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of Transportation
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Office of Research,
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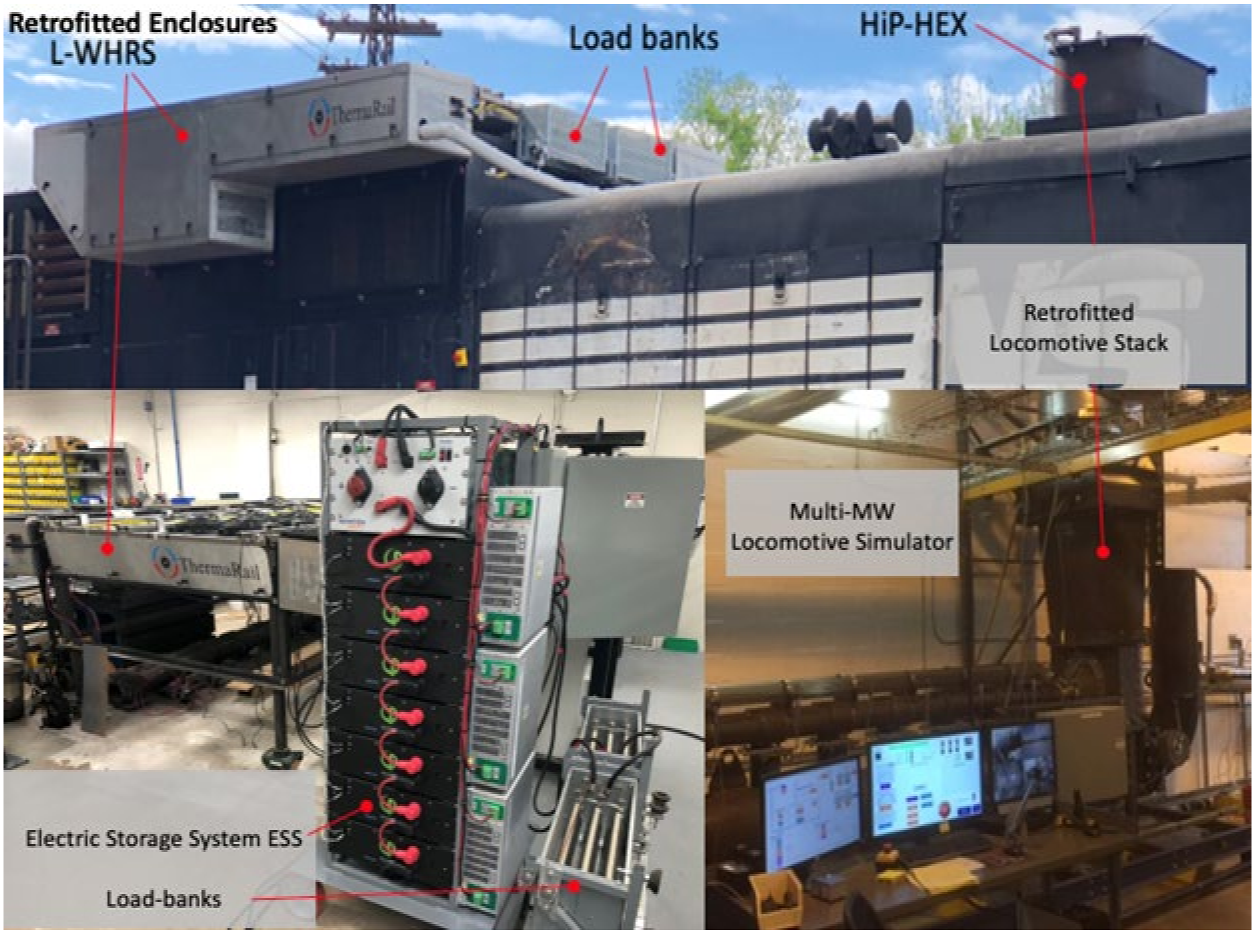
Washington, DC 20590

Hybrid Locomotive Waste Heat Recovery System (L-WHRS) Safety and Field Demonstration



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Dr Claudio Filippone - ThermaDynamics Rail LLC
ORCid #: 0000-0002-1312-0218
Melissa Shurland, ORCid#: 0000-0002-9055-6584

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

ThermaDynamics Rail LLC
9207-C Enterprise Court
Manassas Park, VA 20111

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1200 New Jersey Ave, SE
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14. ABSTRACT

ThermaDynamics Rail LLC (TDR) developed the Locomotive-Waste Heat Recovery Systems (L-WHRS) formed by high-pressure heat exchangers coupled to a closed-loop Organic Rankine Cycle (ORC). The L-WHRS can be configured to be non-invasively retrofitted onto different types of locomotive engines to recover and convert locomotive waste thermal energy into conditioned, pollutant-free, electrical power. Under the sponsorship of the Federal Railroad Administration (FRA), TDR successfully completed a series of demonstration phases that increased the technology readiness level to a full-scale operational system. Full-scale L-WHRS testing involved static tests using simulator and dynamic over-the-road locomotive tests under various operational conditions. This report describes the design and testing of the L-WHRS electrical system configured to supply electric power to selected locomotive electrical loads and to an advanced Energy Storage System (ESS). These tests demonstrated feasibility to utilize the L-WHRS as an electric generator that can simultaneously supply power to the ESS and locomotive electrical loads.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

VOLUME (APPROXIMATE)

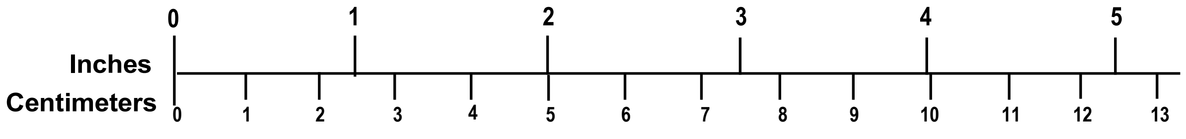
1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)

1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

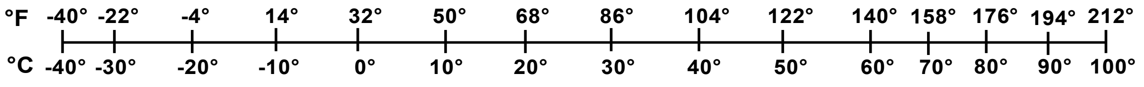
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

From September 27, 2018, to March 31, 2022, ThermaDynamics Rail LLC (TDR) developed the Locomotive-Waste Heat Recovery System (L-WHRS) configured to recover energy from the exhaust gases vented through the stack of locomotive engines and convert this otherwise wasted thermal energy into pollutant-free electricity. The L-WHRS is constructed with vibration and thermal-cycling tolerant components that are non-invasively retrofitted and interfaced with locomotive equipment. The retrofitting installation of the L-WHRS consists of inserting “flexible” High-Pressure Heat Exchangers (HiPHEXs) inside the engine exhaust stack in place of the “flare suppressor” and then coupling the HiPHEXs to non-invasive L-WHRS enclosures supported by the locomotive structure. The HiPHEXs can be scaled and customized to adapt to different locomotive models, engine power, and exhaust stack shapes without impacting the locomotive’s turbocharger performance, and failure of the L-WHRS does not impair normal locomotive operations. The L-WHRS enclosures comprise the electrical and thermal-hydraulic equipment which, together with the HiPHEX, form a bottoming vapor Rankine cycle utilizing water or organic working fluids circulating in a closed loop. The L-WHRS produces pollutant-free electric power proportional to the locomotive engine duty-cycle (i.e., the time duration at which the locomotive operates at medium to high notch settings). As a result of thermal to electric conversion, the L-WHRS produces conditioned electrical energy that can be utilized to charge advanced Energy Storage Systems (ESS), while also supplying electric power to locomotive hotel loads. The overall results of retrofitting locomotives with the L-WHRS include lowered locomotive operating costs, pollutant and thermal emissions reductions, and uprating of the locomotive electric power supply system.

In this project, the pollutant-free L-WHRS electric power is conditioned and interfaced with the advanced ESS and selected locomotive electrical loads to demonstrate safe power flows across the electrical buses connecting the L-WHRS power supply and locomotive electrical loads. The ESS operates independently of and reduces the electric load on the locomotive lead-acid battery, reducing the otherwise frequent lead-acid battery deep discharges caused by the operation of the Automatic Engine Start/Stop (AESS) system and the continuous operation of locomotive cab heating, ventilation, and air conditioning systems (HVAC) and lights by the crew. Deep-discharging the lead-acid locomotive battery results in premature and more frequent replacement of this component as well as operational disruptions.

The advanced ESS was selected from top-ranked battery technology candidates based on various performance parameters. The Failure Mode, Effect, and Criticality Analysis (FMECA), executed in previous research efforts, was updated to include failure modes associated with equipping the locomotive power supply system with an advanced battery management system and electronic interfaces regulating power flows from the L-WHRS, the ESS, and locomotive electrical loads. In this project, the L-WHRS was coupled to the selected ESS and locomotive electrical loads through customized interfaces. The resulting electrical system was tested at full-scale operating conditions, in agreement with locomotive operational data via a locomotive simulator and interface that mimics different electrical configurations and power flows.

The research demonstrated safe operations of power flows between the electrical components coupled to the L-WHRS, the ESS, and selected locomotive electrical loads. The milestones completed in this project provided validations and test data to execute future L-WHRS design amendments and optimization to lower the L-WHRS components production cost, increase

conversion efficiency, and enable autonomous L-WHRS operations via a customized, micro-processor-based, electronic controller embedded with the locomotive interface.

1. Introduction

ThermaDynamics Rail LLC (TDR) demonstrated the technical and economic feasibility of using High-Pressure Heat Exchangers (HiPHEXs) in the development of a scalable Locomotive Waste Heat Recovery System (L-WHRS) optimized for non-invasive retrofit installations on locomotives. HiPHEXs are specialized heat exchangers designed to operate under harsh operating conditions and capable of withstanding fire engulfment, high vibratory stressors, and off-normal pressure variations. HiPHEXs extract thermal energy from the locomotive's exhaust gases and transfer the recovered energy to a working fluid executing a bottoming Rankine thermodynamic cycle. The working fluid is expanded through a direct-drive turbine-generator with specialized bearings capable of withstanding high radial and thrust accelerations. The recovered thermal energy is converted into electricity for various locomotive uses, thus reducing the locomotive operational cost, while decreasing pollutant emissions. Figure 1 illustrates the simplified L-WHRS working principles of a tandem (bottoming) Rankine cycle thermally coupled to the locomotive exhaust gases, wherein the "boiler" of a traditional Rankine vapor cycle is represented by the HiPHEX. Federal Railroad Administration (FRA) sponsored TDR to conduct the research between September 27, 2018, and March 31, 2022. The research took place at TDR's testing facility in Manassas Park, VA. TDR also worked closely with a Class I railroad in the development of the L-WHRS.

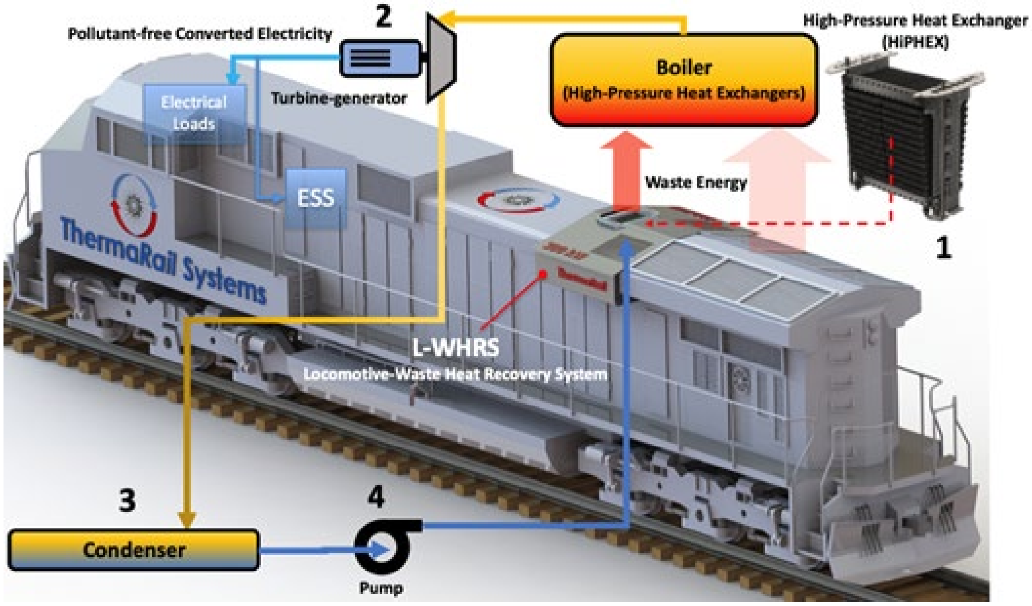

Figure 1. Closed-loop L-WHRS main components

1.1 Background

The initial phases of this project were dedicated to validation of the technical and economic feasibility of the HiPHEXs and the L-WHRS power conversion components through locomotive testing (Filippone, 2020). Testing of the L-WHRS components was further supported by a multi-megawatt locomotive-simulator operated at the TDR testing facility. During these initial phases, different HiPHEX configurations were coupled to the L-WHRS components for testing and optimization.

TDR conducted several rounds of Failure Mode, Effect, and Criticality Analysis (FMECA) on the L-WHRS and updated it as the research effort progressed to include the electrical interfaces between the L-WHRS components, the locomotive electric loads, and the power management system of an advanced Energy Storage System (ESS).

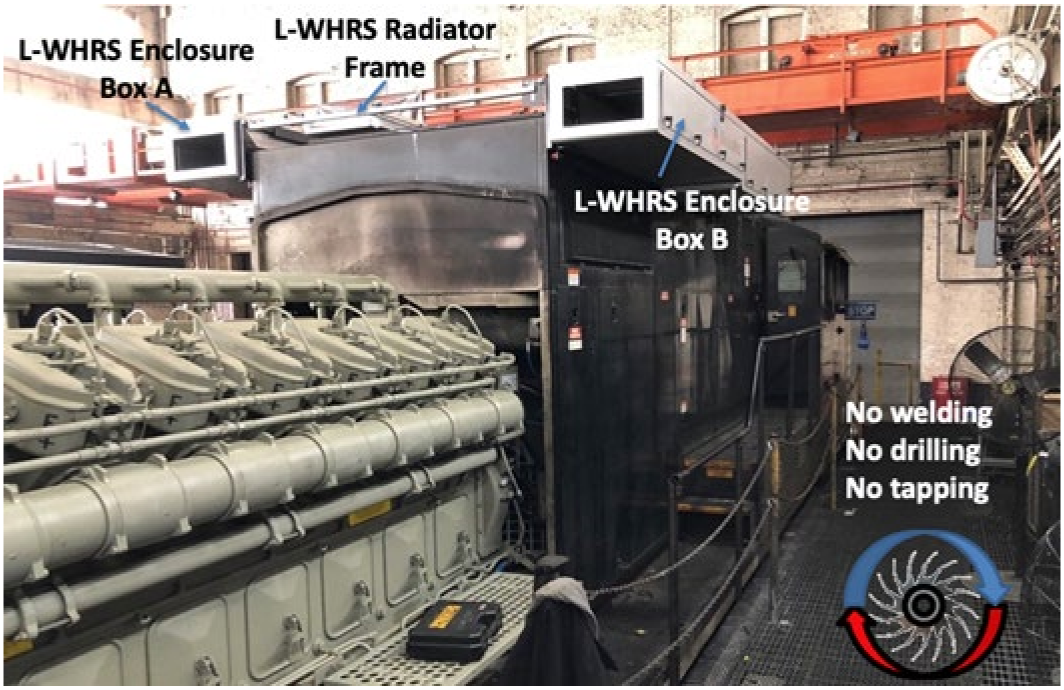

Figure 2. Non-invasive installation of L-WHRS' thermal-hydraulic and electrical enclosures

Locomotive tests included mechanical, thermal-hydraulic, and electrical coupling of the L-WHRS components to the electrical bus and structure of a General Electric (GE) model Dash-9 locomotive, rated at 4,400 horsepower (HP). The retrofitted locomotive was operated from low-idle to notch 8 under various electrical load scenarios. Figure 2 above illustrates the non-invasive retrofit installation of the L-WHRS enclosures mechanically coupled to the locomotive. The original equipment manufacturer's (OEM) lifting lugs, normally welded at specific locations on the locomotive body, were used to mechanically secure the L-WHRS enclosures to the locomotive structures.

Figure 3 illustrates the HiPHEX within the locomotive exhaust stack and in place of the flare suppressor and exhaust gas stack top flange. The vacuum gauge shown was monitored during testing to ensure the HiPHEX would not cause over-pressurization of the crankcase during testing and locomotive operations.

