26317 Riding the Solar Curve — Smartville

Cooperative Research and Development Final Report

CRADA Number: CRD-22-22480

NREL Technical Contacts: Kandler Smith and Andrew Schiek

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-89297
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: March 1, 2024

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: Smartville, Inc.

CRADA Number: CRD-22-22480

CRADA Title: 26317 Riding the Solar Curve - Smartville

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

Kandler Smith | Kandler.Smith@nrel.gov | PI

Andrew Schiek | Andrew.Schiek@nrel.gov | Co-Author

Name and Email Address of POC at Company:

Trish Tran | trish@smartville.io

Megan Lloyd | megan@smartville.io

Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$75,000.00
TOTALS	$75,000.00

Executive Summary of CRADA Work:

NREL will apply its battery machine learning pipeline on Smartville datasets to estimate 2nd-use battery state of health from operational data and show how Smartville data can transfer that knowledge to a certifiable product for solar plus storage markets.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope,
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities.

Summary of Research Results:

This report contains Protected CRADA Information, which was produced on 03/01/2024 under CRADA No. CRD-22-22480 and is not to be further disclosed for a period of six (6) months from the date it was produced except as expressly provided for in the CRADA. (Delay for journal paper to publish prior to this CFR.)

TASK DESCRIPTIONS:

Purpose:

Smartville would like to deploy their battery reconditioning/second-use business model in geographically diverse locations, for multiple models of used EV battery packs for which there is little or no state-of-health (SOH) or lifetime data. Smartville's approach cycles batteries and conditions them using a "life-balancing" strategy to bring multiple batteries to a common SOH. NREL will apply its machine learning pipeline to estimate battery SOH from Smartville cycling data. Based on its life models, NREL will forecast remaining useful life (RUL) of batteries under 2^{nd} use storage + solar application.

The Participant will perform the following tasks:

Task 1 – *Provide battery charge/discharge cycling data from used automotive batteries under test at Smartville, including cell-to-cell voltage variability as an indicator of EOL.*

Task 1 Results:

Smartville provided data from used Nissan and Tesla batteries tested at Smartville's test facilities. This data included cell-to-cell voltage, current, and temperature data along with measured capacity and approximate values for internal resistance. The data was sufficient for fitting State-of-Health (SOH) models that could be compared to models fit on publicly available data sets. Below some of the data is visualized to summarize trends. On the diagonal of the figure is kernel density plot of the distribution of that variable to get an idea of how normal the distribution is. The other plots correspond to a scatter plot of a variable on the y and on the x to help visualize if there are any trends or dependencies between variables.

