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Milestone Report
NREL/MP-5400-62853
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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LOWER-ENERGY ENERGY STORAGE SYSTEM (LEESS) COMPONENT EVALUATION

Background/Introduction

Automakers have been mass producing hybrid electric vehicles (HEVs) for well over a decade, and the technology has proven to be very effective at reducing per-vehicle fuel use. However, the cost of HEVs such as the Toyota Prius or Ford Fusion Hybrid remains several thousand dollars higher than the cost of comparable conventional vehicles, which has limited HEV market penetration. The battery energy storage device is typically the component with the greatest contribution toward this cost increment, so significant cost reductions and/or performance improvements to the energy storage system (ESS) can correspondingly improve the vehicle-level cost vs. benefit relationship. Such an improvement would, in turn, lead to larger HEV market penetration and greater aggregate fuel savings.

In recognition of these potential benefits, the United States Advanced Battery Consortium (USABC) asked the National Renewable Energy Laboratory (NREL) to collaborate with its Workgroup and analyze the trade-offs between vehicle fuel economy and reducing the decade-old minimum energy requirement for power-assist HEVs. NREL's analysis showed that significant fuel savings could still be delivered from an ESS with much lower energy storage than the previous targets, which prompted USABC to issue a new set of lower-energy ESS (LEESS) targets and issue a request for proposals to support their development. To validate the fuel savings and performance of an HEV using such a LEESS device, this jointly funded activity between the U.S. Department of Energy Vehicle Technologies Office Energy Storage and Vehicle Systems Simulation and Testing programs has designed a test platform in which alternate energy storage devices can be installed and evaluated in an operating vehicle.

Approach

The approach in previous fiscal years (FY12–FY13) included establishing a cooperative research and development agreement between NREL and Ford Motor Company to support conversion of a Ford Fusion Hybrid into a test platform for evaluating LEESS devices. NREL subsequently acquired a 2012 Fusion Hybrid, designed the conversion, and entered into agreements with JSR Micro, Inc. to provide (at JSR Micro's expense) lithium-ion capacitor (LIC) modules as the first LEESS device to be evaluated in the vehicle. The LICs are asymmetric electrochemical energy storage devices possessing one electrode with battery-type characteristics (lithiated graphite) and one with ultracapacitor-type characteristics (carbon). In FY13 NREL completed bench testing on the LIC replacement pack in comparison to the production nickel metal hydride (NiMH) battery pack from the 2012 Fusion Hybrid and integrated the modules into the Fusion Hybrid test platform.

The approach in FY14 included troubleshooting and shakedown testing to get the vehicle fully operational with the alternative LEESS modules. Subsequently, on-road and chassis dynamometer testing were used to perform back-to-back comparison of operation using the LIC replacement pack relative to the production NiMH configuration. While this testing was being completed (using multiple energy storage configurations of the LIC modules), NREL established agreements with Maxwell Technologies to provide ultracapacitor modules as the second LEESS device to evaluate in the vehicle (again at the supplier's expense). In the second half of FY14, NREL completed bench testing on the Maxwell ultracapacitor modules, removed and returned the JSR Micro LIC modules, and integrated the Maxwell ultracapacitor modules into the vehicle test platform. The remainder of the planned in-vehicle testing will be completed in FY15.

Results

Figure 1 shows a photograph of the production high-voltage traction battery (HVTB) unit, which mounts between the rear seat and the trunk area in the Fusion Hybrid. Important components of the HVTB include the high-voltage bussed electrical center (BEC), the battery pack sensor module (BPSM), and the battery energy control module (BECM). The BEC acts as an interface between the high-voltage output of the HVTB and the vehicle's electric motor, air conditioning compressor, and DC/DC converter. The BPSM measures the voltage and temperature of the NiMH cells and communicates with the BECM, which manages the charging/discharging of the battery and also communicates with the other vehicle control modules over the high-speed controller area network (CAN) bus.

Figure 1. Photo of the Fusion Hybrid's HVTB (Photo credit: John Ireland, NREL).