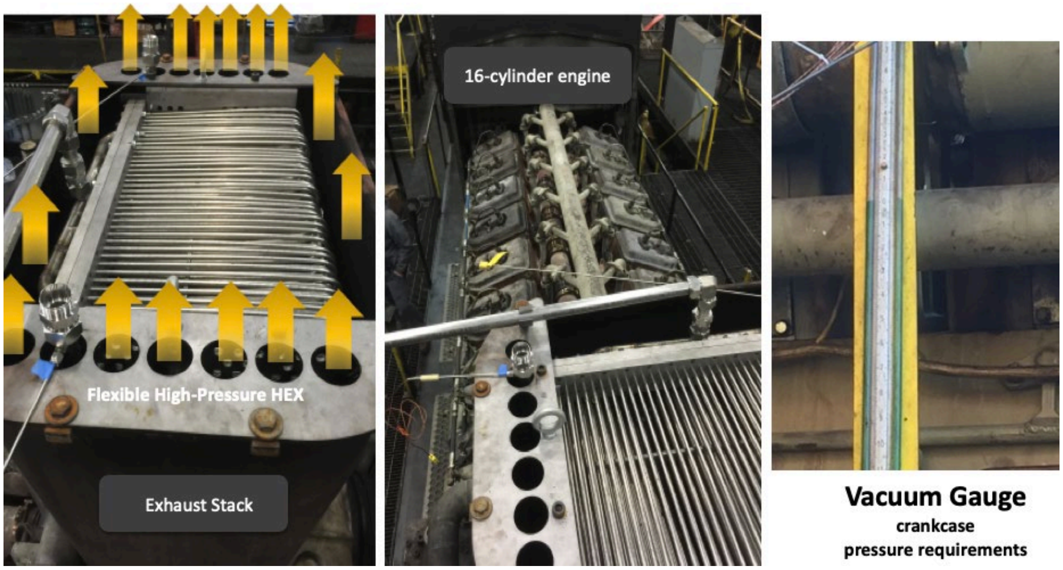

Figure 3. Non-invasive locomotive retrofitting installation of the HiPHEX

A multi-megawatt (MW) locomotive-simulator was developed by TDR to accelerate development of the L-WHRS through prolonged static testing and minimize dependency on locomotive availability. The locomotive-simulator is formed by a modified aviation turbojet engine configured to supply exhaust gases with thermal energy and flow-rates comparable to the exhaust gases from locomotives operated at different notch settings. Figure 4 illustrates the locomotive simulator and control interfaces. The locomotive simulator supplies exhaust gases to a GE Dash 9 locomotive exhaust gas stack retrofitted with the HiPHEX. In this configuration, the HiPHEX is hydraulically coupled to the L-WHRS to mimic actual locomotive non-invasive installation and operations at high notch setting.

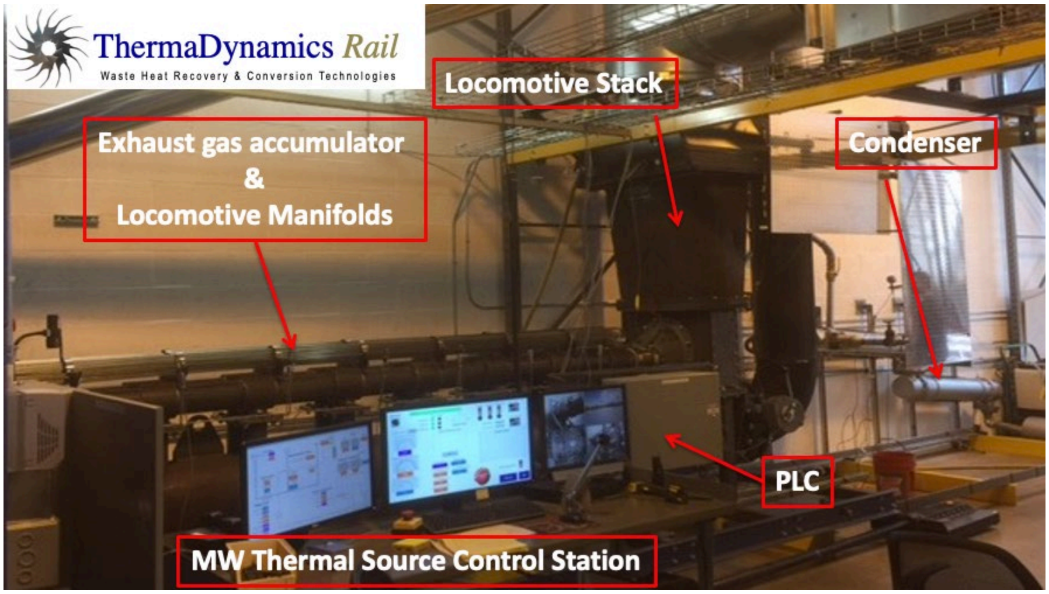

Figure 4. TDR 6 MW locomotive-simulator and testing facility

Overall, the components forming the L-WHRS (i.e., the HiPHEXs, turbine-generators, controllers, pumps, condenser, and balance of plant) are fully integrated and equipped with "locomotive interfaces" for locomotive long-term field testing. Figure 5 illustrates the operational L-WHRS retrofitted onto a GE Dash-9 locomotive for on-the-road testing.

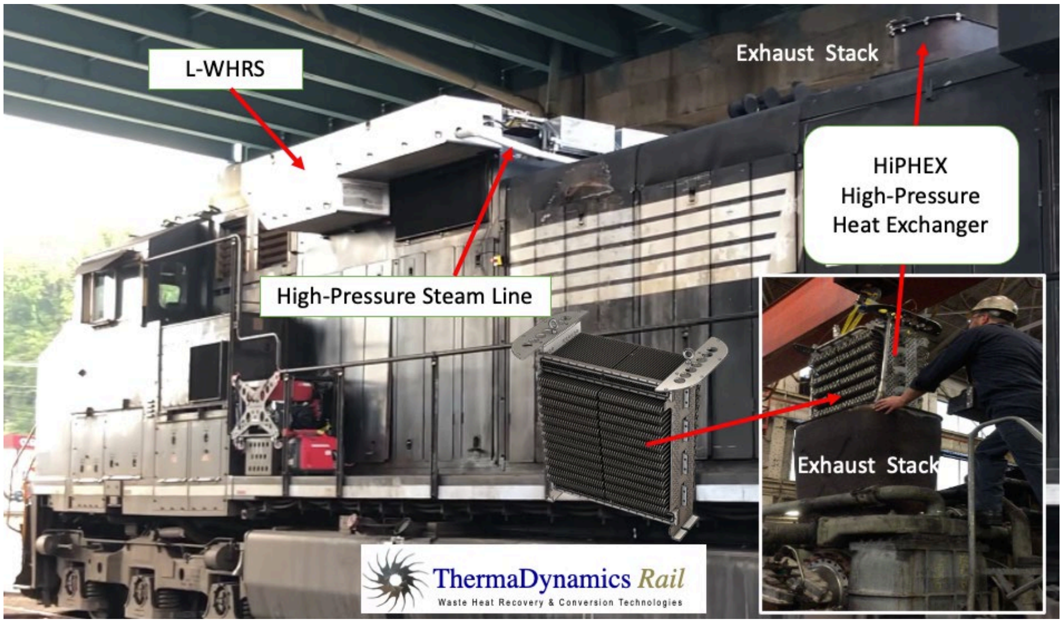

Figure 5. Non-invasive retrofitted L-WHRS

1.2 Objectives

The main research objective focused on the demonstration of safety and the technical and economic performance of the L-WHRS configured to manage pollutant-free electric power supplied to an advanced ESS and selected locomotive electrical loads under various operational scenarios.

Another research objective was to demonstrate that the L-WHRS can effectively decrease the locomotive operating cost by increasing fuel utilization (locomotive efficiency), augment the on-board electric power rating (uprating), supply ever increasing demand from hotel loads, and increase safety for operators and the public by reducing pollutant emissions.

1.3 Overall Approach

Research activities were organized in six main tasks focused on the design optimization and validation of the electrical interfaces between the L-WHRS, the ESS, locomotive equipment, and selected electrical loads. These activities included adapting the design to include dedicated electrical interfaces, components integration, and testing of the ESS with the L-WHRS electronic controls coupled to the power generation components. These activities enabled verification of power flows across these components with safe control while switched on or off under various operational conditions. As part of the overall approach, task activities included the selection, procurement, coupling, and testing of suitable advanced batteries with integrated power management controls forming the ESS, and verification of systems compatibility for interfacing with the L-WHRS. Additional tasks included the selection of locomotive alternate current (AC) or direct current (DC) electrical loads to be operated with electric power supplied by the combined L-WHRS and ESS power supplies while actively switching these electrical loads from the locomotive electric buses. At the same time, the FMECA conducted in previous phases of the research was updated to include potential risks developed when the ESS, L-WHRS, and locomotive electric loads formed an electrical system independent of the locomotive electric bus. The ESS was selected, and the research activities focused on systems integration and testing at full-scale operating conditions via TDR locomotive simulator, mimicking locomotive operating conditions. The ESS power management and power supply systems were electrically coupled to TDR-developed electronic interfaces to validate safe regulation of the power flows from and to the electronic interfaces coupling the L-WHRS, the ESS, and locomotive electrical loads.

1.4 Scope

The scope of the research was limited to the selection of ESS technologies that are safe for rail operations, selection of locomotive electrical loads for system validation, and the development of electrical and electronic interfaces for coupling and controlling the L-WHRS, ESS, and their ancillary components. The technical and safety performance of these components was tested and verified when coupled to locomotive power systems and/or loads.

1.5 Organization of the Report

The report is organized into eight main sections. Section 1 provides background information as well as project scope and objectives. Section 2 describes the project activities dedicated to the identification and procurement of the ESS for integration with the L-WHRS. Section 3 describes key aspects of selected locomotive electrical loads and their requirements, determined with the cooperation of Class I railroad technical staff. Section 4 focuses on the development of the L-WHRS Power Management System, and the identification of safety risks associated with the interfaces between the L-WHRS, ESS, and the selected locomotive electrical loads. Section 5 discusses updating the FMECA to include L-WHRS, ESS, and electrical loads interfaces, their perceived safety risks, and risk mitigation or elimination. Section 6 reports the activities dedicated to “system integration” consisting of electrically coupling the high-power interfaces of the L-WHRS, ESS, and locomotive electric loads for integration with the locomotive cabin electrical interfaces and locomotive power AC or DC buses. Section 7 summarizes testing activities by reporting the results of seven power flow cases executed with the L-WHRS interfaced with the ESS and locomotive electrical loads, and conclusions from testing activities; while also providing lessons learned, recommendations, and future activities.

2. Advanced ESS Identification, Procurement, and L-WHRS Integration

TDR, in cooperation with Class I railroad technical staff, identified suitable battery storage technologies that are safe for rail application and can be used to store the L-WHRS conditioned electric power. The selection of the most suitable ESS technologies factored locomotive operational duty-cycles, charge and discharge rate, energy capacity, environmental conditioning (e.g., air versus liquid cooling), vibration and shock coping capability, as well as general rail operating environments and requirements for system integration with the L-WHRS. The ESS selection process leveraged the methodology adopted by the railroad technical staff and lessons-learned based on data collected by railroad operators with experience on projects involving equipping locomotives with large capacity ESS. The key performance parameters considered included:

- Charge and discharge current
- Charge and discharge duration
- Restart power
- Duty cycle and temperatures
- Locomotive distance travelled
- Locomotive real-estate and locomotive compartment environmental conditions

Accordingly, three suitable ESS technologies were identified for the research:

1. Advance lead-acid battery stack
2. Valve regulated lead-acid (VRLA)
3. Lithium battery stack

2.1 FRA Approval of the ESS

Of the three candidate technologies identified, two top-ranked battery technology candidates were selected and presented to FRA for review and approval. These were the “Ultrabattery” battery stack, based on advanced lead-acid chemistry produced by East Penn Manufacturing, and the “SimpliPhi” high-voltage battery stack, based on lithium iron phosphate (LFP) chemistry. Figure 6 illustrates the battery stacks and power management components from SimpliPhi and Ultrabattery.

Figure 6. SimpliPhi lithium battery stack, UltraBattery advanced lead-acid stack

The UltraBattery option (based on lead-acid + supercapacitor) was analyzed against two lithium battery chemistries, “Corvus” Energy AT6500 (based on Lithium Nickel Manganese Cobalt (Li-NMC)) and SimpliPhi LFP. The UltraBattery option is characterized by an operating temperature range of -18 to 70 °C (-0.4 to 158 °F). The Corvus operates in the 5 to 55 °C (41 to 131 °F) range. As a result, Li-NMC batteries would require more complex and costly environmental conditioning, potentially involving active heating or cooling. Due to these additional complexities, this option was removed from consideration. For the purposes of the research, the UltraBattery ESS required a relatively complex interface solution comprised of three DC-AC inverters, a customized transformer, and an Active-Front-End[1] (AFE) electronic system to connect to the motor drive of the L-WHRS. SimpliPhi’s LFP batteries’ operating temperatures range from -20 to 60 °C (-4 to 140 °F), similar to the UltraBattery’s operating temperature range. However, the SimpliPhi LFP batteries required a relatively simpler and less expensive interface, with only a single DC-DC converter to be connected to the L-WHRS motor drive. Additional ESS ranking parameters included safety performance, life cycle, access to real-time battery cells data, procurement lead-time, and cost.

The SimpliPhi high-voltage battery stack was ultimately selected for integration with the L-WHRS. The SimpliPhi LFP battery chemistry was determined to be optimal because it does not require maintenance, presented inherent protection against thermal runaway or fire hazards when punctured, and requires a much smaller volume and footprint considering the required external power conversion devices. The SimpliPhi battery stack also had a higher energy capacity and included a battery management system (BMS) with real-time data communication capability—a required feature for integration with the L-WHRS. A comparative performance summary of the UltraBattery and SimpliPhi parameters in shown in Table 1.

Table 1. Comparison of advanced lead acid and lithium batteries

Parameter	UltraBattery (Advanced Lead Acid)		SimpliPhi (Lithium Iron Phosphate)	
Weight [lbs.]	2656		592	✓
Size [m^3]	1.374		0.254	✓
Energy Capacity [kWh]	17.4		22.4	✓
Power Output [kW]	20.4	✓	11.4	
Maintenance	Monthly Refresh Cycle		None	✓
Lifetime (years)	10		10	
Access to Real Time Data	No		Yes	✓
Approximate Cost per kWh [$]	1,440		1,340	✓

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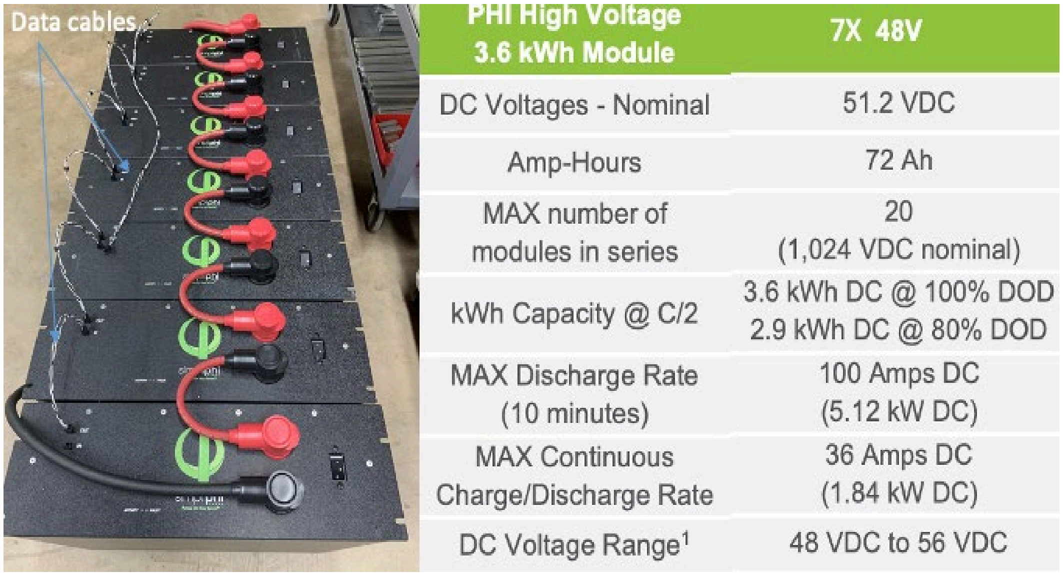
[1] Active Front End drive is a special type of electronic rectifier that enables regenerated power to be supplied back to the generator.

2.2 Final Selection and FRA Approval of ESS Technology

The selection and approval of the ESS for integration with the L-WHRS was informed by the FRA program manager’s prior experience from sponsored research projects dedicated to equipping rail equipment with ESS. The key parameters for the top ranked battery technology candidates were discussed with FRA, and the features and requirements of each battery stack were analyzed. By comparing it with other technologies, it was determined that the SimpliPhi battery stack had higher net efficiency due to fewer power conversion losses, a smaller footprint to reduce potentially invasive modifications of locomotive real estate, and safer expected operation with less impact on the environment and locomotive personnel. Based on these considerations, TDR presented the SimpliPhi high-voltage battery stack as the best option for integration with the L-WHRS, and FRA approved.