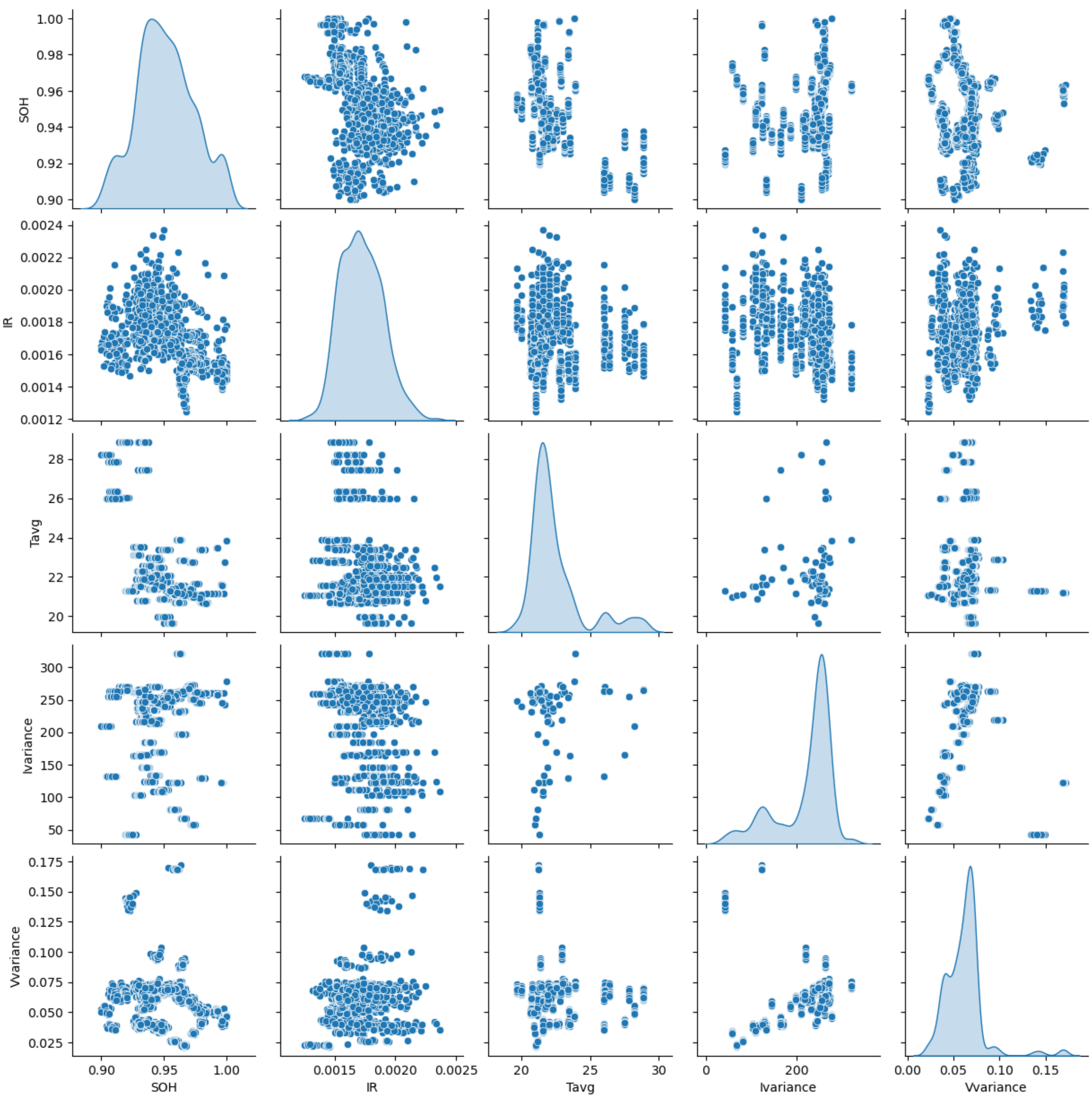

Figure 1. Kernel Density and Scatter plots of SOH, Internal Resistance (IR), Average Temperature, Current Variance, and Voltage Variance. We see no clear trends between any variable and SOH indicating a need for our advanced fitting software.

Task 2 – ***Provide example business scenarios how Smartville expects its 2nd-use batteries to be operated in solar + storage applications***

Task 2 Results:

Smartville provided a limited data set from a prototype Modular-Assembly Battery (MOAB) as an example business scenario. As we progress into future work, we will receive more MOAB data and be able to more broadly test the models and approach. Additionally, Smartville provided graphics for the application of its 2nd-use batteries applied to solar and storage applications during their commissioning. A few images of that are provided below.

