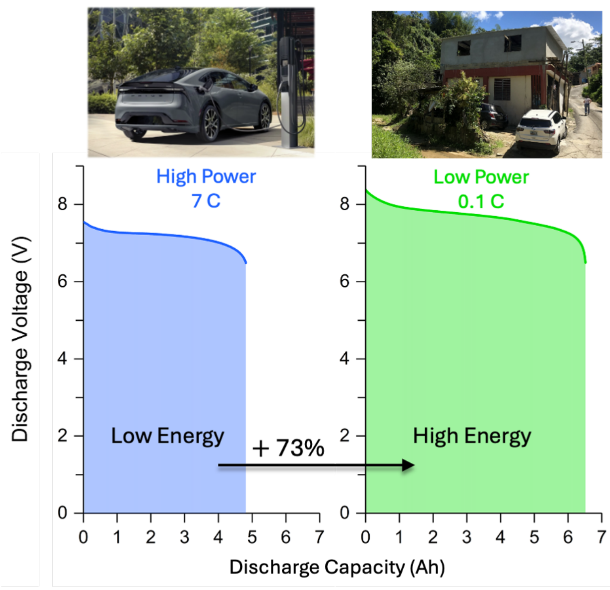

Figure 2. Toyota modules discharged at high and low C-rates. House is site where our group installed repurposed modules.[10]

Battery modules intended for repurposing must be rated at C-rates relevant to their new application to ensure accurate performance assessment. The available watt-hour energy (Wh) is calculated by integrating voltage (V) over Ah capacity (C) from 0 Ah to the cutoff capacity (eq. 2). It is time-consuming, however, to measure this integral at multiple relevant C-rates.

$$Wh = \int_0^C V\, dC \tag{2}$$

Peukert's law (described in the next section) describes the dependence of capacity on discharge current. However, because it provides no corresponding projection of the average working voltage, V_{ave}, it cannot be used to determine the available non-expansion work vs. current. This omission is addressed by the framework developed here. Full module characterization including C and V_{ave}, for Wh determination, is essential for both aftermarket and repurposing pathways.

A practical approach for obtaining these metrics involves rescaling the time axis of module voltage-versus-time curves by the applied currents. This produces voltage versus capacity curves. Integrating these curves up to the end-of-discharge (on the fly) yields reliable Wh energy values, as shown in eq. 2. Dividing this integral by the end of discharge C provides V_{ave} (eq. 3):

$$V_{ave} = \frac{1}{C}\int_0^C V\,dC \tag{3}$$

Peukert's Law

High parameter accuracy is required for reliable reuse battery remanufacturing. Capacities and average working voltages at currents as low as at 0.1 C must accompany remanufactured products. The acquisition of discharge curves at 0.1 C is time consuming. These low-C-rate parameters must be derivable from high-C-rate measurements. Peukert's law (eq. 4) provides a starting framework by relating discharge time (t) to current (I) at a defined end-of-discharge voltage (EODV):

$$t = \widehat{H}\left(\frac{\widehat{C}}{I\widehat{H}}\right)^{k} \tag{4}$$

where $\widehat{H}$ and $\widehat{C}$ are the discharge time and Ah capacity, respectively, at which a module is rated (i.e. reference values) and k is Peukert's constant.[12]

Researchers have applied or extended Peukert's law to estimate battery capacity under varying discharge rates, highlighting both its utility and limitations. Doerffel and Sharkh critically evaluated the applicability of the classical Peukert equation to both lead-acid and lithium-ion chemistries and showed that its accuracy is limited to moderate current ranges, with increasing error at high rates.[13] Gong et al. adapted Peukert-type parameters for lithium-ion cells and demonstrated their usefulness for state-of-health estimation and capacity projection under practical loads.[14] Li et al. developed an electrochemical model to improve capacity prediction under high C-rates, addressing some limitations of simpler empirical models, though it requires detailed parameterization and may not generalize across chemistries.[15] Eddahech et al. combined experimental discharge data with parametric identification to estimate usable capacity and degradation trends during aging.[16] Likewise, He et al. integrated current-dependent capacity relations with equivalent-circuit modeling to support real-time capacity and performance estimation in battery management systems.[17] These studies show that Peukert-type and extended capacity models provide a computationally efficient bridge between laboratory characterization and practical capacity assessment. However, we are not aware of any methods to project V_{ave} or energy using an extended Peukert law.