2.3 Procure Selected ESS Technology

After obtaining FRA approval, the SimpliPhi LFP battery modules were procured, and the battery stack was assembled. Low-power data communication cables were connected from the battery stack to a computer interface to verify correct functioning of each battery module, while collecting various parameters such as power management, data communication, state of charge, power distribution, and other considerations. Figure 7 shows a total of seven 3.6 kilowatt hour (kWh) modules forming the ESS SimpliPhi battery stack along with battery performance specifications from the manufacturer.



PHI High Voltage 3.6 kWh Module	7X 48V
DC Voltages - Nominal	51.2 VDC
Amp-Hours	72 Ah
MAX number of modules in series	20 (1,024 VDC nominal)
kWh Capacity @ C/2	3.6 kWh DC @ 100% DOD 2.9 kWh DC @ 80% DOD
MAX Discharge Rate (10 minutes)	100 Amps DC (5.12 kW DC)
MAX Continuous Charge/Discharge Rate	36 Amps DC (1.84 kW DC)
DC Voltage Range[1]	48 VDC to 56 VDC

Figure 7. SimpliPhi battery stack data communication with TDR L-WHRS equipment

The “data cables” shown in Figure 7 were connected from the battery stack to a computer interface establishing connection with the BMS.

Data communication with the battery management system was established as part of individually testing each power component forming the L-WHRS, ESS, and locomotive electrical load, so that initial battery status and system verification could be completed.

3. Locomotive Electrical Loads Requirements Determination

Researchers identified and selected locomotive electrical loads to customize the L-WHRS power control system architecture. The terms "power control system" and "power management system" will be used interchangeably in the remaining portions of this report. The following sub-sections describe the main research activities that enabled the completion of the milestone under this task.

3.1 Electrical Loads Requirements Determination

TDR worked with Class I railroad technical staff to select electrical loads that the locomotive operator ranked with high importance. Locomotive electric bus measurements conducted in previous research (Filippone, 2020) indicated that the rectified DC bus voltage supplying power to the locomotive traction motors is electro-magnetically noisy. The oscilloscope trace of the DC bus voltage obtained when the locomotive engine power was set at Notch 8 is shown in Figure 8.

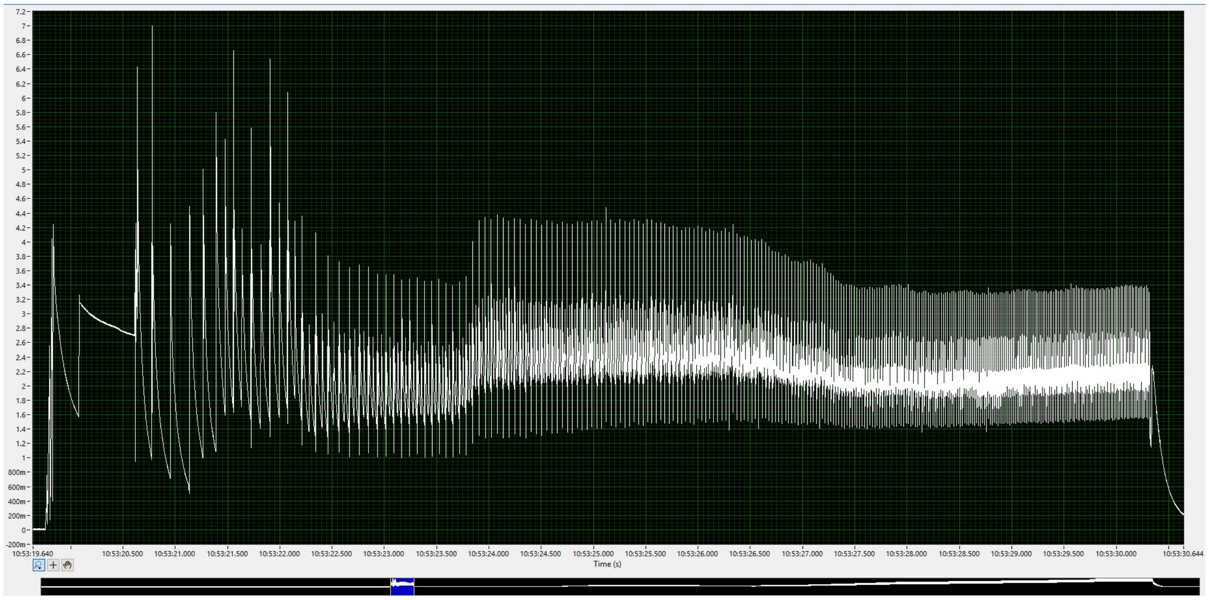


Figure 8. DC bus voltage of locomotive at notch 8

Figure 8 shows that the DC power bus noise manifests with unstable voltage levels, high-frequency, and high-voltage spikes with several hundred volts amplitude, inducing electro-magnetic interference (EMI). The oscilloscope trace shown was sampled directly on the DC power bus without signal filtering. To a certain extent, this type of electrical noise can be filtered with specialized shunts and noise suppressors. However, the power rating of these filtering components, their reliability when operated in a locomotive environment, and their cost represent several challenges. Some types of noise suppressors require active cooling and their failure modes might impair locomotive operations. Overall, coupling the L-WHRS electrical system directly to the locomotive DC bus was deemed costly and inefficient, while presenting a potential for locomotive operations disruption. In compliance with the L-WHRS non-invasive retrofitting requirements, operations or malfunctions of the components forming the L-WHRS may not adversely impact normal locomotive operations. To eliminate risks associated with EMI filtering, the L-WHRS electrical system could be directly coupled to a dedicated DC (or AC) traction motor (decoupled from the locomotive DC or AC power bus). Alternatively, other locomotive electrical loads can be automatically decoupled from the locomotive electrical system when the electrical power is sourced in the L-WHRS, the ESS, or both. With the cooperation of the Class I railroad technical staff, TDR identified and selected various locomotive electric loads whose electric power could be directly supplied by the L-WHRS.

The locomotive electrical loads identified included:

- Alternator Blower (30 hp)
- Fuel Pump (7 hp)
- Exhauster Motor (8 hp)
- Air Compressor (50 hp)
- Radiator Fan (100 hp)
- Cab HVAC (13 hp)

3.2 Final Selection of Locomotive Electrical Loads

TDR worked with locomotive operators and technical staff to identify a cost-effective interface architecture for the L-WHRS when configured to supply conditioned power to selected locomotive electrical loads while coupled to the ESS. During locomotive operations with the engine at idle, electrical power is supplied to computer equipment, lights, pumps, compressors, and the Cabin HVAC unit, which provides the locomotive crew with a comfortable environment. Figure 9 shows an example of HVAC units equipping locomotives. When the locomotive is not moving and the engine operates at idle for prolonged amounts of time, the AESS system shuts down the locomotive engine. During this time, the locomotive generator is de-energized and the electrical supply to selected locomotive electrical loads, including the HVAC unit, is sourced in the locomotive OEM lead-acid battery. As a result, the OEM battery may experience deep discharge when the locomotive engine is shutdown, as well as high-amperage power flows when fast-recharging as the locomotive engine is restarted. High-rate battery charge/discharge operations of the OEM battery shortens the useful life of this component, which becomes prematurely inoperable and often disrupts operations.

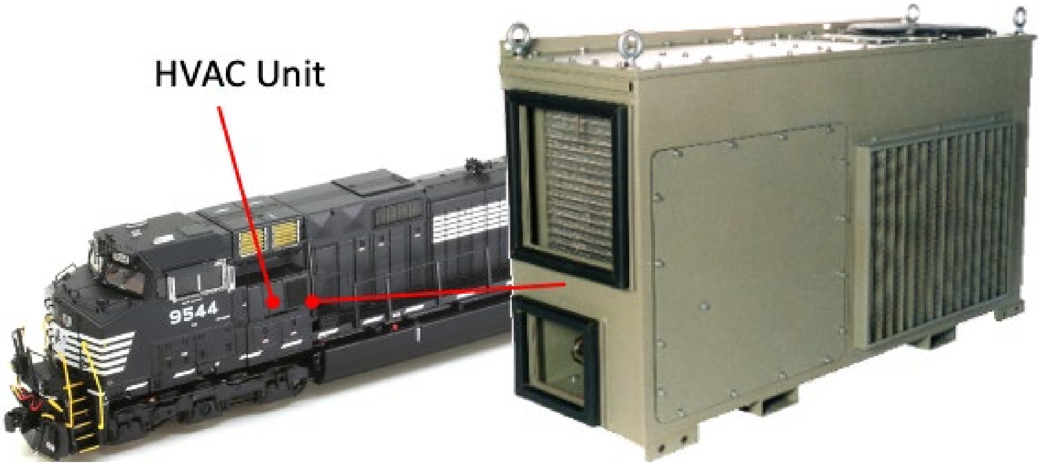


Figure 9. **GE Dash-9 side mount HVAC unit**

By recovering waste heat energy from the exhaust gases produced during locomotive operations at medium to high notch settings and converting this energy into pollutant-free electricity supplied to the ESS and/or selected locomotive electrical loads, the OEM lead acid battery can be bypassed and effectively replaced by the L-WHRS and ESS. Under this configuration, the OEM battery is no longer subjected to damaging charge/discharge cycles, thus increasing its reliability and lifespan while preventing premature and costly replacement of this component. Based on the recommendations of locomotive operators, the cab HVAC system was selected as one of the electric loads that can deeply discharge the OEM lead acid battery. For these reasons, and for the purposes of this research, the HVAC system was selected as one of the locomotive electrical loads that can be shed from the normal locomotive power supply. Accordingly, the L-WHRS and ESS interfaces were configured to supply power to the HVAC system. The resulting microgrid was formed by the ESS electric power supply, which was recharged by the L-WHRS, and the HVAC system. Interfacing this electrical load with the L-WHRS and the ESS allows the crew to operate the HVAC unit for a time duration proportional to the ESS capacity while the locomotive engine is shut down, resulting in reduced fuel consumption and pollutant emissions.

The HVAC unit model selected for this research is powered by a 72 Volts DC (VDC) locomotive battery bus and has a maximum power consumption of 11.25 kW. The capacity of the SimpliPhi LFP-based ESS used for testing enables powering the HVAC unit for approximately 3 hours on high cool and 2.25 hours on high heat. In compliance with non-invasive retrofitting requirements (see Section 3.3), the power management system, control system, and electrical interfaces of the L-WHRS and ESS enable the HVAC unit to be powered by three electrically coupled power supplies while using the HVAC interface cabin breakers (see Figure 19 and Figure 20):

1. Locomotive generator via OEM battery DC bus (normal configuration)
2. L-WHRS interface when waste heat energy is available as the locomotive operates at power
3. ESS interface when L-WHRS is not providing electrical power as the locomotive engine is at idle or low notch settings (insufficient thermal power availability at the locomotive stack)

These operational cases represent "power flow" variations. Electrical power for the HVAC unit can be supplied by any of the available power supplies represented by the locomotive 72 VDC bus, the L-WHRS, and the ESS, independently or combined (to be shown in greater detail in Section 6). Overall, the HVAC unit was selected as a representative locomotive electrical load for the design and integration of the L-WHRS-ESS interfaced with locomotive electrical loads. However, the L-WHRS-ESS interface can also be configured to supply power to multiple AC or DC locomotive electrical loads.

3.3 L-WHRS Power Management System

The power management system architecture was defined following the approval and procurement of the ESS and the selection of the HVAC unit to represent one of the locomotive electrical loads. The ESS, the L-WHRS turbine-generator motor-drive, and the HVAC operate with DC power. Accordingly, the power management system architecture was configured as a "DC power grid" with three separate DC buses coupled via DC-to-DC converters. Figure 10 illustrates the power management system architecture with three DC buses coupled to form an electrically connected system or L-WHRS DC power-grid.

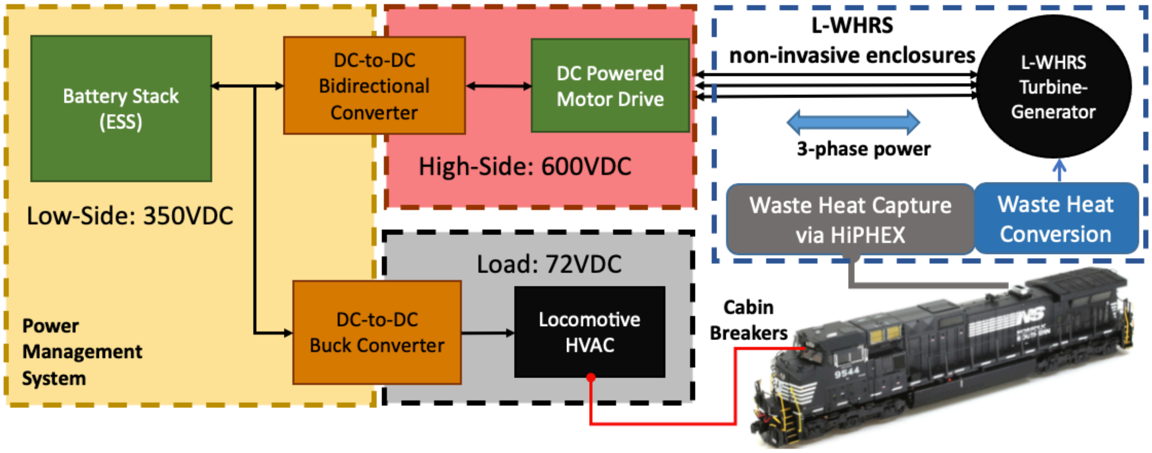


Figure 10. Power management system architecture

The low-side DC bus voltage is driven by the battery stack voltage at 350 VDC. However, this value varies depending on the state of charge. The high-side DC bus voltage was selected to operate at 600 VDC nominal, which is the mid-point of the operating voltage range of the L-WHRS motor drive. Similarly, the load DC bus voltage was configured to operate at 72 VDC, which matches the operating voltage of the locomotive HVAC unit.

As shown in Figure 10, electric power from the L-WHRS is converted between the low-side (yellow module) and high-side (pink module) buses with a bidirectional DC-to-DC converter. This configuration was selected to control the “power flow direction” under all operating conditions. To illustrate how the power flow between components changes, the ESS can be used to “black-start” the L-WHRS when the locomotive engine shifts operations from idle to medium-high notch settings. A black-start is a L-WHRS status in which there is no electricity generated by the L-WHRS turbine-generator, and the thermal energy available at the locomotive stack becomes sufficient to support electric conversion. This is a characteristic of the L-WHRS using water-steam as working fluid. When the L-WHRS uses an organic fluid with low vapor pressure, the L-WHRS starts to produce electric power when the locomotive engine is at idle even with low thermal energy at the exhaust stack. The thermal power available for conversion by the L-WHRS at the locomotive exhaust stack is proportional to the engine notch settings; only when sufficient thermal energy is converted by the HiPHEX will the electronic interfaces of the L-WHRS “switch on” from a black-start condition and the L-WHRS starts electricity production. During the transition, for a relatively short time, electric power flows from the ESS to the L-WHRS to control the turbine-generator until it converts sufficient electric power to self-sustain the L-WHRS operations. From this point onward, the power flow changes direction from the L-WHRS to the ESS.

The L-WHRS black-start configuration shown in Figure 10 involves the bidirectional converter which steps-up the voltage (boost mode) to allow current to flow from the low- to the high-side of the interface, thus providing power to the motor drive during the L-WHRS start-up. During the L-WHRS start-up procedure, the bidirectional converter also enables powering and gradually spins the turbine-generator from zero revolutions per minute (RPM) to an operational speed of approximately 20,000 RPM, after which superheated vapors, supplied by the HiPHEX, expand in the turbine to produce torque at the generator shaft, which ultimately converts thermal-energy into electricity regulated by the motor drive. Once the turbine-generator begins generating power, the bidirectional converter steps-down the voltage, thus allowing current to flow from the high-side to the low-side, while providing power to charge the ESS and the selected electrical load (e.g., HVAC unit or other loads). Power conversion from the low-side bus to the load bus is achieved using a unidirectional DC-to-DC converter with a fixed 72 VDC output operated in "buck" mode.[2] When this load converter is enabled, power is supplied by the ESS and the conditioned power output from the turbine-generator, or both depending on the L-WHRS operating mode, which in turn depends on the locomotive duty cycle and corresponding amount of waste thermal energy available at the locomotive stack.

As a result of these operations, power flows in various directions among the L-WHRS components, the ESS, and the locomotive electrical loads. For the purposes of this research, the L-WHRS uses distilled water as the working fluid. Primarily for this reason, the thermal energy produced by the locomotive engine at idle and low notch setting is generally insufficient to trigger electricity production by the L-WHRS. However, versions of the L-WHRS operated with organic fluids with low vapor pressure can generate electricity even at low thermal power from the locomotive engine.