For implementing the vehicle conversion, NREL kept the production HVTB installed in its original position so that direct comparison testing could be conducted by switching back and forth between the production battery and the alternative LEESS under test. Figure 2 shows a schematic of this configuration, where parts from a second HVTB acquired by NREL (including the BECM, BEC, BPSM, module sense leads, and various wiring harnesses) were reconfigured to work with the alternative LEESS under test. The dSpace component represented in the schematic is a dSpace MicroAutoBox (MABx), which is used to intercept certain CAN signals pertaining to the BECM's calculations for the production NiMH battery (state of charge, power capability, etc.) and to replace them with corresponding calculations for the alternate LEESS under test. The MABx also records data and handles safety controls during the testing.

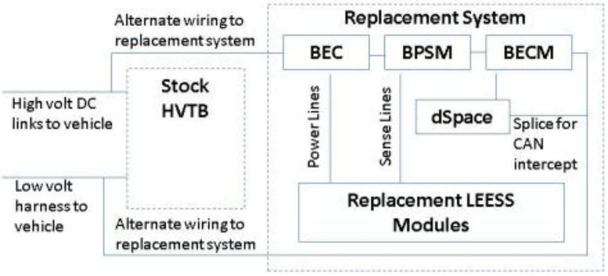

Figure 2. Schematic of connections between replacement components and the vehicle.

Prior to actually integrating the JSR LIC modules into the test vehicle, NREL first performed bench testing with the modules mounted in an environmental chamber (see Figure 3). The purposes of the bench testing included confirming expected LIC performance, comparing the LIC pack's operation to that of the production battery over a representative driving profile, and generating test data for calibrating the custom state estimator model to implement in the dSpace MABx. Results from the LIC module hybrid pulse power characterization (HPPC) bench testing are presented later alongside the results from the comparable testing on the Maxwell ultracapacitor modules.

Figure 3. JSR LIC modules in an environmental chamber during bench testing, with the production 2012 Fusion Hybrid NiMH modules in the background (Photo credit: John Ireland, NREL).

Following bench testing, the LIC modules were integrated into the Fusion Hybrid test platform to enable the in-vehicle comparison testing. Figure 4 shows a picture of the fully integrated conversion system, including LIC modules, mounted in the trunk of the Fusion Hybrid. The LIC modules along with the replacement BEC are shown in the large box with the clear lid; to the side, the picture shows the MABx mounted on top of an electronics box containing a voltage divider circuit and related components.

Figure 4. Fully integrated conversion system mounted in the trunk of the Fusion Hybrid test platform (Photo credit: Jon Cosgrove, NREL).

Along with the physical components shown in Figure 4, completing the vehicle integration involved validating the custom state estimator code (for calculating the LEESS state of charge and charge/discharge capability at any moment in time) against the bench test data. This code was incorporated into the MABx and included temperature dependence functionality calibrated against the various temperature conditions from the bench testing (-20°C, 25°C and 45°C).

Initial driving tests focused on confirming proper operation of the converted vehicle. This included making sure the vehicle could operate while intercepting and re-broadcasting modified signals over the vehicle CAN bus. Further shakedown tests verified proper functioning of the safety controls and the state estimator model for the alternate LEESS device. Once confirmed, NREL conducted closed-course performance testing on the vehicle in both the LIC and production configurations (see Figure 5 and Figure 6).

Figure 5. Closed road acceleration performance testing (Photo credit: Petr Sindler, NREL).

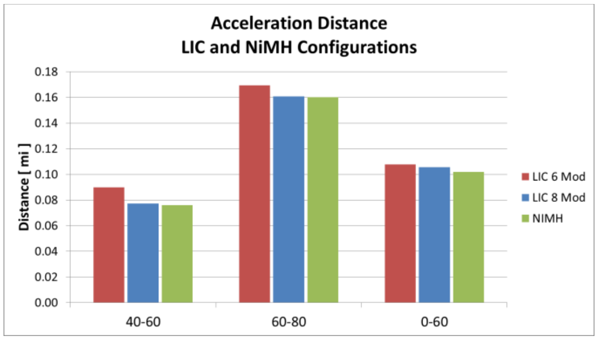

Figure 6. Acceleration distance for NiMH, 8 module LIC, and 6 module LIC configurations while performing 0-60, 40-60, and 60-80 MPH accelerations.

