American Made Challenges Battery Voucher Program Cooperative Research and Development Agreement

Cooperative Research and Development Final Report

CRADA Number: CRD-21-17533

NREL Technical Contact: Dustin Weigl

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-83535
July 2022

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NOTICE

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Cooperative Research and Development Final Report

Report Date: July 19, 2022

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Renewance, Inc

CRADA Number: CRD-21-17533

CRADA Title: American Made Challenges Battery Voucher Program Cooperative Research and Development Agreement

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Sponsoring DOE Program Offices:

- Office of Energy Efficiency and Renewable Energy (EERE), Advanced Manufacturing Office (AMO)
- Office of Energy Efficiency and Renewable Energy (EERE), Advanced Manufacturing Office (AMO), Vehicle Technologies Office (VTO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$55,000.00
TOTALS	$55,000.00

Executive Summary of CRADA Work:

Renewance is a Phase II winner of the U.S. Department of Energy Lithium-ion Battery Recycling Prize. The Prize is designed to incentivize American entrepreneurs to develop and demonstrate processes that, when scaled, have the potential to profitably capture 90% of all discarded or spent lithium-based batteries (LIB) in the Unites States for eventual recovery of key materials for re-introductions into the U.S. supply chain.

The objective of this work is to enable a more efficient evaluation of battery sources for second life applications prior to ultimately being recycled, through evaluation of chemistry characteristics, projected battery lifetime, and application history. This work will develop the capability to identify groups of batteries that may be useful for second life and reduce the cost of end-of-life (EOL) LIB evaluation and repurposing.

To meet the objective, NREL will use existing and new data to create a refined algorithm that could be used to evaluate batches of batteries for potential reuse based on manufacturing date and historical use characteristics. Based on current battery market prices and compiled literature data, a starting-point estimate of the market value of the batteries for reuse based on expected lifetime will be included in the algorithm.

With the projected surge in LIB demand, battery second life is a new area ripe for development and investment from companies like Renewance. With so few large format batteries reaching EOL to date, this is a new market with a variety of areas for optimization and adding value. This work with Renewance is an example of how existing expertise in battery degradation at NREL can be used to reduce the cost of shifting a battery into a second life application.

With these cost reductions, this work is also facilitating the development of a battery circular economy in the United States. A robust circular economy can maximize the utilization of critical metals demanded by battery technology such as nickel and cobalt while also reducing the costs of batteries in the marketplace for the many end-uses needed for the green energy transition. The supply of these metals is limited, and we face a supply chain shortage both domestically and globally unless we can ensure they are being used to their maximum potential. This research can improve the economics of a battery circular economy to make it a more likely path for EOL batteries with critical metals.

CRADA Benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope competencies
- Uses the laboratory's core competencies

Summary of Research Results:

NREL Task 1 Description:

Review the industrial LIB market segments for reuse, both in terms of the first-life battery source and the specific second-life application and propose a simple algorithm that may be used to address cost and reliable. The primary metric used for this evaluation is estimated battery state of health based on basic input parameters by market segment such as battery type, original nameplate performance characteristics, and application history.

NREL Task 1 Results:

For this task, NREL coded an algorithm for Renewance that gives a first-degree approximation for the state of health of a given EOL LIB based on assumed the generalized use characteristics from its original application. This work resulted in an interface that Renewance can use to evaluate incoming EOL LIBs from their various suppliers. When repurposing batteries for second life, Renewance incurs a cost for every battery they physically test to determine the remaining state of health. This cost can be minimized by estimating, given an assumed first life use profile, the likelihood that an incoming lot of batteries is appropriate for second life. If the estimated state of health is too low (as determined by Renewance and their partners) then it does not undergo physical testing and is recycled instead. On the other hand, if the algorithm-estimated state of health is relatively high then it is worth incurring the cost for physical testing before repurposing the batteries for a second life application.

The algorithm is written in python and shared with Renewance as a package including installation instructions for additional customization beyond the period of performance for the Battery Recycling Prize voucher contract. The back-end is built on previous work at NREL modeling the degrade in battery state of health for Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) lithium-ion cells (Gasper et al. 2021). The original model was adapted to python to be more cleanly integrated into this project. The inputs for the back-end model include (1) the operating temperature, (2) the amount of time the battery was in use or stored before being brought to Renewance, and (3) the daily estimated state of charge profile. When the user runs the algorithm, they can select the first two of these three inputs directly and then the third is derived based on several additional input selections. These selections are pictured in a sample of the interface window below.