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[2] Buck mode refers to a DC-to-DC converter that steps down the voltage from its input.

4. Power Management System and Selective Electrical Load

The power management system monitors, limits, and directs the power flow to the various electrical conversion, inversion, storage, and electrical load subsystems. The power management system actuates the conversion of waste heat energy recovered by the L-WHRS into conditioned electric power to be stored in the ESS and/or to be distributed to selected locomotive electric loads.

4.1 Power Management System

The blue bidirectional arrow in Figure 11 shows the power flow direction between the L-WHRS components (Recovery & Energy Conversion) and the ESS (part of the Energy Management system), while the monodirectional arrow indicates the power flow for the components representing the “Energy Utilization,” in this case represented by the HVAC unit.

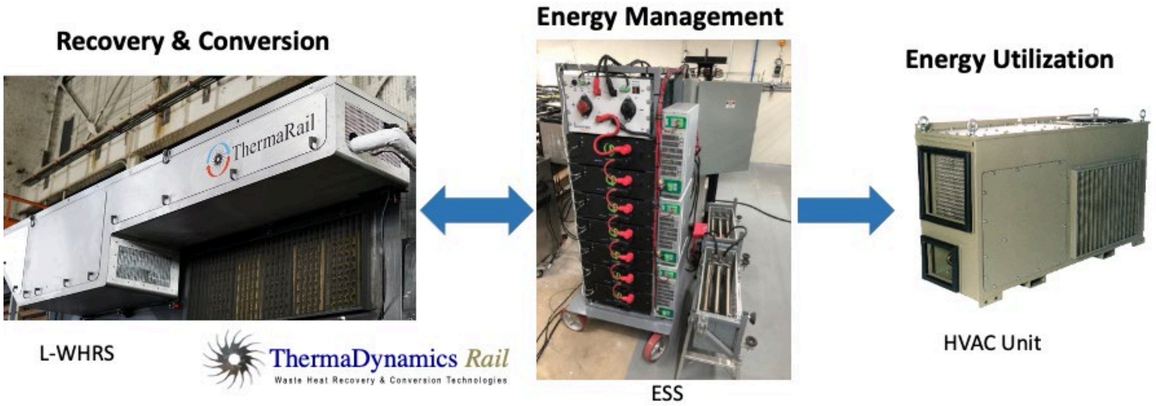


Figure 11. Phase IV power management top level systems

A central component of the power management system is the Controller and User Interface (CUI) which communicates with and controls various subsystems via a Controller Area Network (CAN) bus while displaying real time data and allowing user override control. The CUI retrieves and records operational data and controls the operation of the following CAN devices:

- Bidirectional DC-to-DC Converter – manages power flow between the low- and high-side DC buses
- Battery Management System (BMS) – monitors the state of the ESS and intervenes if programmable fault conditions exist
- Motor Drive – controls the speed of the turbogenerator and optimizes power generation

The power management system’s low-side and high-side control circuits use electro-mechanical contactors to safely connect or disconnect various circuits and interfaces. These contactor switching circuits are controlled from the CUI and incorporate pre-charge circuits for limiting inrush current, fuses for overcurrent protection, and an emergency stop push-button that opens all contactors and halts any flow of power. Inrush current is the instantaneous current spike caused when connecting a voltage source to a capacitive load. The interfaces between the various power management subsystems are shown on the block diagram in Figure 12. As shown in Figure 12, the CUI is coupled to the stack switchgear BMS, the low-side control circuit to manage electrical loads, and the bidirectional DC-DC converter to establish power flow to and from the motor drive. This can be operated in black-start motor-mode or as the power source when the turbogenerator is converting waste thermal energy from the exhaust gases. In addition to the general definition provided in Section 3.3, the L-WHRS black-start also includes provisions that enable the ESS, or any other electric source, to start "spinning" the turbine-generator when the working fluid is still cold (at the start of locomotive engine operation). When the L-WHRS working fluid transitions from subcooled liquid to superheated vapor, the controller shifts power flow to transition the turbine-generator from motor-mode operation to generation-mode.

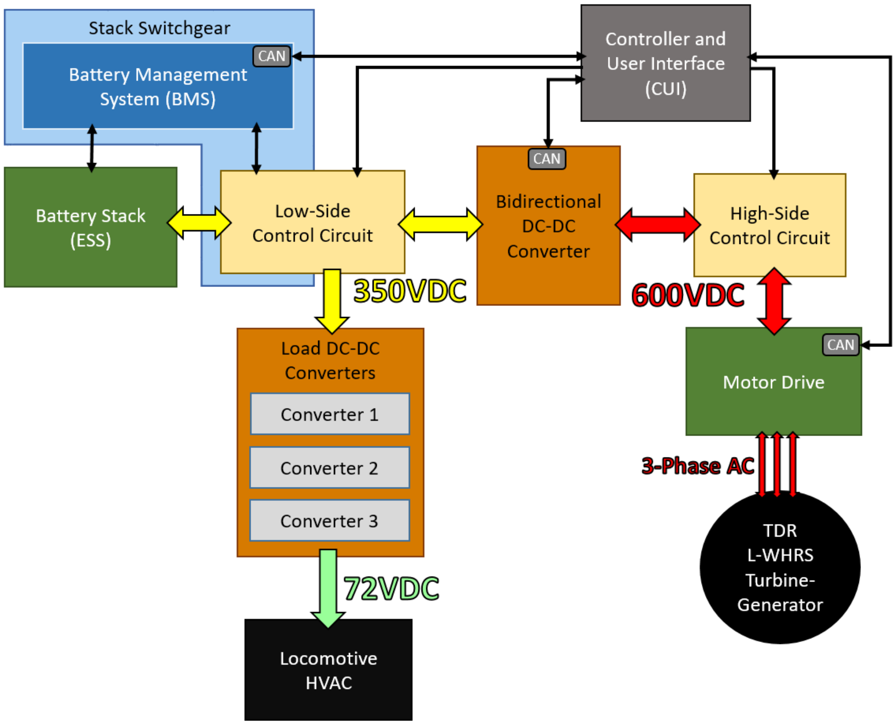
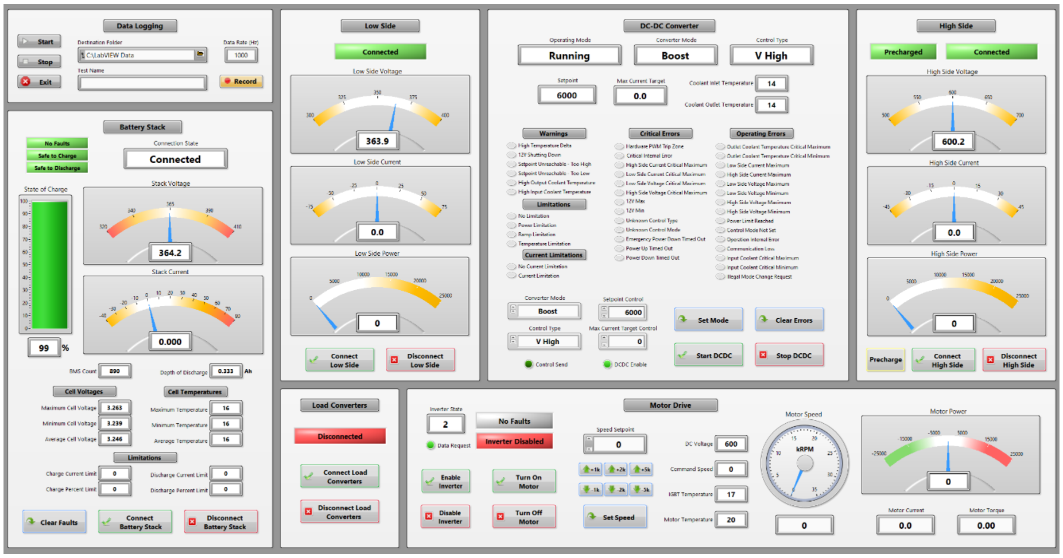


Figure 12. Phase IV power management system block diagram

4.2 Controller and User Interface (CUI)

The CUI programs operational setpoints and enables safe switching of the low- and high-side control contactors. The CUI layout is shown in Figure 13 and in greater detail in Figure 36.


Data Logging
Destination Folder C:\LabVIEW Data
Data Rate (Hz) 1000
Test Name

Battery Stack
Connection State Connected
State of Charge 99 %
Stack Voltage 364.2
Stack Current 0.000
BMS Count 890
Depth of Discharge 0.333 Ah

Cell Voltages
Maximum Cell Voltage 3.263
Minimum Cell Voltage 3.239
Average Cell Voltage 3.246

Cell Temperatures
Maximum Temperature 16
Minimum Temperature 16
Average Temperature 16

Limitations
Charge Current Limit 0
Charge Percent Limit 0
Discharge Current Limit 0
Discharge Percent Limit 0

Low Side
Connected
Low Side Voltage 363.9
Low Side Current 0.0
Low Side Power 0

Load Converters
Disconnected

DC-DC Converter
Operating Mode Running
Converter Mode Boost
Control Type V High
Setpoint 6000
Max Current Target 0.0
Coolant Inlet Temperature 14
Coolant Outlet Temperature 14
Converter Mode Boost
Control Type V High
Setpoint Control 6000
Max Current Target Control 0

High Side
Precharged
Connected
High Side Voltage 600.2
High Side Current 0.0
High Side Power 0

Motor Drive
Inverter State 2
No Faults
Inverter Disabled
Speed Setpoint 0
DC Voltage 600
Command Speed 0
IGBT Temperature 17
Motor Temperature 20
Motor Speed 0
Motor Power 0
Motor Current 0.0
Motor Torque 0.00

Figure 13. CUI

TDR developed the CUI to read and display all L-WHRS, ESS, and electrical load power management system data, while providing user control of power flow direction and magnitude using CAN bus connected devices. The CUI is based on programming National Instruments' (NI) LabVIEW software and controls for the power management system through an NI cDAQ-9174 chassis and two NI C-series interface modules. The CUI establishes and connects with the CAN bus with an NI 9862 High-Speed CAN Module and controls the power management system contactors with an NI 9482 Electromechanical Relay Module. The CUI chassis and modules are shown in Figure 14.

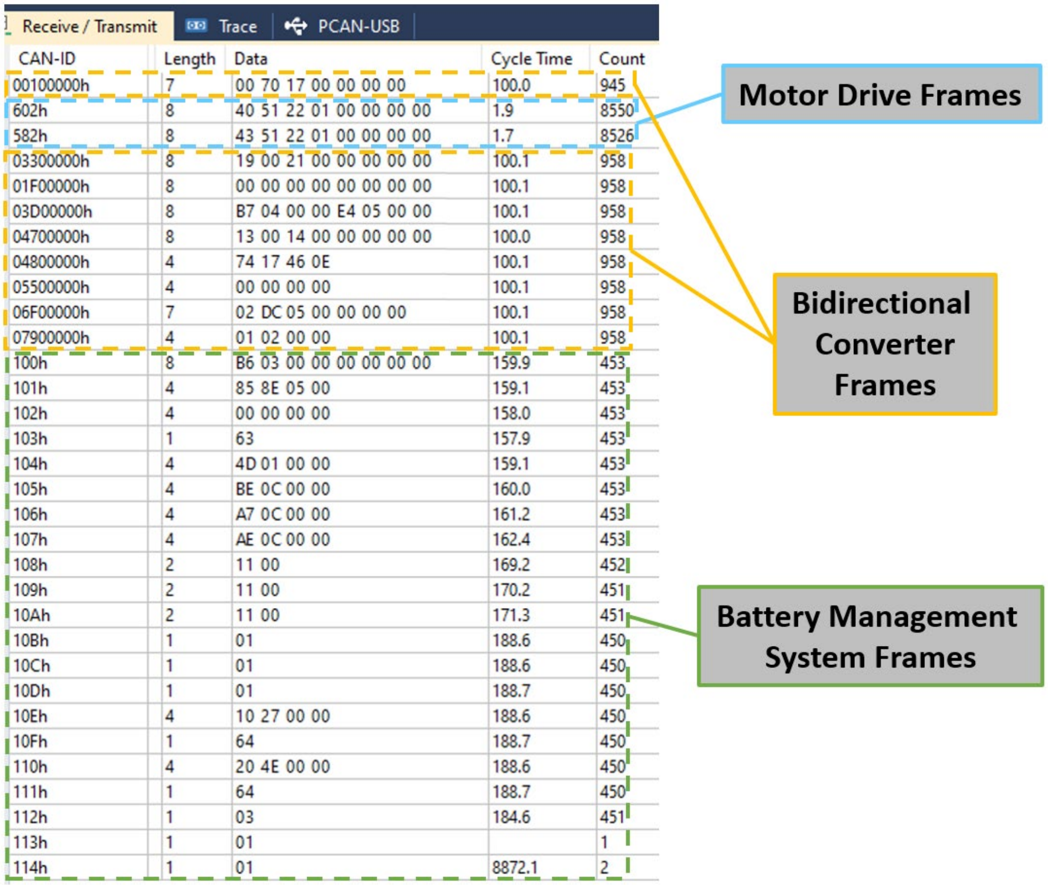
Figure 14. CUI chassis and modules

The high-speed CAN bus is configured for 500 kilobits (kb) per second and has four nodes, or connection points. Each of the following is a node on the network:

- Bidirectional DC-to-DC converter
- BMS
- Motor drive
- CUI

As a multi-master serial bus, CAN bus protocol allows any node on the network to initiate transfer. Since all four nodes share the CAN bus and are capable of transmitting data at any time, each node or message type transmitted on the bus has a unique identifier. The CUI is programmed to sort received CAN message frames by each node identifier and parse the payload data to extract the information. An example of the frame traffic on the CAN bus is shown in Figure 15.

The CUI developmental work executed in this research paves the way to transition to a fully integrated L-WHRS power management system based on a custom-made electronic processor that also controls the user interface.



CAN-ID	Length	Data	Cycle Time	Count
00100000h	7	00 70 17 00 00 00 00	100.0	945
602h	8	40 51 22 01 00 00 00 00	1.9	8550
582h	8	43 51 22 01 00 00 00 00	1.7	8526
03300000h	8	19 00 21 00 00 00 00 00	100.1	958
01F00000h	8	00 00 00 00 00 00 00 00	100.1	958
03D00000h	8	B7 04 00 00 E4 05 00 00	100.1	958
04700000h	8	13 00 14 00 00 00 00 00	100.0	958
04800000h	4	74 17 46 0E	100.1	958
05500000h	4	00 00 00 00	100.1	958
06F00000h	7	02 DC 05 00 00 00 00	100.1	958
07900000h	4	01 02 00 00	100.1	958
100h	8	B6 03 00 00 00 00 00 00	159.9	453
101h	4	85 8E 05 00	159.1	453
102h	4	00 00 00 00	158.0	453
103h	1	63	157.9	453
104h	4	4D 01 00 00	159.1	453
105h	4	BE 0C 00 00	160.0	453
106h	4	A7 0C 00 00	161.2	453
107h	4	AE 0C 00 00	162.4	453
108h	2	11 00	169.2	452
109h	2	11 00	170.2	451
10Ah	2	11 00	171.3	451
10Bh	1	01	188.6	450
10Ch	1	01	188.6	450
10Dh	1	01	188.7	450
10Eh	4	10 27 00 00	188.6	450
10Fh	1	64	188.7	450
110h	4	20 4E 00 00	188.6	450
111h	1	64	188.7	450
112h	1	03	184.6	451
113h	1	01		1
114h	1	01	8872.1	2

Figure 15. CAN bus traffic

4.3 Energy Storage System with Battery Management System

As discussed in Section 3, TDR reviewed and selected locomotive loads in cooperation with Class I railroad technical staff. Both the battery stack system, comprising the ESS and BMS subsystems, and the HVAC unit represent DC electrical loads that were coupled to the L-WHRS. As shown on the right of Figure 16, the ESS is comprised of seven LFP battery modules connected in a series. Each battery module has a capacity of 3.6 kWh and a nominal voltage of 51.2 VDC. This battery module configuration results in a battery stack total capacity of 25.2 kWh and a nominal stack voltage of 358 VDC. The amount of time the ESS can provide the locomotive cab with air-conditioning by operating the HVAC unit in cold or hot mode is based on these parameters.

Each battery module contains internal BMS cell interface modules (BMS modules) that measure individual cell voltages and temperatures. This data is relayed to the BMS via linkbus protocol through connectors provided on the front panel connecting each battery module to the stack switchgear. The BMS modules can be installed at any distance from the battery modules. The stack switchgear enclosure location depends on the locomotive free space availability. In the test configuration shown in Figure 16, the stack switchgear is installed on top of the frame comprising the ESS and contains the BMS modules.