A linearized version of Peukert's law is commonly plotted to obtain k values (eq. 5 and 6). Ultimately the product of capacities by average voltages yields watt-hours.

$$\ln t = \ln\widehat{H} + k\cdot \ln\left(\frac{\widehat{C}}{I\widehat{H}}\right) \tag{5}$$

$$\ln t = \ln\widehat{H} + k\cdot \ln\left(\frac{\widehat{C}}{\widehat{H}}\right) - k\cdot \ln I \tag{6}$$

By adding *ln* I to both sides of eq. 6, a linear expression for *ln* C versus *ln* I is obtained (eq. 7):

$$\ln C = \ln\widehat{H} + k\cdot \ln\left(\frac{\widehat{C}}{\widehat{H}}\right) + (1-k)\cdot \ln I \tag{7}$$

Unfortunately, we find that actual plots of *ln* C vs *ln* I are, in fact, nonlinear. We clarify this problem and develop new equations for capacity and average voltages for projection of energy from measured data at higher C-rates in the technology approach section.

Technology Approach

Figure 3a shows constant-current discharge curves of a Toyota Prius NiMH module collected at 25 °C over currents ranging from 0.5 to 30 A, using a 6 V end-of-discharge voltage (EODV). The midpoint voltages, V_{mp} (colored dots), vary approximately linearly with current. The energy delivered at any current can be estimated as the product of the associated Ah capacity and the average working voltage. For NiMH modules, a rectangle defined by $V_{mp} \times$ Ah provides a remarkably good approximation of discharge energy because the polarization curves are approximately antisymmetric, yielding $V_{ave} \approx V_{mp}$. Although V_{ave} is the more theoretically meaningful quantity, its near equivalence to V_{mp} indicates that the V_{ave}–I relationship is mathematically well behaved and suitable for reliable energy projections.

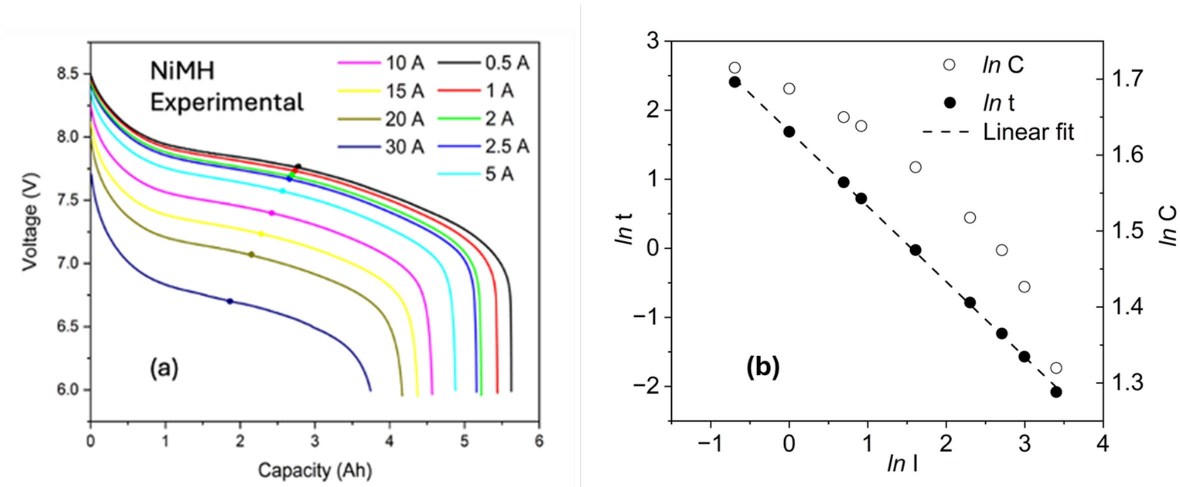

Figure 3. (a) Discharge curves for Toyota Prius NiMH module; (b) Plot of *ln* t vs *ln* I with linear regression, and plot of *ln* C vs *ln* I.

Importantly, as discussed above, lower C-rates correspond to larger thermodynamic integrals, providing the fundamental basis for increased energy availability at reduced discharge currents.

In Figure 3b, the plot of Peukert's law (*ln* t vs. *ln* I) shows deviation from linearity at extreme values (0.5 A and 30 A). This deviation at the extremities of current is often ignored. However, this deviation is strongly amplified when each point in time is multiplied by the corresponding current values to obtain Ah capacity (Fig. 3 open circles). Moreover, it is the values at the extremities that are most important when projecting low C-rate parameters from measured high C-rate values.

Figure 3b highlights the core dilemma of Peukert's law and why it has never been extended to quantify total non-expansion work. This framework enables projections of available energy at lower power levels, precisely the regime relevant for residential repurposing. Later we will explain how this supports pathways for marginalized households in Puerto Rico to participate directly in a circular battery economy.