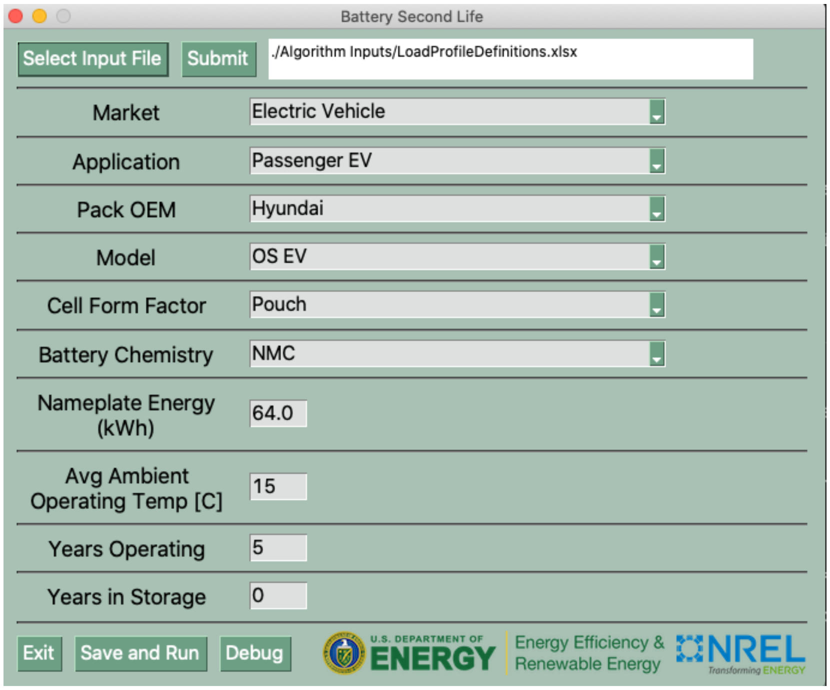

Figure 1: Sample set of inputs for the algorithm interface used to calculate the estimated degrade for lithium-ion battery state of health

The available options from the dropdown menus in *Figure 1* take, as inputs, battery catalog data stored in Renewance's internal tracking database "Renewance Connect". These inputs are stored in a digestible spreadsheet format and include the Pack OEM, battery model, chemistry, nameplate energy, and cell form factor. When the battery model is selected, the other fields are auto-filled based on the characteristics of that model. Although users can select a range of chemistries as defined by the Renewance database, the back-end model is specified for only NMC or LFP batteries. Any selection outside of these two options defaults to LFP. There are additional fields stored in this input file that could be used for identifying appropriate second life uses outside of the operation of this interface.

Then, the "Input File" selected by the user (LoadProfileDefinitions.xslx in *Figure 1*) defines the state of charge profile assumptions for each of the end-use battery markets including stationary energy storage, EVs, and any other lithium-ion battery market of interest. For each specific application within these markets, the Input File defines the Annual Full Cycle Equivalent, Low state-of-charge, High state-of-charge, C-rate, and charging C-rate (see **Error! Reference source not found.Error! Reference source not found.**). The algorithm uses these inputs to create an assumed load profile for that application. Batteries in each use category are likely to have similar operating standards and these inputs are a shortcut to evaluate how those assumed operations would likely impact the battery state of health. These assumptions will be further refined by Renewance as their database of EOL batteries grows and accumulates known operating profiles by battery application.