Figure 6 shows the standing and passing acceleration performance from six- and eight-module configurations of the LIC replacement pack compared to the production NiMH system. NREL evaluated different configurations of the LIC storage system to examine tradeoffs between size/energy content (which would ultimately influence component cost) and measured in-vehicle performance. As Figure 6 indicates, the eight-module configuration achieved similar performance to the production system in all three of the evaluated acceleration categories. While the six-module configuration demonstrated a slight performance penalty, it is very possible that more extensive controls calibration than was possible as part of this investigation could eliminate this difference. NREL therefore concluded that the LEESS LIC configurations can support comparable level-road acceleration performance to the production configuration, but that the smallest LIC scenario evaluated may be on the edge of some small acceleration performance degradation.

For HEV fuel economy evaluation, NREL utilized chassis dynamometer testing facilities at SGS Environmental Testing Corporation in Aurora, Colorado. Tests included standard certification cycles such as the Federal Test Procedure (FTP) and its constituent Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Test (HWFET), the aggressive US06, and the hot SC03 cycle (including air conditioning). These tests allowed NREL to evaluate in-vehicle ESS performance under a variety of conditions, including moderate (24°C), hot (35°C) and cold (-7°C) temperatures.

Figure 7 shows test results on the stop-and-go UDDS driving profile for both the production NiMH configuration and for a low-energy LIC scenario. The ESS energy profile for both storage system configurations shows oscillations in energy usage aligned with the individual microtrips in the driving profile—i.e., when the vehicle accelerates from a stop to some nominal driving speed then later decelerates back to a stop, the ESS profile shows some amount of discharge to support accessories while stopped as well as to assist the acceleration, and then later recaptures energy through regenerative braking during the deceleration. For the low-energy LIC scenario, these oscillations remain within a 60-Wh window whereas the production NiMH configuration shows a bulk energy swing in addition to the microtrip-scale oscillations that span over a 170-Wh window. Comparing the cumulative fuel consumption curves for the two configurations, the NiMH case shows slightly more fuel use during the period where bulk ESS charging is occurring and slightly less during the bulk discharging period, but by the end of the test cycle, the fuel use between the two cases is essentially equal.

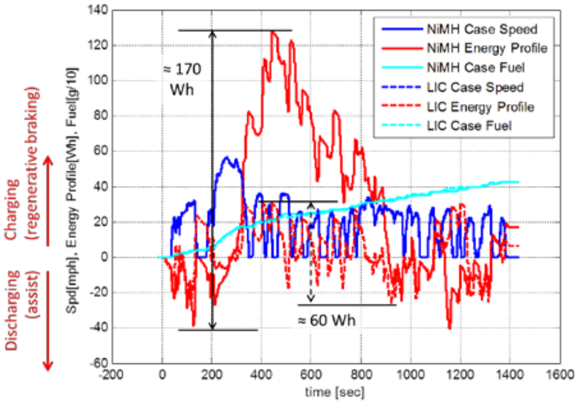

Figure 7. ESS energy profile and fuel use for 24°C UDDS tests of production NiMH and low-energy LIC configurations.

Figure 8 shows similar results for a low-energy six-module LIC configuration as compared to the production NiMH case over the 35°C SC03 cycle. This figure shows equivalent cumulative fuel use between the two scenarios, along with similar engine on/off behavior over the test cycle.

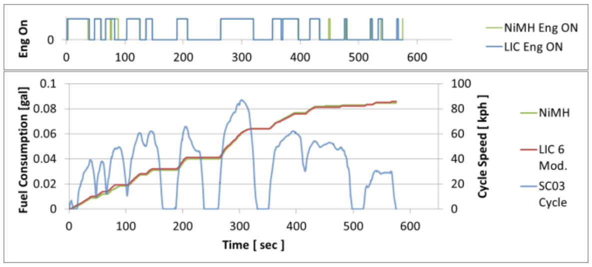

Figure 8. Fuel consumption and engine on/off cycling during hot (35°C) SC03 testing with air conditioning.