The application of an extended Peukert's law will enable the development of rapid diagnostics for Toyota NiMH modules after reconditioning (Fig. 3). Instead of performing a time consuming low-current discharge test, each module will be discharged at a high current (30 A) for approximately 10 minutes to quickly measure the delivered energy at 30 A. The extended Peukert model to be described will then project the energy at a low current (0.5 A), which more closely represents the capacity conditions for low power usage. This approach reduces the total testing time from roughly 10 hours to about 10 minutes per assay, significantly accelerating the assay process while maintaining reliable energy estimation. Consequently, this method greatly improves throughput and operational efficiency during large-scale module screening and evaluation.

Discussion

Energy Projection

NiMH Wh energy projections are obtained from capacity (C) and working voltage measurements (V_{ave}), which are independently parameterized as functions of current (I). Figure 4(a) shows a cubic dependence of C on $I^{1/2}$ (eq. 8) across more than an order of magnitude in discharge rate.

$$C = \mathbf{a} + \mathbf{b} \cdot I^{\frac{1}{2}} + \mathbf{c} \cdot I + \mathbf{d} \cdot I^{\frac{3}{2}} \tag{8}$$

Figure 4(b) shows a strong linear dependence of V_{ave} on I (eq. 9), indicating that voltage polarization scales predictably with current over the investigated range.

$$V_{ave} = \mathbf{m} \cdot I + \mathbf{n} \tag{9}$$

This linearity also reflects the relatively symmetric nature of the polarization curves for NiMH chemistry (Fig. 3a), for which midpoint voltage provides a close approximation to the true average voltage. Current-dependent watt-hour energy projections (Wh vs. I) are obtained by the product of V_{ave} and C (eq. 10).

$$Wh = V_{ave} \cdot C \tag{10}$$

Taken together, Eqs. 8–10 constitute what we term an extended Peukert's law. The observed nonlinearity in current-dependent energy (Fig. 4c) arises from the nonlinear current dependence of capacity (Fig. 4a). Yet, the resulting energy–current relationship retains excellent predictive accuracy (R^2 = 0.9998). This outcome is nontrivial: while Peukert's law captures capacity fade with increasing current, it does not account for the concurrent reduction in average working voltage. The present formulation resolves this limitation by incorporating both effects explicitly, thereby enabling direct projection of total non-expansion work versus discharge rate.

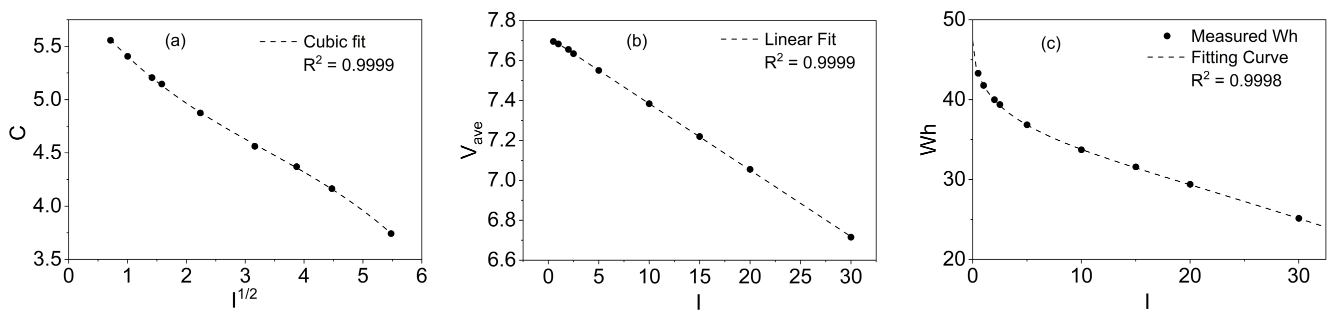

Figure 4. (a). C vs. $I^{1/2}$ with cubic regression; (b). V_{ave} vs. I with linear regression; (c). Wh vs. I with fitting curve.

Practically, these relationships permit reliable estimation of low C-rate energy delivery using short-duration, high-current discharge data. This capability eliminates the need for time-intensive, low-current testing while preserving thermodynamic fidelity. As a result, this framework provides a quantitative bridge between laboratory characterization and field deployment, enabling rapid screening and classification of reconditioned modules for reuse, repurposing, or recycling pathways.