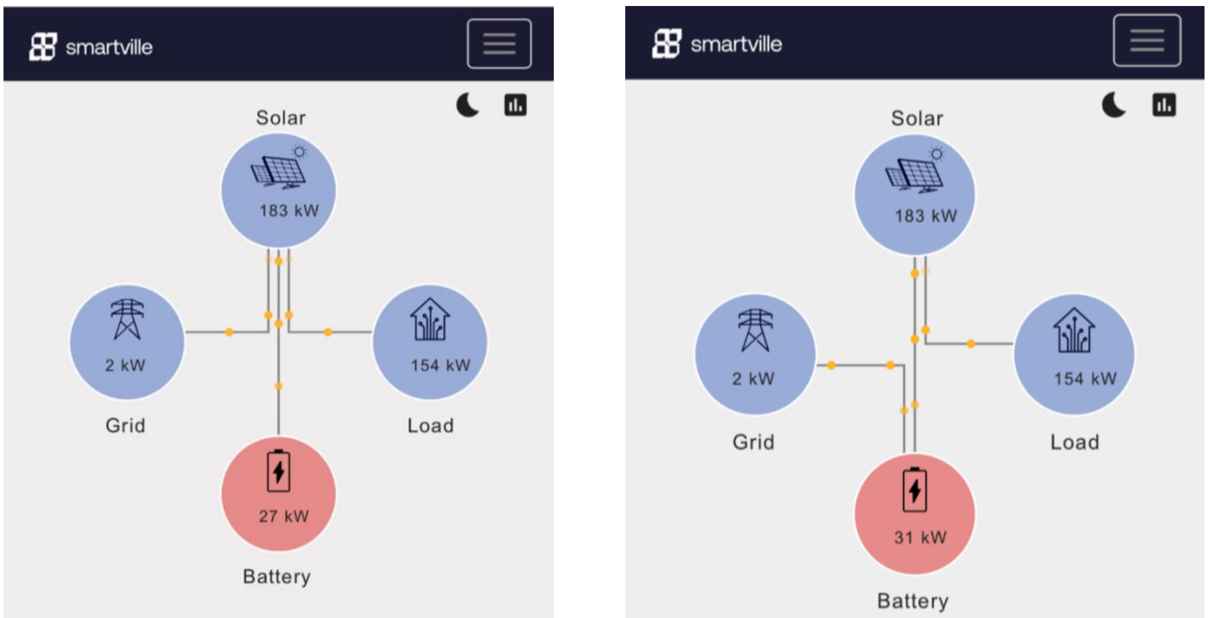

Figure 2. Example application of Smartville's MOAB system. In the image on the left we see the grid being powered by solar and on the right we see the battery delivering power to the grid.

NREL will perform the following tasks:

Task 1 – ***NREL will apply its ML data pipeline to Smartville's battery module and pack data to estimate battery SOH. NREL will document the algorithm and results for integration by Smartville's engineers. NREL will consult on electrochemical features to inject into battery normal operation to aid accurate observation of SOH.***

Task 1 Results:

NREL delivered and documented code for its ML data pipeline for estimating battery SOH. During the project, we applied the code base to Smartville's battery module and pack data. Over the course of testing, we found that we could achieve an accuracy of better than 0.005 Root Mean Square Error (RMSE) and better than 0.3% Mean Absolute Percentage Error (MAPE). RMSE has units matching that of the predicted variable, so both error metrics tell us that we're able to very accurately predict SOH.

When choosing which model will be best for Smartville's application we considered how well the model performs on unseen data compared to fitted data, a visualization of the actual value to the predicted value, and how easily the features chosen could be gathered from Smartville's MOAB system. To measure how the models performed on unseen data we took the difference between the test and training error. Most models performed well, and this only eliminated a few, but it's important to note that we had a limited data set so magnitude of error and difference and error are impressive but might vary as the models see more data. An example of the visualizations we produced for judging fit accuracy is below. In these plots we're looking for any trends or clustering of deviation from the red line. The red line is the "perfect" fit line where the actual value matches the prediction. Finally, we put preference on models that used data mostly or exclusively from the current and voltage data. This is going to be easier to collect from the MOAB system with lower measurement error. Predictors, like internal resistance, were helpful for fitting models and understanding trends but is easier to collect at the lab level. Smartville indicated to us that they will have low certainty in this measurement on the MOAB system.

After considering the magnitude of error, the difference between test and train error, the fit visualization, and which metrics were chosen, we landed on a model using no additional feature engineering, the ReliefF feature selection model, and fitting with GPR for improved accuracy and Random Forest for speed. The relief feature selection model selected features of maximum current, variance of current profile, range of current profile, maximum voltage, and the range of the voltage curve. The difference between using the GPR model or random forest is primarily speed. Random Forest fits significantly faster than GPR, but GPR has slightly lower error and relative difference between test and train error.