Figure 9 shows the ESS energy profile and cumulative fuel consumption results for the aggressive US06 cycle, which was the one test profile where the low-energy LIC configuration showed higher cumulative fuel consumption (by about 4%) than the production NiMH configuration. The energy window sizes for each configuration are approximately the same as for the UDDS test shown in Figure 7, but for the US06 test the bulk depletion of the NiMH in the middle of the cycle helps to measurably reduce the cumulative fuel consumption over that high-speed driving section. The NiMH ESS is then able to recapture regenerative braking energy during the decelerations at the end of the cycle to remain charge-neutral over the test (whereas the low-energy LIC scenario does not have enough available capacity to capture as much energy during those braking events).

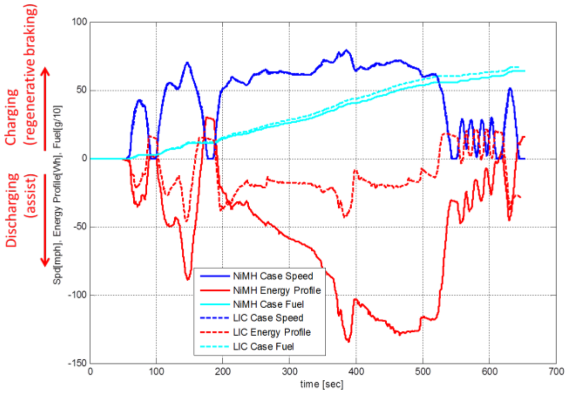

Figure 9. ESS energy profile and fuel use for 24°C UDDS tests of production NiMH and low-energy LIC configurations.

Figure 10 summarizes the fuel consumption and energy window comparisons between multiple ESS configurations over five different test cycles. Note that the test matrix included intermediate LIC energy scenarios as well as the low-energy scenarios discussed in the previous plots. These intermediate energy scenarios still fall under the LEESS category for power-assist HEV ESS as they possess much lower nominal energy content than the roughly 1.4 kWh production NiMH ESS.[1] Several of the relatively higher energy content LIC scenarios tested achieved comparable energy window sizes and fuel consumption as the NiMH reference case—including over the US06 cycle. For all cycles other than the US06 (including the -7°C FTP and the HWFET in addition to those already discussed), even the lowest energy LIC configurations were able to match the fuel consumption of the reference NiMH test (using roughly 60-Wh energy windows compared to energy windows closer to 200 Wh for many of the NiMH tests).

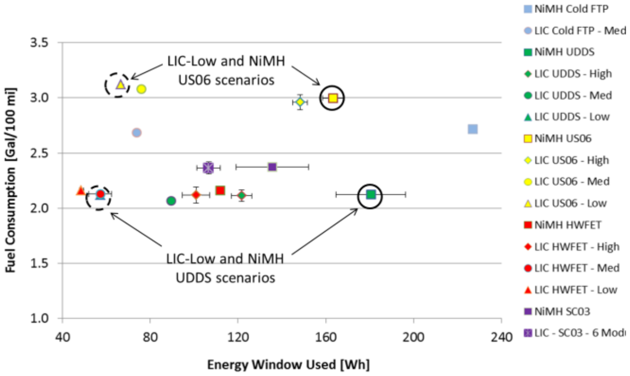

Figure 10. Summary fuel consumption and energy window results for multiple test cycles and vehicle configurations.

The final set of FY14 results involve the ultracapacitor or electrochemical double-layer capacitor (EDLC) modules provided by Maxwell Technologies. These 48-V modules underwent a similar suite of bench tests as the JSR LIC modules. Figure 11 shows a comparison of the 2-second and 0.5-second pack level resistance for the indicated LIC and EDLC configurations. These calculations derive from the HPPC test results and depend on the time scale over which the measurement is taken because of the combined influence of impedance and changing energy content when measuring voltage rise/drop following each pulse. These results indicate roughly three times lower internal resistance for the LEESS devices than for the production NiMH ESS.[1]