Closed loop battery economy

Figure 5 shows a color-coded classification scheme for Toyota NiMH modules into three categories based on high current evaluation data. Considering the data from Figure 3a, the capacity rated at 30 A is 3.74 Ah, corresponding to a discharge time of 7.5 min, while the capacity rated at 0.5 A is 5.63 Ah, corresponding to a discharge time of 11.3 h. These discharge time values are calculated by using t = C/I. Therefore, this process saves over 10 hours by using Peukert's law extension. The green category represents the aftermarket; modules projected to deliver more than 44 Wh at 0.5 A, approximately 77% of nominal capacity, are considered suitable for continued reuse in HEV applications. The yellow category denotes modules delivering between 30 and 44 Wh at 0.5 A, reflecting moderate degradation. The red category denotes modules that fail to meet the minimum performance threshold of 30 Wh, corresponding to approximately 55% of nominal capacity, indicating substantial degradation; these modules are removed from service and slated for recycling.

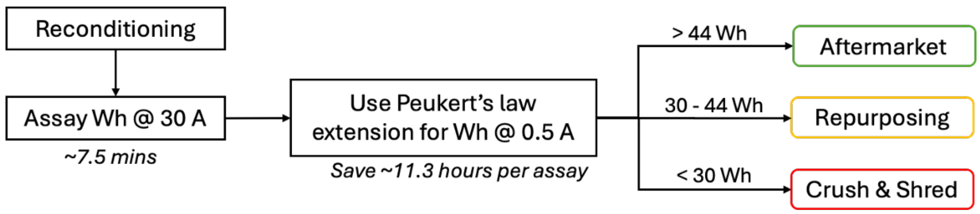

Figure 5. Decision criteria for Toyota NiMH module triage

This visual classification provides a straightforward, standardized approach for large-scale assessment of NiMH modules, enabling efficient sorting and consistent decision-making for second-life and EOL management. By clearly distinguishing among aftermarket, repurposing, and crush-and-shred modules, the criteria support safer operation, improved reliability, and more effective resource recovery within battery repurposing and recycling workflows. Economic considerations of new, reconditioned, and EOL Toyota Prius NiMH modules suggest a closed-loop business model that integrates community-level repurposing without imposing additional process burden on the reconditioning operation.

Modules suitable for repurposing are transferred from the reconditioning center without additional vendor-specific processing beyond existing reconditioning workflows. This allows the reconditioner to capture incremental value from inventory that would otherwise be routed to low-value recycling. Community participants deploy the repurposed modules in second-life applications until EOL, after which the modules are returned through the same logistics channel to replace depleted modules. The reconditioner thereby recovers EOL modules in aggregated form for downstream recycling, while communities gain reliable access to low-cost energy assets.

The yellow pathways in Figure 6 thus represent a value-preserving loop in which underserved communities function as active participants in maintaining the circular battery economy. Economic value is retained at each stage, module lifetimes are extended, and material recovery is deferred to the point of maximum utility, without added operational complexity for the reconditioning center.