The BMS modules are also shown in Figure 17. After reading all cell and stack data from the linkbus, the BMS compares the values against pre-programmed thresholds and issues warnings and faults and can disconnect the ESS immediately upon any fault condition to ensure safety.

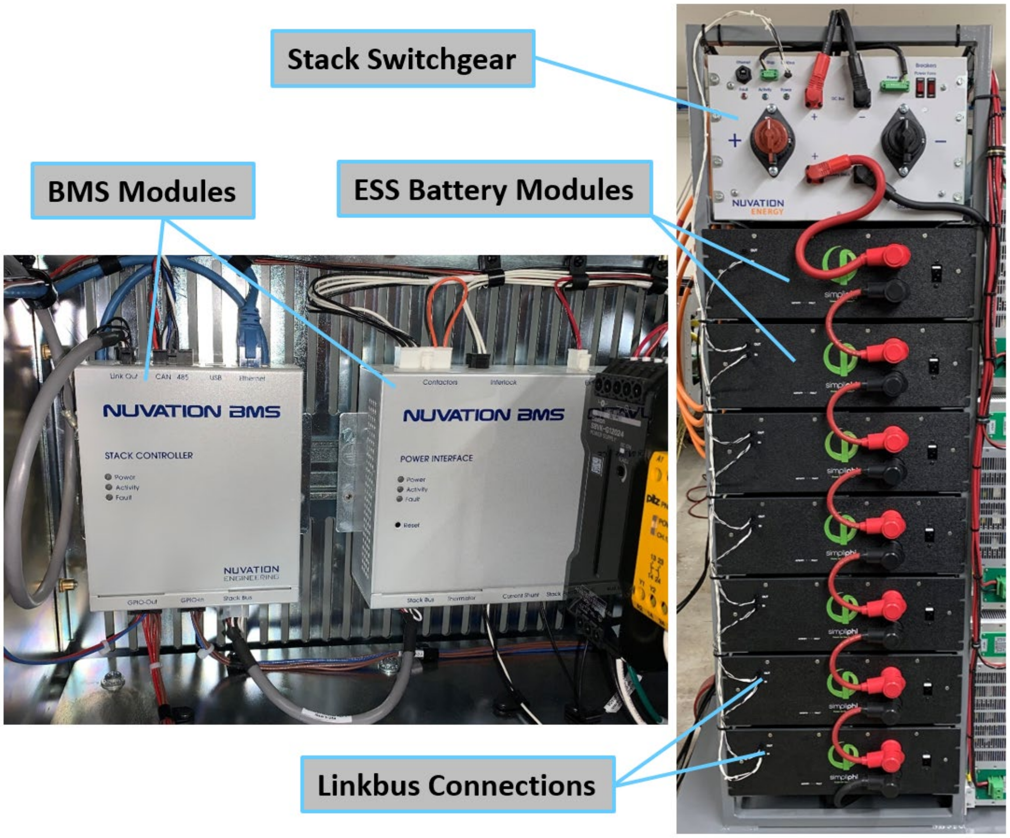


Figure 16. BMS modules, ESS, and stack switchgear

The BMS contains programmable warning and fault thresholds for the following parameters:

- Battery cell
    - Voltage – max, min
    - Temperature – max, min
- Battery stack
    - Voltage – max, min
    - Current – max, min
    - Pre-charge current – max
    - Charging temperature – max, min
    - Discharging temperature – max, min

Cell voltage imbalances can lead to premature cell failure and localized heating. As a result, the BMS implements passive cell balancing to equalize the voltages of cells connected in a series. Passive cell balancing discharges higher voltage cells via internal bleed resistors, which are enabled on a per cell basis. Both absolute and relative cell voltage measurements are used for determining cell imbalances.

Cell temperature is monitored to prevent overheating. The following programmable parameters define the conditions in which the BMS will activate cell balancing:

- Cell voltage – min (relative)
- Cell voltage – min (absolute)
- Temperature – max
- Stack charging current – max
- Stack discharging current – max

The BMS connects to the CUI via CAN bus and transmits all stack data, cell data, warnings, and faults at 100 millisecond intervals. In addition to receiving data from the BMS, the CUI sends CAN messages to clear faults and disconnect or connect the ESS to the power management system's low-side DC bus.

4.4 Motor Drive and Operations

The power management system's high-side DC bus is used solely for powering the motor drive during start-up of the L-WHRS and to source power from it when the L-WHRS is generating electrical power. The motor drive is responsible for controlling the high-speed induction motor of the turbine-generator. It is rated for an operating voltage range of 420–746 VDC and is powered from the high-side of the bidirectional DC-to-DC converter with 600 VDC nominal. When the motor drive is on, the CUI initiates communication over the CAN bus, and at 100 millisecond intervals the CUI requests and reads real-time motor drive data, such as motor drive status, warnings, or faults, as well as motor performance data including speed, current, torque, power, and temperatures.

When commanded by the CUI to begin operation, the motor drive activates the internal bidirectional three-level inverter to change the 600 VDC input voltage into a three-phase AC output and then ramps up the output frequency to match the desired speed of the turbine-generator. As the L-WHRS begins to convert waste heat energy through mechanical work produced by the turbine shaft, the motor drive applies a reverse torque through the turbine-generator induction motor mechanically coupled to the turbine shaft; it then stores and loads the generated electrical energy with the internal bidirectional inverter. This generated energy is stored in the internal DC-link capacitor bus and the bus voltage begins to rise above the nominal 600 VDC. Subsequently, the CUI commands the bidirectional DC-to-DC converter to reverse the power flow direction to off-load the generated energy from the motor drive for charging the ESS or to supply power to the HVAC unit.

If a motor drive fault occurs, such as a loss of inverter power or an unexpected over-speeding of the turbine-generator, the motor drive releases control of the turbine-generator and safely disables the inverter circuit.

Additionally, the power management system's emergency stop push-button is integrated with the motor drive's inverter enable-circuit, and when activated will also safely disconnect the turbine-generator.

4.4.1 Load DC-to-DC Converters

The System Electric Loads (SEL) defines the method that the power management system will use to power the selected locomotive loads. As discussed in Section 3.2, the locomotive HVAC unit was selected as the representative load to be powered by the L-WHRS. However, any other DC electric loads with similar voltage and current characteristics can be applied to the locomotive DC power grid.

The HVAC unit is powered using three identical unidirectional buck DC-to-DC converters. This device contains an inductor that always bucks or acts against the input voltage.

Each converter is rated for 5 kW with a high-side voltage operating range of 300–400 VDC and a fixed low-side output voltage of 72 VDC. The three off-the-shelf load converters (Figure 17) are connected in parallel, increasing the total power output to 15 kW to match the power requirements of the locomotive HVAC unit. A single converter with a custom power rating can be integrated with the L-WHRS when considering mass-production. The converters contain built-in internal circuit protection, such as inrush current limiting and output fuses for safety. Power flow through the load converters is enabled by the CUI via contactors on the low-side DC bus, and input power is sourced from the battery stack, motor drive, or both depending on the current L-WHRS operating mode.

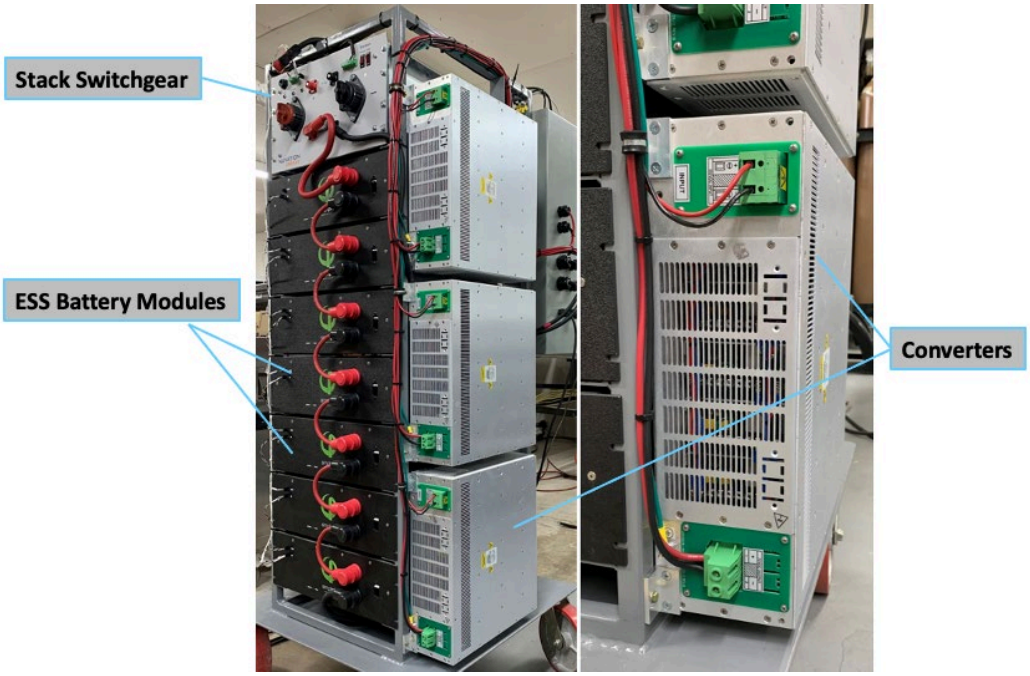


Figure 17. Locomotive HVAC "Load DC-to-DC Converters"

4.4.2 Bidirectional DC-to-DC Converter

The power management system's low-side and high-side DC buses are connected to a bidirectional DC-to-DC converter rated at 30 kW with a low-side voltage operating range of 300-400 VDC and a high-side voltage operating range of 500-700 VDC. Power is converted between the low-side and high-side buses and power flow direction is determined by the converter mode, "boost mode" or "buck mode." In boost mode power flows from the low-side to the high-side, and in buck mode power flows from the high-side to the low-side. In both boost and buck modes, the converter can operate as a current source or a voltage source via the selection from the following control types:

- P Low – Limits maximum low-side power.
- P High – Limits maximum high-side power.
- I Low – Limits maximum low-side current.
- I High – Limits maximum high-side current.
- V Low – Sets low-side voltage.
- V High – Sets high-side voltage.
- V High I Lim – Sets high-side voltage and limits maximum high-side current.
- V Low I Lim – Sets low-side voltage and limits maximum low-side current.

The mode, control type, and operating commands are sent by the controller and user interface on the CAN bus. The converter must receive a CAN operating command from the CUI every 100 millisecond or it will stop converting and enter standby mode as a safety precaution. The converter sends all current, voltage, power, and temperature measurements at 100 millisecond intervals. In addition, the converter reports all warnings, operating errors, and critical errors, and safely stops converting immediately upon a critical error. The error limits and operating limits, such as the minimum and maximum current and voltage, are programmed by the CUI. On startup of the L-WHRS, the power management system allows connection of the ESS to the low-side of the bidirectional converter. The CUI sets the converter to boost mode with “V High” control type and programs the voltage setpoint to 600 VDC.

When waste heat to electric power conversion is started and the high-side motor drive contactors are closed, current flows from the ESS on the low-side to power the motor drive on the high-side. As discussed in Section 1.1, the L-WHRS working fluid is water and the thermal-to-electric conversion is executed by a steam-Rankine power cycle when the thermal energy represented by the exhaust gases is sufficient to produce superheated steam at relatively high-grade thermodynamic parameters (e.g., high steam temperature and pressure). This occurs when the locomotive engine is operated at medium power and high notch settings. However, L-WHRS configurations using organic working fluids can start thermal-to-electric conversion with low-grade waste heat produced when the locomotive engine is idling and at low notch settings.

When the L-WHRS power generation begins and the motor drive voltage rises above the nominal 600 VDC, the CUI instructs the converter to stop and sets the converter to buck mode with “I Low” control type, then programs the current limit to reverse the direction of the power flow. When conversion is started, current flows from the motor drive on the high-side to charge the ESS and, if enabled, powers the locomotive load converters on the low-side to supply power to the HVAC unit.

The ESS drives the low-side DC bus voltage when connected to the system. However, when generated power from L-WHRS is powering the HVAC unit and charging the ESS is not desired or needed (e.g., the ESS is fully charged), the CUI disconnects the ESS from the power management system by opening its contactors. In this case, the CUI commands the converter to remain in buck mode, changes the control type to “V Low,” and programs the voltage setpoint to 350 VDC. This enables the low-side DC bus voltage to remain within the voltage operating limits of the load converters, and current continues to flow from the motor drive on the high-side to the load converters on the low-side without charging the ESS.

The low-side and high-side control circuits use electromechanical contactors and circuit protections to safely connect or disconnect various power management subsystems. This provides the CUI with individual power flow control of the ESS, load DC-to-DC converters, motor drive, and both sides of the bidirectional DC-to-DC converter.

These contactor switching circuits contain fuses for overcurrent protection and pre-charge circuits for limiting inrush current to the highly capacitive inputs of the DC-to-DC converters and motor drive when powered on. Pre-charge circuits use a power resistor connected in series with the voltage source to limit the inrush current. The CUI closes a contactor to temporarily connect the pre-charge circuit until the input capacitors have sufficiently charged, then closes another contactor to bypass the power resistor for normal operation. The low- and high-side control circuits are shown in Figure 18.

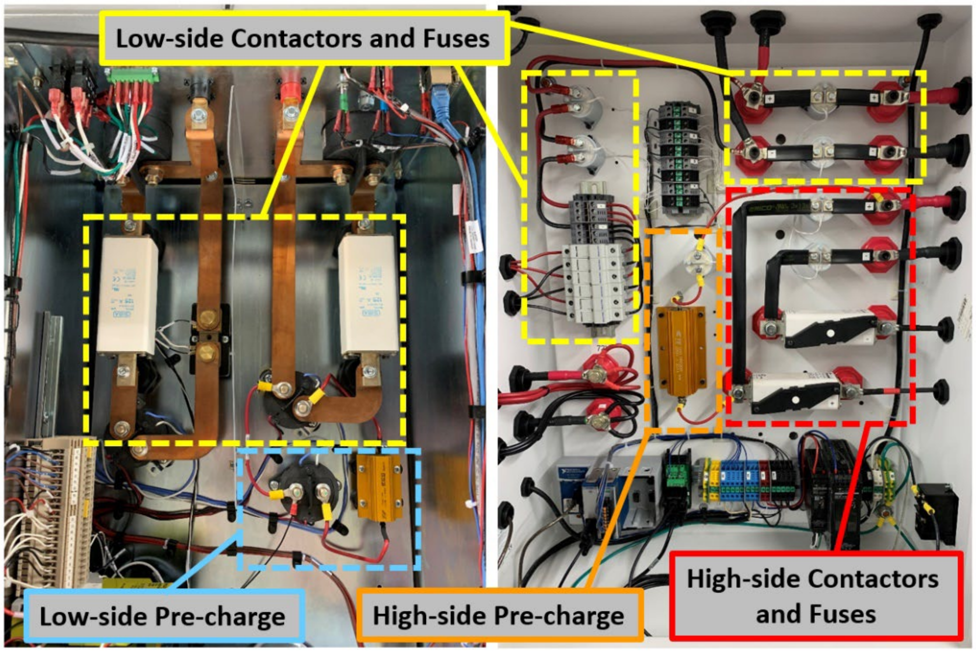


Figure 18. Low-side and high-side control circuits (EB-03 contactor switching circuits)

The control circuit contactors operate with a 24 VDC coil voltage, electromechanically closing the contactor when the voltage is applied. For redundancy and to increase safety, the power management system is also equipped with an overriding manual emergency stop push-button. When activated, the emergency stop circuit physically disconnects the 24 VDC contactor coil bus, thus opening all contactors and effectively disconnecting all subsystems of the power management system, halting any flow of power.

4.5 Locomotive HVAC Interface

The COVID-19 pandemic caused significant delays in conducting locomotive tests of the L-WHRS system. Tasks directly involving locomotive over-the-road testing were replaced with tasks executed using locomotive data obtained in previous phases of the research, simulator data from the L-WHRS operated at full-scale conditions at the TDR testing facility, and by developing a locomotive simulator CUI that factored all operational power flow configurations. The “commercial or final locomotive cab interface” will utilize the CUI system developed using locomotive simulation of electrical loads and power flows between the power source, represented by the L-WHRS (electricity recovered from waste thermal energy), the ESS, and selected locomotive electrical loads.

Based on the test-validated CUI, transitioning to a processor based locomotive cab interface will be simpler, fully automated, and more reliable. Specifically for the HVAC unit controls, the L-WHRS integrates OEM locomotive electrical control circuitry to power the locomotive HVAC unit. When the ESS is charged and the load DC-to-DC converters are enabled, two additional steps are required to switch-on the HVAC system from the locomotive Cabin HVAC interface. The first step consists of switching the battery charger and computer circuit breaker to the ON position (see Figure 19). The second step involves flipping the control switch circuit breaker to the ON position (located on the cab control console).