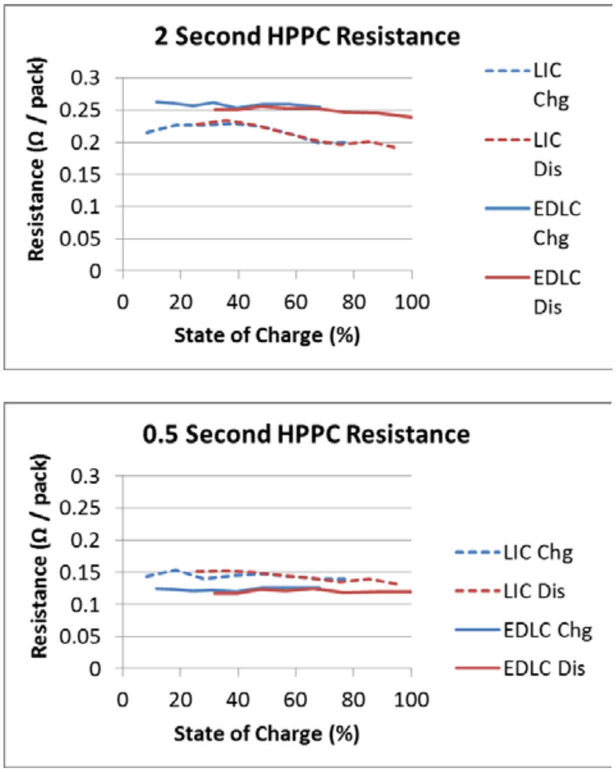

Figure 11. Pack level 2- and 0.5-second resistance for the ("high-energy") eight-module LIC and the seven-module EDLC configurations.

The EDLC modules were also characterized for drive cycle performance and power capabilities. This data was used to calibrate the models running on the MABx in a similar manner as was used for the LIC configuration. As shown in Figure 12, the EDLC modules have been installed in the test vehicle. In addition to conducting many of the same tests that were completed for the LIC configurations, NREL hopes to assess any operating advantage the modules may see at very cold temperatures (as low as -20°C). This testing had been planned for the LIC configurations, but the test facility was not able to maintain such a low chamber temperature during summer testing, whereas the

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[1] Based on a fact sheet published by Idaho National Laboratory: www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/hev/batteryfusion4699.pdf

facility expects to be able to maintain lower temperatures during winter testing.

Figure 12. Installed Maxwell EDLC seven-module configuration (Photo credit: Jon Cosgrove, NREL).

Conclusions

Alternate HEV storage systems such as the LIC and EDLC modules described in this report have the potential for improved life, superior cold temperature performance, and lower long-term cost projections relative to traditional battery storage systems. If such LEESS devices can also be shown to maintain high HEV fuel savings, then future HEVs designed with these devices could have an increased value proposition relative to conventional vehicles, thus resulting in greater HEV market penetration and aggregate fuel savings. This jointly funded activity between the U.S. Department of Energy Vehicle Technologies Office Energy Storage and Vehicle Systems Simulation and Testing programs developed a vehicle test platform to help validate the in-vehicle performance capability of alternative LEESS devices and to identify unforeseen issues.

This report describes successful creation of the Ford Fusion Hybrid test platform for in-vehicle evaluation of such alternative LEESS devices, bench testing of the initial LIC pack provided by JSR Micro, integration and testing of the LIC pack in the test vehicle, and the bench testing and installation of a second LEESS pack from Maxwell Technologies (consisting of EDLC modules). The in-vehicle LIC testing results suggest technical viability of LEESS devices to support HEV operation. Several of the tested LIC configurations demonstrated equivalent fuel economy and acceleration performance as the production NiMH ESS configuration across all tests conducted. The lowest energy LIC scenario demonstrated equivalent performance over several tests, although slightly higher fuel consumption on the US06 cycle and slightly slower acceleration performance. However, more extensive vehicle-level calibration than was possible for this conversion project may be able to reduce or eliminate these performance differences. The overall results indicate that as long as critical attributes such as engine start under worst case conditions can be retained, considerable ESS downsizing may minimally impact HEV fuel savings.

On-going work into FY15 will include completion of in-vehicle comparison testing between the EDLC pack and the production NiMH ESS. Other possible future work topics include evaluating the potential offered by LEESS devices with more extensive vehicle modification, such as by better matching the size of the motor in the vehicle to the LEESS power capabilities. This project has helped demonstrate the technical viability of non-traditional technologies to compete with typical battery systems for HEV energy storage. However, some combination of systems optimization to best leverage LEESS capabilities and cost reductions on the part of suppliers will be necessary to move LEESS technology from mere technical viability to having a compelling business case for broad use in HEV energy storage.

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