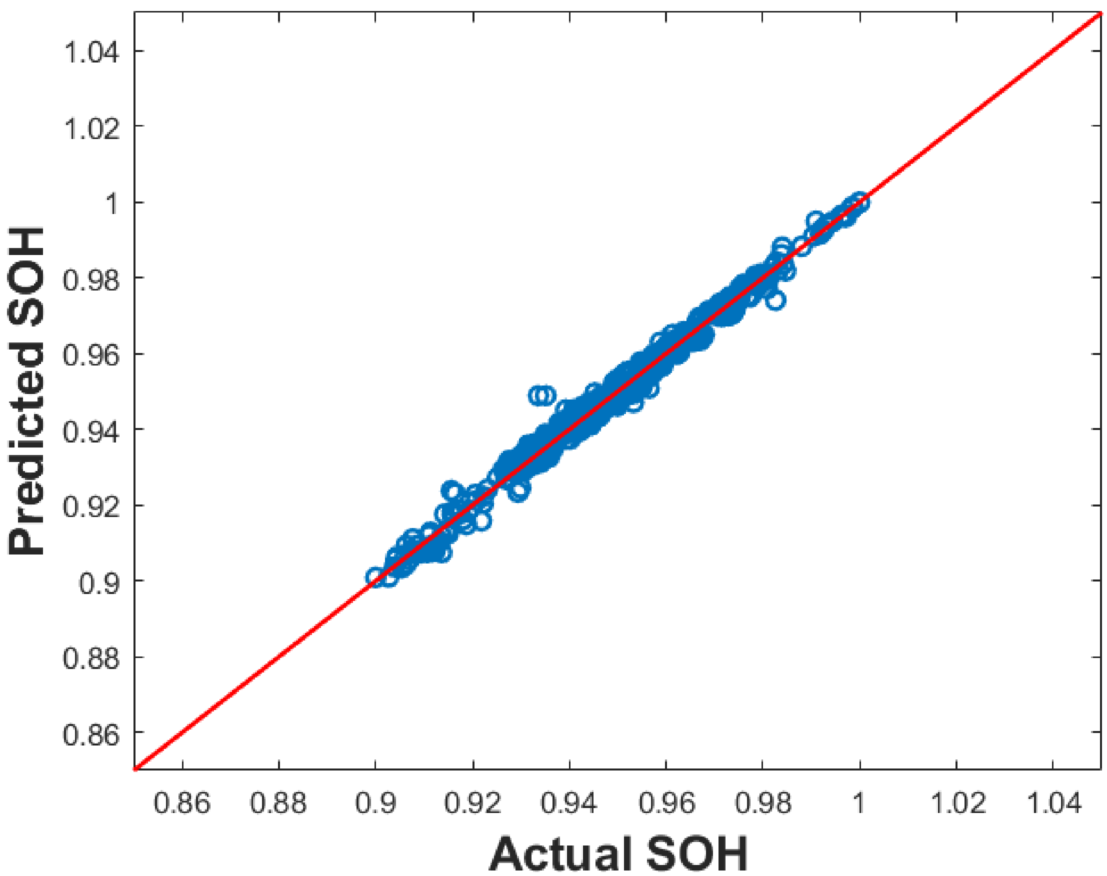

Figure 3. Example fit using the ReliefF algorithm for feature selection and GPR for fitting. We see the actual and predicted values align extraordinarily well with the actual value.

Task 2 – ***NREL will develop an approach by which Smartville's data can be used to support a certifiable energy storage product in the combined solar + storage market. This approach will combine pre-existing battery life models with SOH estimations from Task 1 to forecast RUL.***

Task 2 Results:

We demonstrated during the last voucher that our machine learning models may have trouble predicting outside of the range of seen data. As a result, to forecast RUL, we must implement some domain knowledge from physics-based models. Given the use conditions, from the current data we have, this can help us forecast beyond our given knowledge. We fit a simplified life model to the equation: $q = 1 – b_1 (SOC) \exp(-E_{a1} / T) t^{1/2} – b_2 (DOD) \exp(-E_{a2} / T) N_{100}$ and the results are displayed below. We have more error at high relative capacities (near beginning of life (BOL)) and we can refine these estimates in the machine learning pipeline. Having less error at lower relative capacities gives us higher confidence in predicting RUL as we have higher confidence in our predictions near end of life.