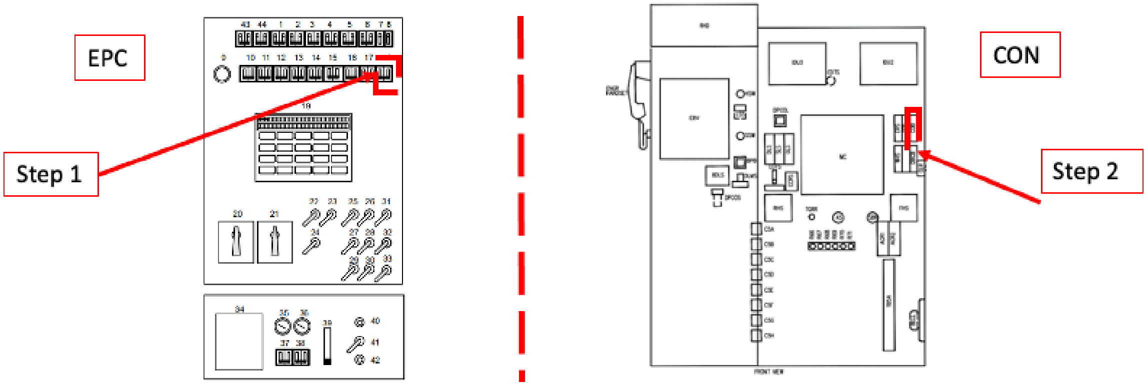


Figure 19: Locomotive cab interface breakers

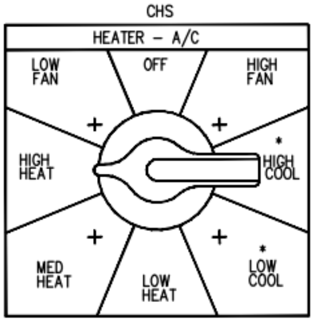


Figure 20. Locomotive cab overhead console HVAC unit control

Once these breakers are triggered by the locomotive crew, the ESS will begin supplying 72 VDC power to the HVAC unit, using power that was generated by the L-WHRS during normal locomotive operation. In compliance with the non-invasive retrofitting approach of the L-WHRS, the HVAC unit can be controlled without modifications through the standard air conditioning/heating dial that is located on the main overhead console in the locomotive cabin (Figure 20).

4.6 Integration of Subsystems

The coupled components forming the L-WHRS, ESS, and HVAC electrical load controlled by the locomotive simulator CUI and the power management system are shown in Figure 21.

Figure 21. Full-scale operational L-WHRS coupled to ESS "Integration Tower"

The locomotive “Selected Electrical Loads” are simulated by load banks that can be coupled in series and/or parallel to form DC or AC electrical loads with different power ratings. The L-WHRS test rig is configured to mimic operational conditions already tested on the locomotive, with the L-WHRS turbine-generator motor-drive coupled to the CUI, the ESS, and the selected electrical loads.

Test data from the locomotive tests executed in previous phases of the research (Filippone, 2020), and motor-drive test data (black-start and transition to electric power generation mode) from the locomotive simulator were used to execute seven power flow cases as described in Section 6.3.1.

Figure 22 shows the piping and instrumentation diagram (P&ID) of the L-WHRS closed loop configuration road-tested in previous phases of the research, with the addition of the CUI to control and manage the power flows to and from the ESS. The P&ID reflects the thermal-hydraulic coupling of the L-WHRS enclosures (Box A, Box B) and condenser radiators as configured when installed on the locomotive (Figure 23).

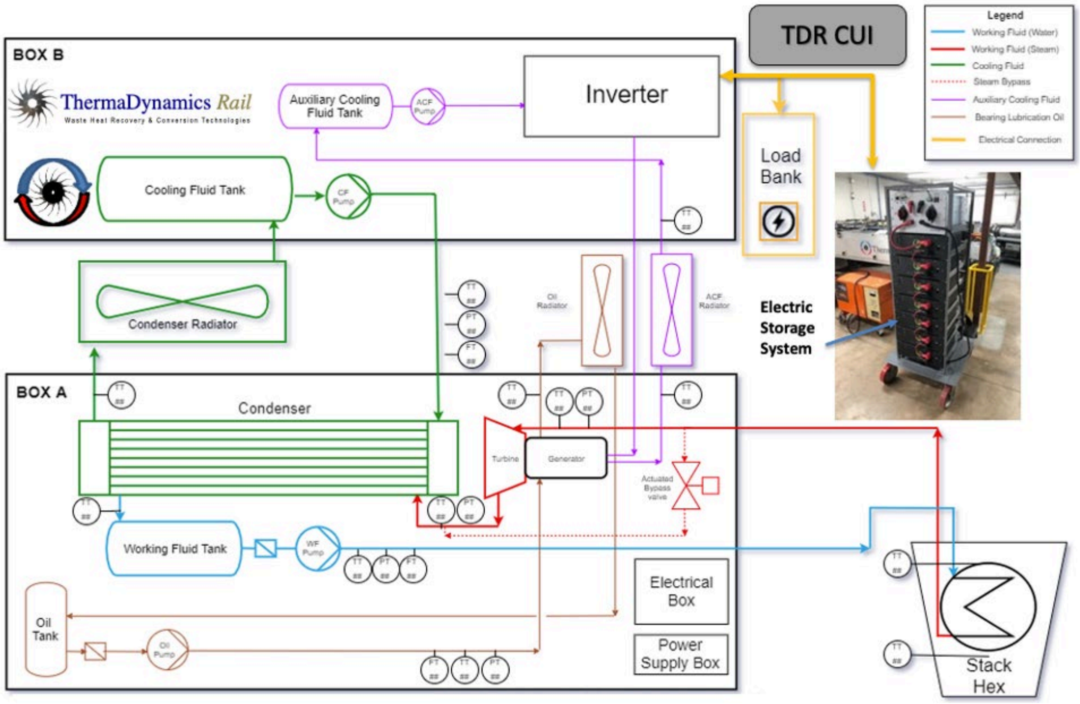


Figure 22. Closed-loop L-WHRS P&ID diagram

Figure 22 shows the functional schematics of the L-WHRS enclosures’ hardware located within Box A and Box B. The hardware includes the balance of plant, pumps, water- and oil-reservoirs, as well as electrical components actuating, for example, safety by-pass valves and interfacing with the CUI. The physical enclosures representing Box A and Box B are shown in Figure 2 during retrofitting installation.

Box A and Box B, coupled to the condenser (radiator systems retrofitted on the locomotive top structures) shown in Figure 23 and Figure 24, and the HiPHEX were tested via on-road locomotive (see Figure 5) and multi-megawatt locomotive simulator at the TDR testing facility (see Figure 4).

Overall, data from these tests were used as reference to design the interfaces that enabled full-scale simulation of the seven power flow cases discussed in Section 6.3.1.

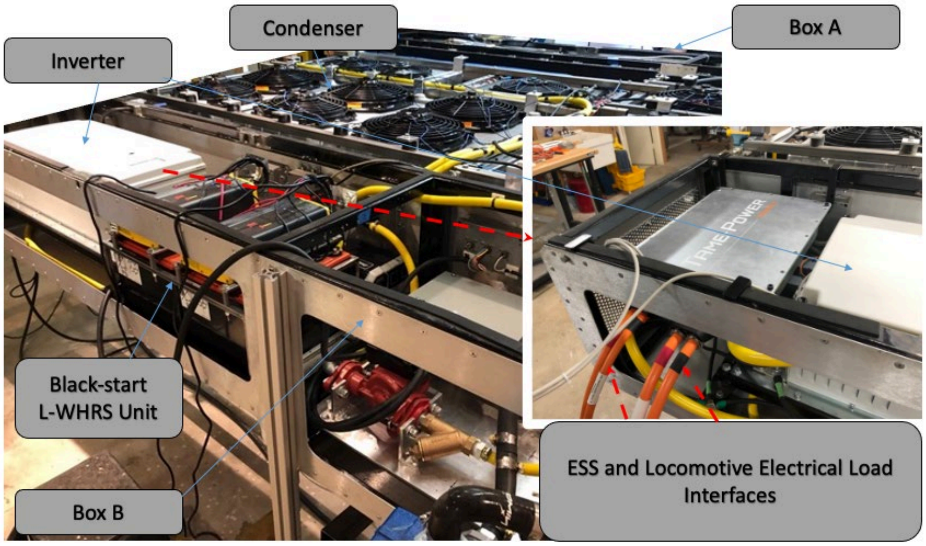


Figure 23. L-WHRS Box B enclosure integrating ESS interface

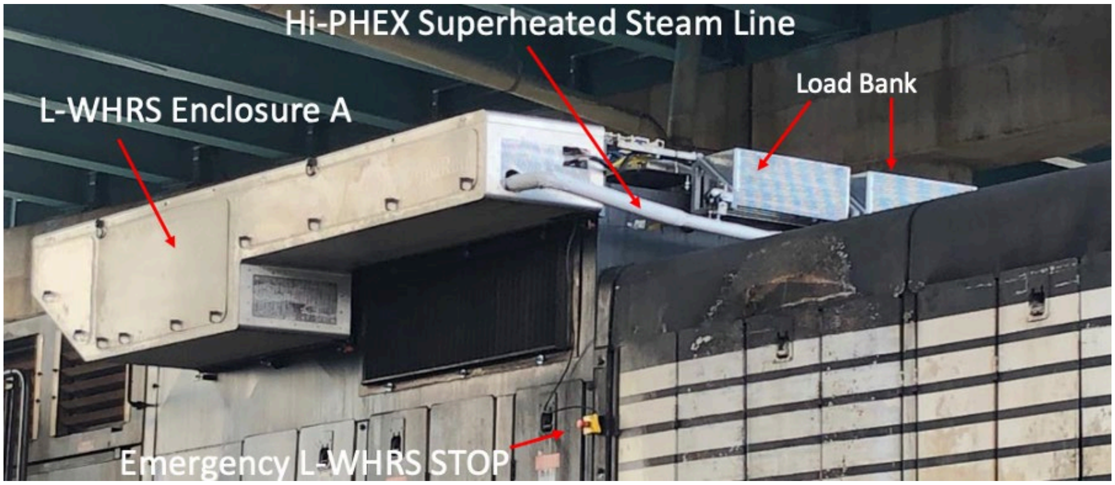


Figure 24. L-WHRS Box A locomotive-installed with simulated locomotive electrical load

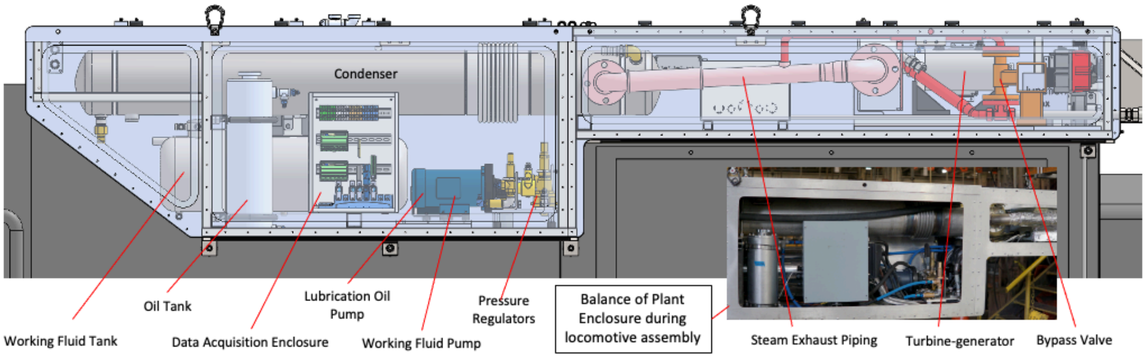


Figure 25. Transparent and actual view of Enclosure A

5. Updated Failure Mode, Effects and Criticality Analysis

The researchers updated the FMECA conducted throughout the development of the L-WHRS to include the interfaces coupling the L-WHRS, the ESS, and selected locomotive electrical loads. Section 5.1 details the FMECA summary update and describes the methodology and inclusion of the L-WHRS interfaces coupling to the ESS and the locomotive loads.

5.1 FMECA Methodology

The FMECA is a systematic technique for failure analysis. It uses inductive reasoning (forward logic) to systematically analyze postulated component failures and identify the resultant effects on system operations. The analysis includes all significant failure modes for each contributing element or part in the system. The generalized ground rules adopted in the FMECA of the L-WHRS and its interfaces are:

- Only one failure mode exists at a time.
- All inputs (including software commands) to the item being analyzed are present and at nominal values.
- Nominal locomotive and L-WHRS operational power are available at the time of failure.

The benefits of a properly implemented FMECA include a thorough identification and assessment of potential failure mechanisms and their impact on system operation, early identification of single failure points and system interface problems, enabling early scheduling of troubleshooting procedures and planning of long-term tests, and exposing test personnel to the operations of a first-of-a-kind technology. The FMECA was executed in cooperation with participating Class I railroad operators and specialized contractors. The involved parties contributed to the identification of interfaces between the HiPHEXs, the L-WHRS components, interfaces, and locomotive equipment. They addressed the various systems and sub-systems that constitute the operation of the HiPHEXs and L-WHRS once interfaced with the locomotive exhaust gases (L-WHRS thermal-source), hydraulics, and electric systems that comprise the interfaces coupling an advanced ESS and selected locomotive electrical loads. As part of the FMECA, researchers developed mitigation strategies addressing perceived risks associated with identified failure modes. FMECA recommendations focused on increasing the safety and reliability of the locomotive-customized waste heat recovery technology are implemented throughout design and operational procedure changes.

The FMECA approach adopted develops through five categories:

1. **Interfaces identification**: The various interfaces between the HiPHEX, L-WHRS, ESS and locomotive electrical loads components
2. **HiPHEX and L-WHRS sub-system identification**: The HiPHEX and L-WHRS sub-systems that constitute the operation of the system as a whole
3. **FMECA**: Detailed FMECA of the interfaces and sub-systems identified for the type of ESS and the interface of this system with the components and interfaces of the L-WHRS
4. **Failure modes, mitigation strategy, countermeasures, and design changes**: Countermeasures and/or design changes proposed to prevent or mitigate the perceived risk associated with each failure mode and effect pair to be implemented in the L-WHRS

closed loop (comprising the locomotive integration activities executed under Phase III and Phase IV of this project)

5. **FMECA report preparation**: Completed written report with the results and recommendations addressing design changes to support closed-loop L-WHRS integration and interface with locomotive equipment for safe prolonged field-testing

5.2 L-WHRS Internal New Components and Updated FMECA

The components forming the HiPHEX and L-WHRS developed and outlined in previous research (Filippone, 2020) were improved and modified in agreement with perceived safety challenges and risks identified through execution of FMECAs. Included in this research effort were tasks focused on updating the information on the FMECA of the L-WHRS subsystems conducted in previous phases of the project.

TDR updated the FMECA of the HiPHEXs, L-WHRS components, the ESS, and locomotive HVAC electrically coupled to the L-WHRS power supply. Based on the FMECA results, the designs for the HiPHEX, L-WHRS, and the components to be connected to the ESS were optimized for integration with locomotive interfaces to enable long-term locomotive field-testing.

The main objective of the FMECA is to identify potential failure modes that might represent safety risks to locomotive operators, the public, and the environment, and that could impair locomotive operations. The FMECA consisted of an exhaustive analysis at the component level to identify root-causes of subsystem failure modes for HiPHEX, L-WHRS, the ESS and components connecting the L-WHRS to locomotive electrical loads, and countermeasures for failures that could impact operators' safety and locomotive operations. Based on the identified countermeasures and subsequent recommendations for design changes, researchers concluded that under credible design basis failure modes locomotive performance will not be affected and there will be no risks to the safety of locomotive operators even under worst-case and critical L-WHRS failure modes. Additional safety precautions and recommendations have been applied during testing of the L-WHRS-ESS-HVAC coupled system. Under all critical scenarios, the L-WHRS will automatically shut-down and electrically disconnect the various buses in a manner that will not impact safety and normal locomotive operations. When the L-WHRS is inoperable, locomotive operations can continue unimpaired, without the benefit of reduced fuel consumption and pollutant emissions or ESS charging.

As discussed in Section 4.5, the COVID-19 pandemic caused significant delays in conducting locomotive tests of the L-WHRS system. As a result, tasks directly involving locomotive over-the-road testing were replaced with tasks achieving similar objectives by using locomotive test and simulator data obtained in previous phases of the research, and by developing electrical interfaces. Additionally, a locomotive simulator CUI was developed to safely control power flows across various L-WHRS, ESS, and cab HVAC (or other locomotive electrical loads). The HVAC DC electrical load was simulated by a load-bank represented by electrical resistors coupled in series-parallel configurations to match voltage requirements and power rating of different types of locomotive electrical loads. The FMECA was further updated by factoring in failure modes and risks associated with the components forming the interfaces electrically coupling the L-WHRS, ESS, and locomotive electrical loads components (as described in Section 6).