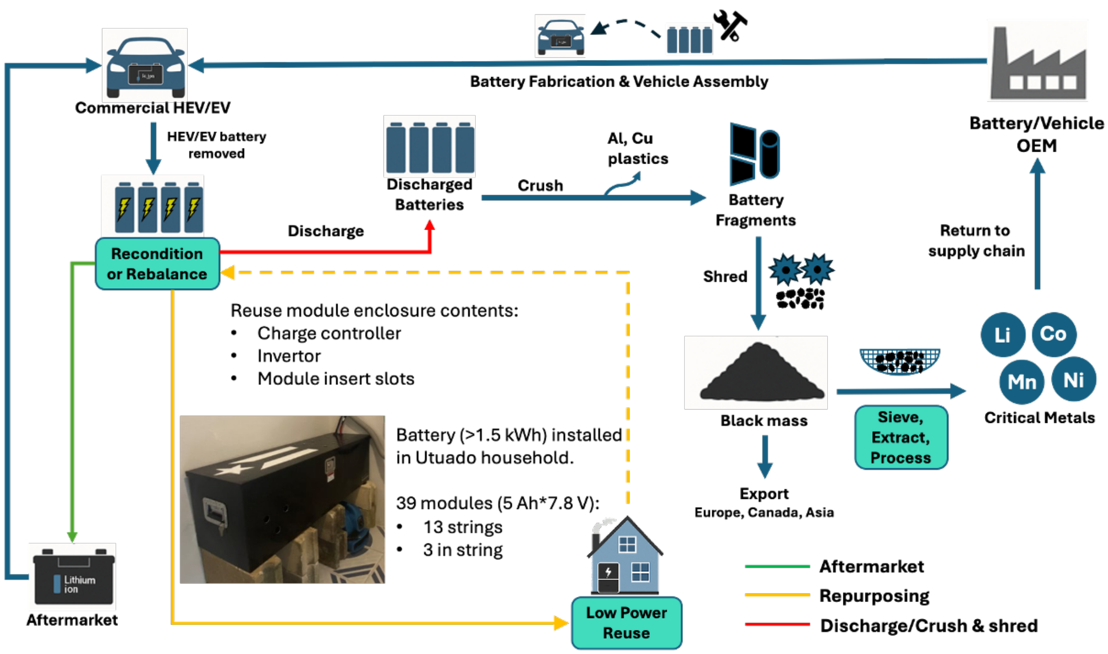

Figure 6. Toyota Prius NiMH module discharge curves at varied C-rates.

Conclusions & Recommendations

This work establishes a thermodynamic and metrological foundation for extending the functional lifetime of HEV battery modules beyond automotive service and into second-life stationary applications. Classical Peukert's law provides a k-value that enables projection of discharge time and Ah capacity versus current. However, it does not capture the total non-expansion work available from a battery module because it does not account for the average working voltage. As a result, energy, rather than capacity, has historically remained difficult to project without time-consuming low-current testing.

Here, that limitation is resolved for NiMH modules by expressing capacity as a power series in the square root of discharge current and by explicitly defining the average working voltage, V_{ave}, as the ratio of the discharge-curve integral to delivered capacity. These average-voltage values exhibit a well-behaved linear dependence on current. Together, these relationships yield an empirical yet highly accurate formulation for energy versus current across a wide range of C-rates.

Thermodynamically, this approach exploits the reduction of reversible losses at lower discharge power. As C-rate decreases, the entropic contribution $T\Delta S$ diminishes, increasing the fraction of the fixed enthalpy ΔH that can be recovered as useful non-expansion work ΔG. Extended Peukert scaling renders this thermodynamic advantage actionable by allowing energy available at low power to be projected reliably from high-current characterization data.

Our resulting energy-projection algorithm enables rapid triage of reconditioned battery modules into aftermarket, repurposing, or recycling pathways using short, high-current assays rather than prolonged low-rate testing. Repurpose-grade modules are generated concurrently with automotive-grade modules, allowing second-life units to be produced at effectively no additional cost beyond standardized enclosures.

When repurposed modules reach the end of their second-life service, households have a built-in incentive to return them through the same logistics channel for replacement. These end-of-second-life modules are then directed to controlled discharge and materials-recovery streams, completing a closed loop. In this structure, underserved households are not passive endpoints of energy deployment, but are instead, active participants in the circular battery economy, with defined roles in the utilization, stewardship, and return of second-life energy-storage assets.

With appropriate infrastructure, including standardized enclosures and targeted government incentives, this framework will extend battery lifetimes, defer material recovery to the point of maximum utility, and strengthen energy resilience in regions with constrained resources. Puerto Rico thus serves not as a special case, but as a scalable prototype for a circular battery economy that integrates thermodynamics, diagnostics, and community participation into a unified and sustainable energy system.

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About the Authors

Yue Li is a PhD student at Northeastern University working at the intersection of battery science and machine learning. His research focuses on leveraging machine learning techniques for battery prognostics, aiming to enhance the prediction and management of battery performance.

Sam Jackson Smith is a PhD candidate and graduate research assistant at Northeastern University. His research focuses on electrochemical catalysis and operando IR spectroscopy.

Dan J. Donnelly III is a research associate in Eugene S. Smotkin's research group. He earned his doctorate in chemistry at Northeastern University under Prof. Smotkin and currently researches hydrocarbon-based ion-exchange membranes for fuel cells and electrolyzers.

Jonathan Doan is the director of product management at NuVant Systems (A3 Global). He earned his doctorate in chemistry at Northeastern University under Prof. Smotkin and joined NuVant Systems in 2017. He played a key role in developing technology for reconditioning hybrid vehicle batteries.

Eugene S. Smotkin is a professor of chemistry and affiliate faculty of Chemical Engineering at Northeastern University, where the central theme of his lab is the discovery of better materials for electrolytes and electrocatalysis.

Corresponding Author: Eugene S. Smotkin
Email: e.smotkin@northeastern.edu | **Phone**: +1 (787) 587-3748

Presenting Author: Yue Li
Email: li.yue2@northeastern.edu | **Phone**: +1 (857) 296-2277