Table 1: Sample Battery Market Input Sheet

Market	Application	Annual FCE Frequency	Low SOC	High SOC	Low C-Rate	High C-Rate	Avg C-Rate	Charge C-rate
Stationary Energy Storage	Utility Solar and Wind	365	20	100	0.25	0.50	0.375	0.5
Stationary Energy Storage	Utility Frequency Regulation	365	20	100	0.25	0.50	0.375	0.5
Stationary Energy Storage	Residential Solar	365	20	100	0.25	0.25	0.25	0.25
Stationary Energy Storage	Commercial Solar	365	60	80	1.00	2.00	1.5	2.0
Stationary Energy Storage	Data Center UPS	12	60	100	4.00	8.00	6	6.0
Stationary Energy Storage	Generator Backup	250	20	100	0.25	0.50	0.375	1.0
Stationary Energy Storage	Telecom Backup	12	20	100	0.10	0.15	0.125	0.2
Electric Vehicle	Commercial EV	315	20	100	0.50	1.00	0.75	2.0
Electric Vehicle	Commercial Hybrid	315	20	80	1.00	2.00	1.5	2.0
Electric Vehicle	Material Handling EV	1000	20	80	0.50	1.00	0.75	2.0
Electric Vehicle	Passenger EV	100	40	80	0.15	1.00	0.575	1.0
Electric Vehicle	Passenger Hybrid	70	60	80	1.00	2.00	1.5	1.0
Other E-Mobility	Wheelchair	150	20	100	0.25	0.25	0.25	0.5
Other E-Mobility	Golf Cart	300	20	100	0.25	0.50	0.375	1.0
Other E-Mobility	Scooter	250	20	100	0.50	1.00	0.75	1.0
Other E-Mobility	E-Bike	50	20	100	0.25	0.25	0.25	1.0
Rail	Rail EV	1000	20	80	1.00	2.00	1.5	2.0
Rail	Rail Hybrid	750	20	80	1.00	2.00	1.5	2.0
Marine	Commercial Boat EV	500	40	80	0.50	1.00	0.75	1.0
Marine	Commercial Boat Hybrid	300	20	80	2.00	3.00	2.5	1.0
Marine	Leisure Boat EV	50	20	80	0.50	1.00	0.75	1.0
Other	Mobile Hospital Equipment	365	20	80	0.25	0.25	0.25	1.0

Work Results

Once the user has selected their input sheet and as many of the other criteria as known, they can execute a run to calculate a battery state-of-health degrade curve based on the chosen values. The output gives the estimated state-of-health after the battery completed operations using both calendar ageing and degrade related to the charge and discharge cycling defined in the user inputs (. For any storage time, the battery is assumed to be left at 40% state-of-charge and only undergoes calendar ageing (a much slower degrade process than battery cycling). As Renewance conducts further physical state-of-health testing they will learn more about any potential differences between expected second life value for batteries that are stored for a significant amount of time compared to batteries received directly from operation. In that case, Renewance could make different decisions on the testing of a battery based on the estimated state-of-health after operating life as compared to the estimated state-of-health after storage.