5.3 Updated FMECA Interfaces

The interfaces between the L-WHRS subsystems and locomotive components are shown as red dashed lines between systems in the functional diagram shown in Figure 26.

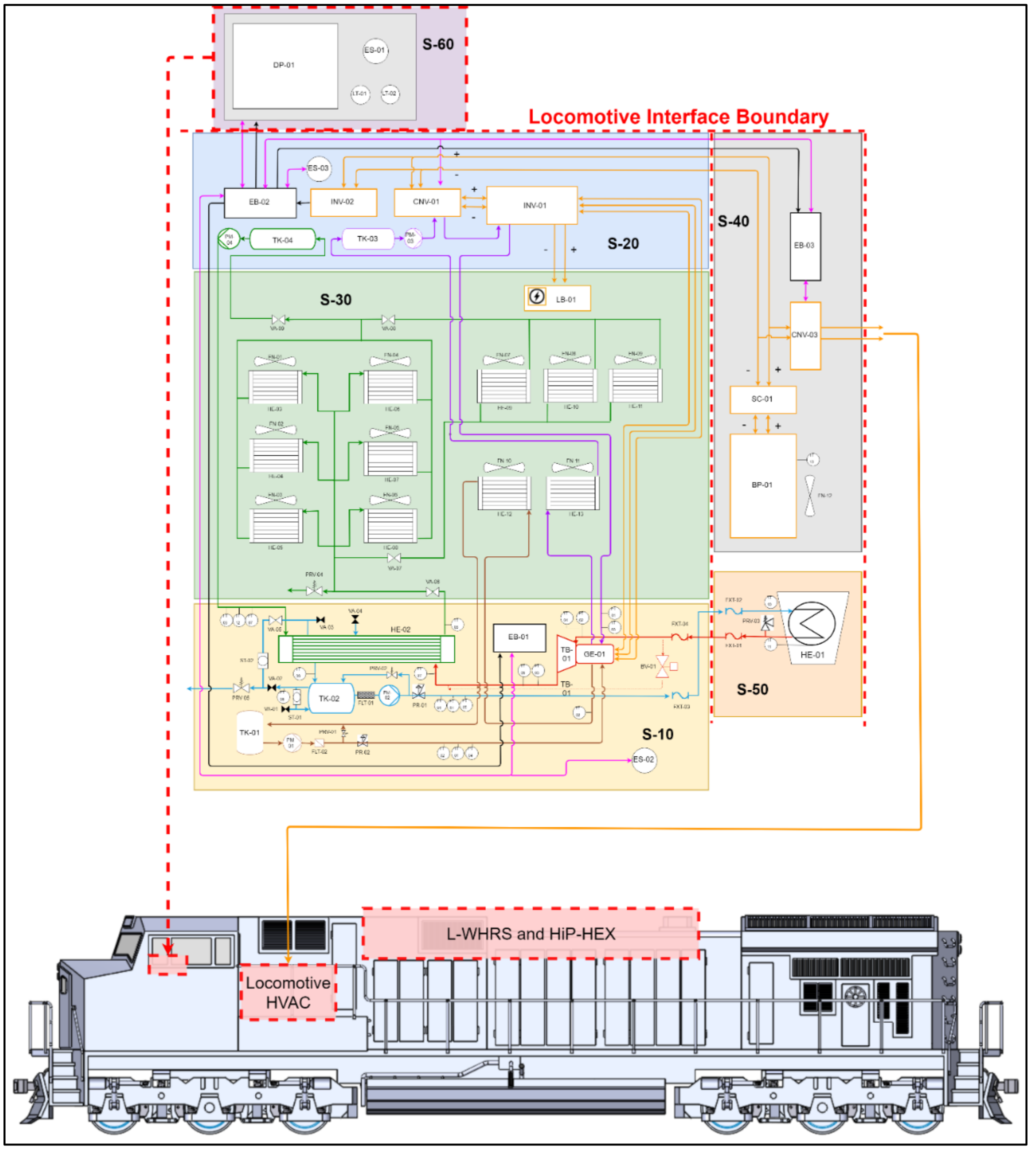


Figure 26. L-WHRS functional subsystems diagram

The CUI's data acquisition and control system is installed in electrical box EB-03, located in S-40 (Figure 26), and replaces the Programmable Logic Controller (PLC) system in electrical box EB-02, located in S-20 and the HMI in S-60.

TDR developed the locomotive simulator CUI to read and display power management system data from the L-WHRS, ESS, and selected electrical loads, while providing safe user control of power flow direction and magnitude. The CUI programs operational setpoints and enables safe switching of the control contactors to simulate all design basis power flow scenarios for the power management system under normal operating conditions of the L-WHRS.

Figure 22 in Section 4.6 shows a simplified P&ID of the L-WHRS closed loop configuration road-tested in Phase III of this research, with the addition of the CUI to control and manage the power flow to and from the ESS. The P&ID reflects the thermal-hydraulic coupling of the L-WHRS subsystems S-10 (Box A), S-20 (Box B), and radiator assembly S-30 as configured when actually installed on the locomotive (subsystems S-10, S-20 and S-30 are shown in Figure 26).

Figure 21 (Section 4.6) shows the coupled components forming the L-WHRS, ESS, and the simulated HVAC electrical load controlled by the locomotive simulator CUI and the power management system. The locomotive-selected electrical loads are simulated by load bank resistors that can be coupled in series-parallel configurations, forming DC or AC electrical loads with various power ratings to simulate a large spectrum of locomotive electrical loads. The L-WHRS test rig is configured to mimic operational conditions already "locomotive-tested" when the L-WHRS motor-drive is coupled to the CUI and ESS, with power flow through the HVAC simulated by a resistive load-bank. In addition to containing the CUI data acquisition system, the electrical box EB-03 (shown in Figure 18, Section 4.4.2) houses the high-voltage switching circuit that enables connection between the motor drive (INV-01), the bidirectional DC-to-DC converter (CNV-01), the load converters (CNV-03), and the ESS (SC-01 and BP-01). The EB-03 contactor switching circuit uses the following safety practices:

- Fuses on all DC+ and DC- bus connections
- Pre-charging circuits to limit inrush current on capacitive loads
- High voltage cables with locking connectors or lug terminals
- Cable gland strain relief and high voltage standoffs for all power connections
- Flyback diodes on contactor coils for transient voltage suppression

These safety practices are shown in Figure 18.

While the CUI allows for user control of the power management system, it incorporates pre-programmed safety features that reduce the risk of operator-induced failures. When certain control and user interface selectable buttons are disabled, forcing the user to follow safe startup procedures. For example, the CUI will not allow operators to connect a circuit branch until the pre-charge circuit is enabled and a pre-programmed timeout has elapsed.

The CUI communicates with the L-WHRS motor drive, DC-to-DC converter, and the ESS battery management system and programs each device's warning and fault safety thresholds based on the power flow test being conducted. If any of these devices report off-normal conditions within the fault thresholds during testing, their internal circuity will automatically disable the device and, after receiving the resulting fault error message, the CUI automatically enters a safe shutdown mode and disconnects all contactors. In addition, the DC-to-DC converter (CNV-01) must receive an operating command message from the CUI every 100 milliseconds, otherwise it stops converting and enters standby mode as a safety precaution.

To simulate a large spectrum of L-WHRS operating conditions during power generation (e.g., at different waste thermal power levels available at the locomotive stack) and mimic a foreseeable number of the interfaces' configurations and corresponding power flow cases (as described in this report), the L-WHRS motor drive was replaced with an adjustable high-voltage DC power supply (Figure 29). The DC power supply provides variable power with programmable current limiters. This device enabled safe preliminary and troubleshooting testing of the various interfaces, while validating the correct CUI and interface protections and safety performance. For these simulated L-WHRS power generation tests, the power supply's programmable current limiter is set for each test, thus actuating an automatic safety-threshold-disconnect in the event of over-current conditions (due, for example, to CUI programming error or interface component malfunctions). The output of the DC power supply replaces the connection from the motor-drive and connects to the switching circuit high-voltage standoffs, as represented in the block diagram shown in Figure 30.

To supply 480 Volts of AC (VAC) to power the adjustable DC supply (to mimic the L-WHRS motor drive), TDR's test facility uses a 208 VAC to 480 VAC step-up transformer with fuses and manual safety "throw switches" on both the primary and secondary sides of the transformer. The manual throw switches are located at a safe distance from the L-WHRS testing location and allow for a backup removal of power if needed.

The CUI test bench computer is located and operated at a safe distance from the L-WHRS-ESS and contains emergency stop switch ES-01 (see an example in Figure 27). During testing at the TDR locomotive simulator facility, an additional set of emergency-stop-switches were physically placed by the CUI operator keyboard and at locations near the L-WHRS test rig to allow test personnel to de-energize the interfaces from multiple locations. Any of the emergency-stop-buttons will, via hardware circuit, disconnect all DC bus contactors when pressed, regardless of the L-WHRS data acquisition and control system and CUI computer communication connection.

Overall, the adoption of TDR CUI coupled to the L-WHRS, ESS, and electrical loads allows for safe component and full-system level integration, testing, and validation of the L-WHRS when coupled to the energy storage system and electrical loads under various power flow scenarios.

Figure 27. Emergency L-WHRS disabling switch

6. Integration, Testing, and Validation via Locomotive Simulator

As discussed in previous sections, some research tasks were amended or merged to reflect testing via full-scale simulators rather than on-the-road locomotive testing during the pandemic. A description of these task results is provided as part of the power flow testing from the L-WHRS to the ESS and HVAC, from the ESS to the L-WHRS (black-start), and from the ESS to the HVAC as the selected locomotive electrical load simulated by a programmed load bank.

6.1 System Adaptations to the Locomotive Simulator Architecture

Integration of the DC powered motor drive and bidirectional DC-to-DC converter subsystems into the L-WHRS power conversion system was expanded to include simultaneous operations of a variable load bank (simulating different types of locomotive electrical loads) and ESS charging/discharging. Figure 23 shows the L-WHRS enclosures used during the on-the-road locomotive tests executed in previous phases of the research. The orange power cables represent coupling of the L-WHRS turbine-generator motor drive interface to the ESS and the CUI interfaces. This configuration enabled ESS testing under the power flow scenario in which the ESS provides source power for the L-WHRS start-up procedures.

6.2 Test Bench/Component Setup & Subsystems Testing for Locomotive Simulator

Each of the CAN connected devices were programmed and tested independently to validate their performance and safety features. This was done to ensure safe operations of all systems and their interfaces when electrically coupled and functioning as a whole "L-WHRS-ESS-HVAC" system operating through a DC micro-grid. After successful CUI development of each individual CAN message structure, the following bench testing was performed:

- BMS – CAN data was verified against values reported by the OEM software, ESS pre-charge and contactor circuits were verified.
- Bidirectional DC-DC converter – operating modes and power conversions were verified using the high-voltage DC power supply with programmed current limiters as an input.
- Motor drive – powered on using the high-voltage DC power supply via the high-side pre-charge circuit, then verified operation with testing of the turbine-generator.

Low-side and high-side contactor switching were tested and verified for full functionality before applying voltage, and the emergency stop circuit was also tested to verify the opening of all contactors with subsequent electrical neutralization of all systems and subsystems. Data from static testing of the L-WHRS, obtained by providing locomotive-equivalent thermal energy to the HiPHEX via TDR locomotive simulator, was used for the power flow cases described in Section 6.3.

The TDR locomotive simulator consists of a turbojet engine configured to provide exhaust gases through a manifold coupled to an actual locomotive exhaust stack that was retrofitted with the same HiPHEX that was retrofitted with the locomotive stack, and then on-the-road tested (Figure 4). The turbojet engine supplies controlled waste thermal energy through the HiPHEX with up to 6 MW thermal capability. The locomotive simulator is also equipped with a "by-pass" valve to change the exhaust gas mass-flow rate to match the actual locomotive exhaust gas flow rate and temperature when operated at different notch settings. Static testing of the L-WHRS turbine-generator motor drive, the ESS, and electrical loads was conducted using data from the locomotive simulator, the CUI, and electronic and electrical interfaces developed by TDR.

6.3 Static Testing via Locomotive Simulator

After verifying the technical and safety performance of the individual subsystems coupling the L-WHRS interfaces to the ESS and simulated cab HVAC, the high-voltage cables were connected to the "integration tower" (Figure 28) and to the L-WHRS interfaces so as to conduct low-power, full-system-level testing of the power management system. To increase safety, TDR conducted verification testing on the power management system using controlled power sources (e.g., DC power supply simulating power from the motor-drive) with programmed current limitations and electrical loads represented by reconfigurable load banks. The locomotive HVAC electrical load was simulated by coupling load resistors connected to the 72 VDC output of the load DC-to-DC converters (Figure 12 and Figure 17). Each load-bank unit represents a resistive impedance of 2.7 Ω which, when connected to the 72 VDC bus, provides 1,920 watts (W) of power dissipation.

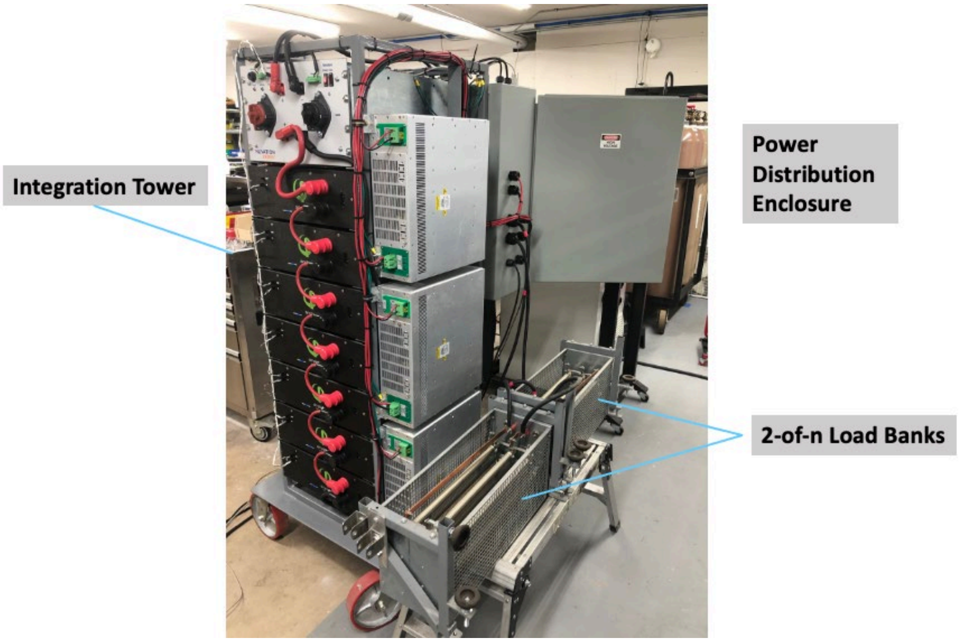


Figure 28. Integration tower and load banks simulating locomotive DC loads

When the L-WHRS converts waste thermal power to electricity, electric power generation begins, and the motor drive's DC bus no longer acts as a DC load while it transitions to operate as a DC power source. To simulate operating conditions of the L-WHRS during power generation and simulate multiple power flow cases, the motor drive DC output was provided by the adjustable high-voltage DC power supply shown in Figure 29. For simulated L-WHRS power generation tests, the output of the DC power supply was connected to the same high-side terminals as the motor drive.

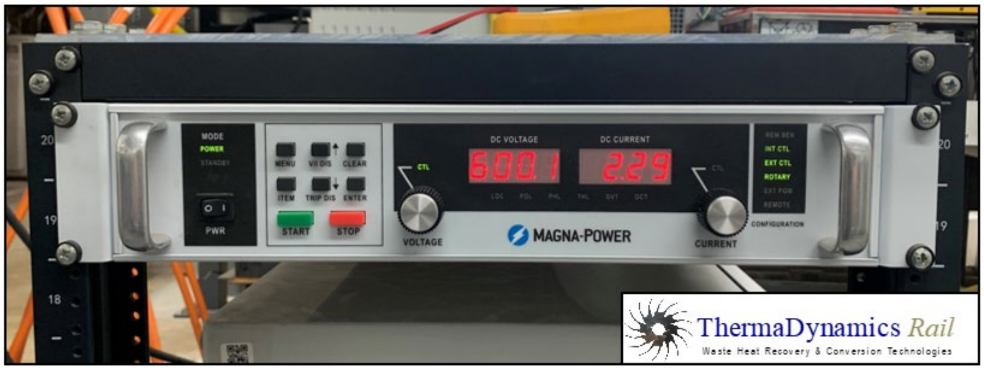


Figure 29. DC power supply (L-WHRS variable power generation simulation)

A simplification of the power management system block diagram shown in Figure 12 was adapted for full-system power testing to exercise the whole system when subjected to variable power flows across the L-WHRS, ESS, and electrical loads components (Figure 30). The testing diagram shows subsystem blocks essential to the flow of power and includes the simulated DC sources and loads used for testing.