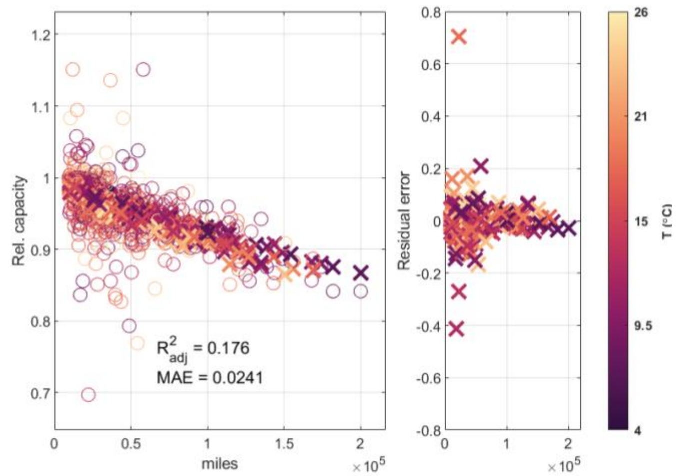

Figure 4. Life model fit to consumer-reported data from Plug-In America for Tesla Model S range reduction (relative capacity loss) with vehicle mileage. Temperature is the average annual temperature for the zip code in which the vehicle was registered.

NREL documented and began developing an algorithm to blend all information from Smartville's MOAB batteries to smoothly estimate battery SOH and RUL. NREL submitted a conference paper on the algorithm to the IEEE Energy Conversion Congress and Exposition conference for fall of 2023. Figure 5 provides a schematic overview of the algorithm. It combines two estimators on two different time scales. The first estimates battery SOC based on fast second-by-second dynamics of battery current, voltage and temperature. The second estimates battery SOH and RUL based on (1) the battery lifetime model (e.g. Figure 4), (2) ML estimates of battery SOH from current/voltage/ temperature features (e.g. Figure 3) and (3) the estimated SOC, and current and temperature measurements.

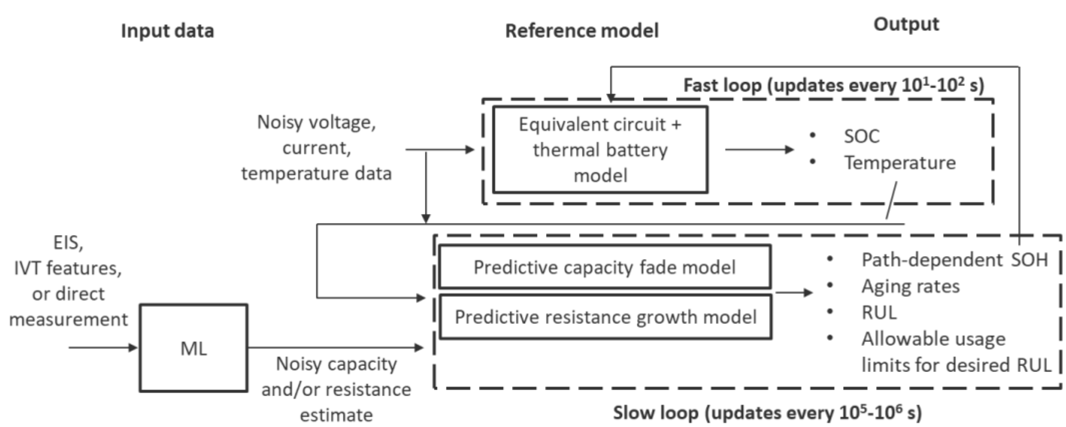

Figure 5. Hierarchical SOC/SOH estimation algorithm.

Task 3 – ***NREL will prepare a CRADA Final Report: Preparation and submission in accordance with Article X***

Task 3 Results:

This is the CRADA Final Report in accordance with Article X. We have prepared this report to summarize the work and findings under the current voucher with Smartville. We have built on algorithms and code developed under previous work and look forward to applying our findings here to future work.

Software Record:

SWR-22-35 "ML Pipeline (Machine Learning Pipeline)

Subject Inventions Listing:

None.

ROI #:

None.