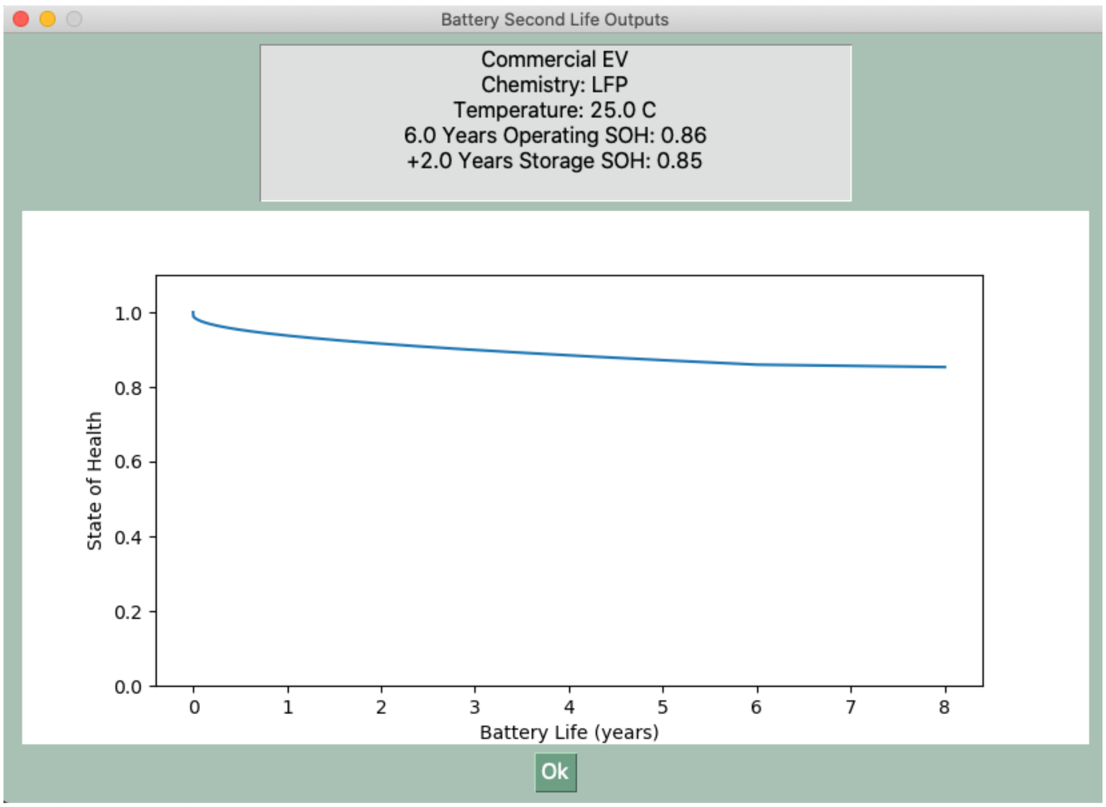

Figure 2: Sample algorithm interface output window

The curve shown in Figure 2 extends based on the input operating and storage time. Therefore, this tool can also be used for estimating the future state-of-health of batteries that are not yet out of service or may remain in storage in case of a lull in demand for second life batteries. With access to the source python code, Renewance can also customize both the input and output windows as their needs evolve. With wide-scale projected growth in the battery market (both in terms of demand and EOL supply), there may be other relevant outputs that can be added to the interface as they are identified. These unknown potential outputs could perhaps complement the additional logic discussed in the Next Steps section below.

Enabling Pilot Validation

The result of the work commissioned through the Battery Recycling Prize voucher will be a useful tool for the development and growth of Renewance's business model. Minimizing costs and time associated with physical testing can help the business scale up- an important aspect of validation to prepare for the projected rapid growth in EOL batteries in the coming years. The tool is also highly flexible. With the source code for the interface and underlying algorithm in hand, Renewance can adapt the tool to changes in the market as needed. And as the Renewance Connect database grows, new input sheets can be generated to easily update the interface menus to match. Finally, the active selection of the Load Profile definitions sheet allows for specification of use characteristics based on the battery vendor, region, or over time as battery technology and use cases evolve. The built-in flexibility of this work will be useful for continued development of the Renewance business and is ready for their growth beyond the pilot scale.

NREL Task 2 Description:

Develop a model to determine a starting-point estimate for battery trade in value based on:

(i) the estimated state of health (as estimated by the algorithm from Task #1),

(ii) the market price for equivalent capacity,

(iii) cost for logistics,

(iv) cost for state of health assessment, and

(v) the cost to recycle the battery.

Logistics cost shall be calculated based on the following input parameters:

(i) location of primary application,

(ii) location of reuse,

(iii) transported lot size,

(iv) mode of transportation.

NREL Task 2 Results:

Due to constraints in available data pricing EOL batteries for second life applications by market segment, and interest in deepening the complexity of the task 1 model by creating an interactive interface coded in python (instead of an Excel spreadsheet), both parties agreed to focus efforts on the development of the model for task 1 of this agreement and we did not pursue development of the battery trade-in value estimator. However, as the volume of batteries processed by Renewance grows, their database can be used to validate and tune the inputs for the task 1 interface for the various market segments that are included. As they gather market data, the estimated state of health output from the task 1 model can still be used to inform a battery trade in model as described in Task 2 part i.

NREL Task 3 Description:

Provide technical progress reports on completion of each of the above tasks.

NREL Task 3 Results:

Technical progress reports were provided summarizing progress made on Task 1. Task 2 was omitted as described under the Task 2 results.

NREL Task 4 Description:

This report serves to meet the requirement for the CRADA Final Report – Preparation and submission in accordance with the agreement's Article X.

NREL Task 4 Results:

The CRADA report was prepared and submitted in accordance with Article X. This Final Report serves to meet that requirement.

Partner Task 1 Description:

Provide the market price for equivalent capacity data to NREL

Partner Task 1 Results:

This data was provided by the partner.

Partner Task 2 Description:

Provide the required reserve for ultimate recycling data to NREL

Partner Task 2 Results:

This data was provided by the partner.

Partner Task 3 Description:

Provide battery's original nameplate characteristics to NREL

Partner Task 3 Results:

This data was provided by the partner as an export from Renewance Connect. The data provided is used as an input to the task 1 model to define the options for various battery characteristics to be selected by the user based on their knowledge of the battery lot in question.

Partner Task 4 Description:

Assist with development of the final CRADA report

Partner Task 4 Results:

The partner will be consulted on the final version of the CRADA report.

Subject Inventions Listing:

None

ROI #:

None