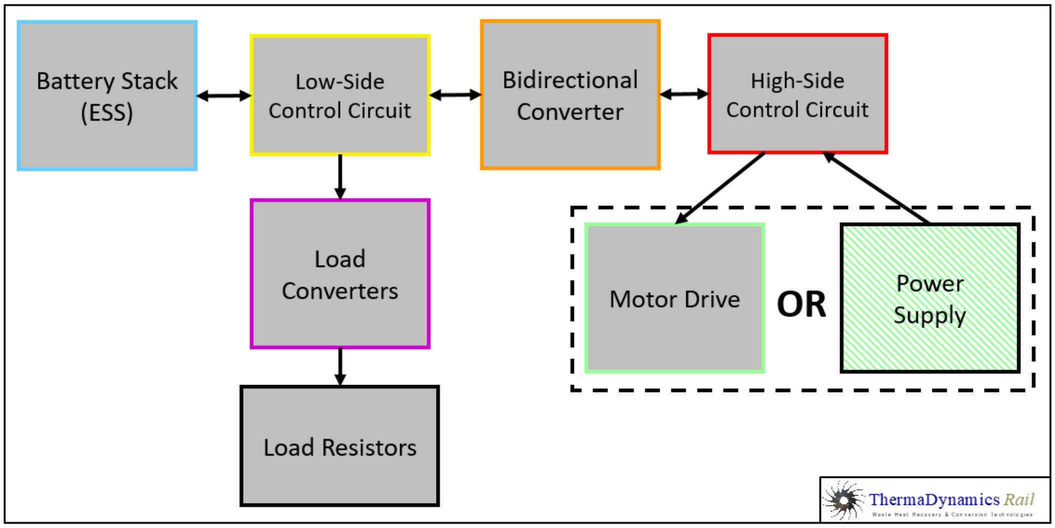


Figure 30. Power management system testing diagram

TDR conducted various tests to simulate all possible power flow scenarios for the power management system under L-WHRS normal operating conditions. Based on the power management system testing diagram shown in Figure 30, a total of seven power flow cases, representative of actual locomotive operational conditions, were developed and tested by controlling the CUI described in Section 4.2. Figure 31 to Figure 37 show Power Flow Cases 1 through 7, which show electrical interactions between the L-WHRS, the ESS, and selected locomotive electrical loads. For example, Power Flow Case 1 shows the ESS discharging while providing DC power to the L-WHRS motor-drive (e.g., to start operations of the L-WHRS as thermal power at the locomotive stack becomes available) and simulates the L-WHRS black-start operations described in Section 3.3. For each power flow case, the red arrow represents the electrical current or power flow direction, indicating the source of power and the integrated L-WHRS-ESS and electrical load interfaces that are impacted.

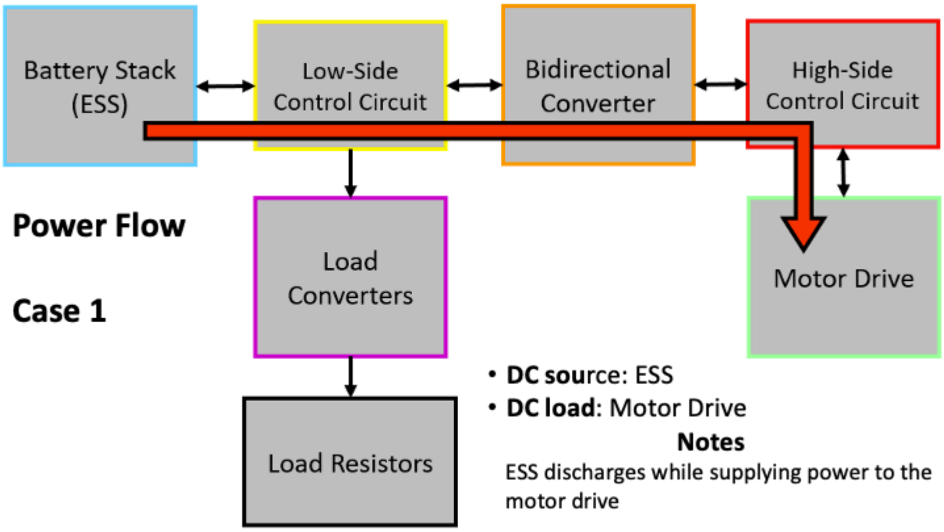


Figure 31. Power Flow Case 1: ESS powering L-WHRS motor-drive

Power Flow Case 2 is shown in Figure 32. This test represents a scenario in which the selected locomotive load is powered (e.g., cabin crew set the HVAC system to "ON" through the manual switch shown in Figure 20). This power flow case also shows that waste thermal conditions at the locomotive stack are unfavorable for the L-WHRS to convert waste thermal energy to electricity (e.g., locomotive shutdown, idling, or at low notch settings); thus, the DC power source for the HVAC or other selected DC locomotive loads is the ESS.

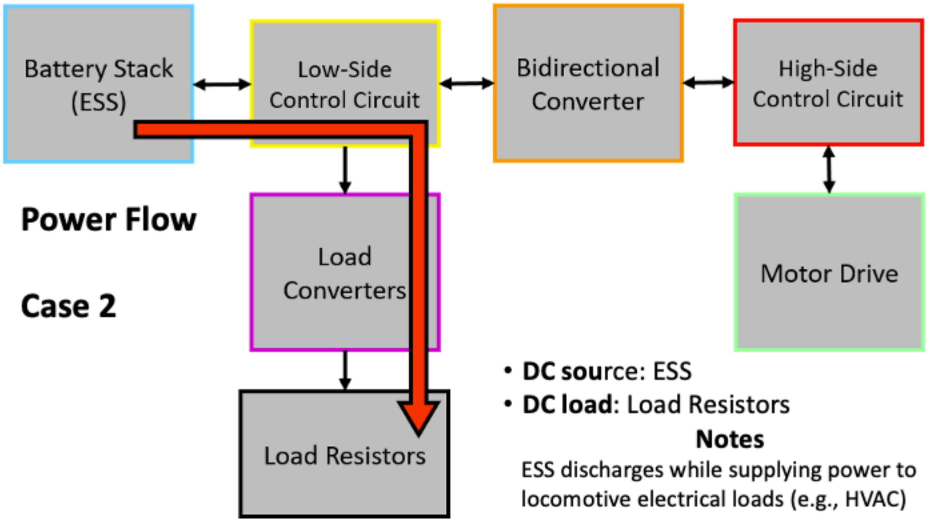


Figure 32. Power Flow Case 2: ESS powering locomotive electrical loads

Power Flow Case 3 is shown in Figure 33. This test represents a scenario wherein the selected locomotive load is powered and the L-WHRS is powering up, but power generation from waste heat recovery has not occurred yet (L-WHRS may transition from black-start to power generation).

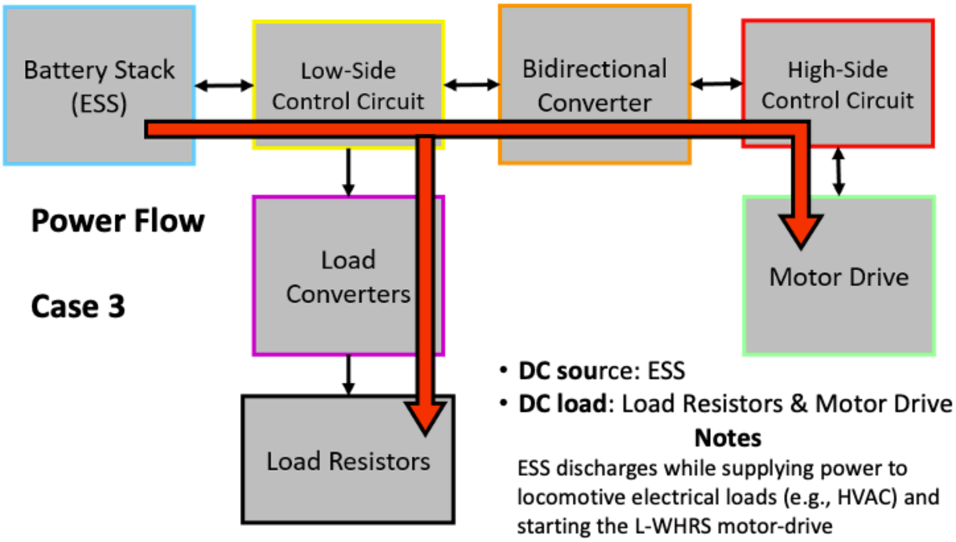


Figure 33. Power Flow Case 3: ESS powering locomotive electrical loads & L-WHRS

Power Flow Cases 4, 5, 6 and 7 (Figure 34 through Figure 37) represent scenarios in which the L-WHRS is generating power and the selected locomotive load is powered on. These tests demonstrated correct interface interactions controlled by the CUI, with power flows inverting direction without causing power surges or conflicts through the different scenarios shown in each case.

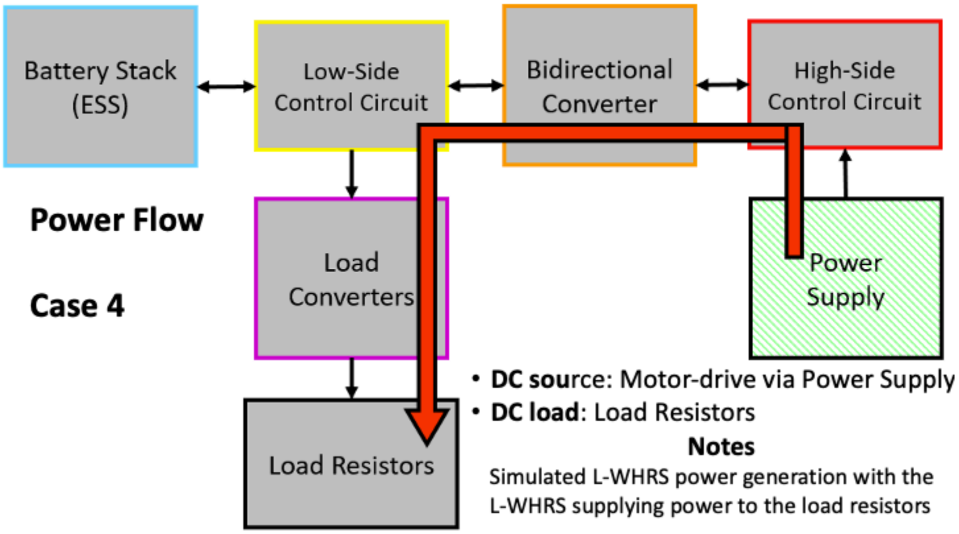


Figure 34. Power Flow Case 4: L-WHRS powering locomotive electrical loads

Power Flow Case 4 (Figure 34) simulates a scenario in which the ESS is fully charged or disconnected, and the L-WHRS supplies power to the electrical load.

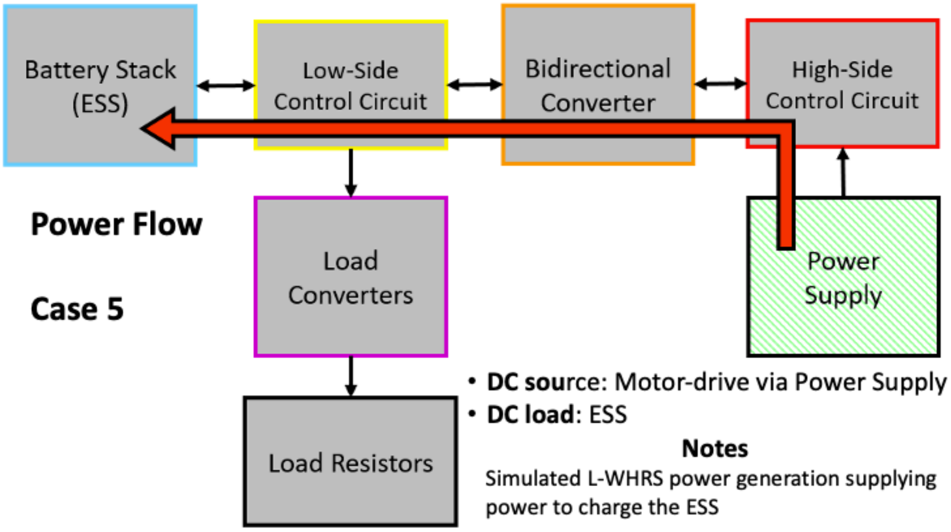


Figure 35. Power Flow Case 5: L-WHRS charging the ESS with no locomotive electrical loads

Power Flow Case 5 (Figure 35) simulates a scenario wherein the ESS state of charge enables the L-WHRS to supply power to the battery stack to recharge it, while there are no locomotive electrical loads on the DC microgrid formed by the L-WHRS, ESS, and their electrical interfaces. In Power Flow Case 6 (Figure 36), the simulated scenario involves simultaneous power supply to recharge the ESS battery stack, while also supplying power to the locomotive electrical loads. This scenario is particularly important, since the HVAC duty cycle is intermittent to satisfy the cabin temperature settings imposed by the cabin crew. Therefore, the L-WHRS turbine-generator drive must provide coupling features that enable it to supply power to the ESS during recharging, while intermittently undergoing a variable demand at the interface with the locomotive electrical load.

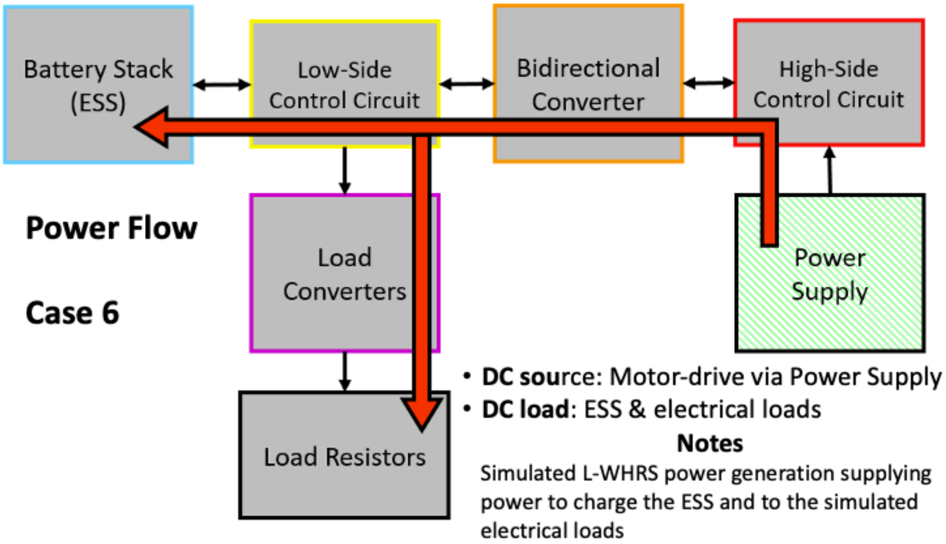


Figure 36. Power Flow Case 6: L-WHRS supplying power to the ESS & electrical loads

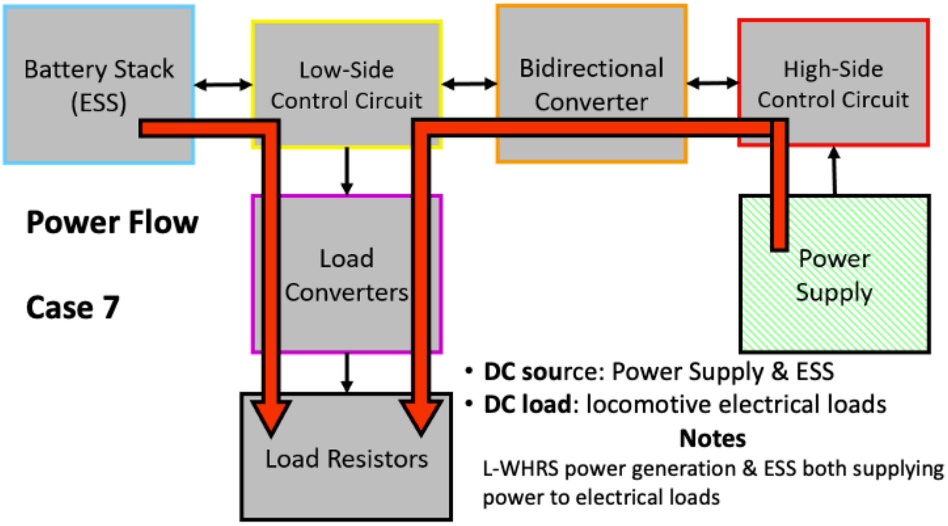


Figure 37. Power Flow Case 7: L-WHRS & ESS supplying power to electrical loads

Power Flow Case 7 (Figure 37) simulates a complex power case in which the L-WHRS motor-drive electric generation is insufficient to fully meet the electrical load power rating requirements. Therefore, a portion of the electric power supplied to the electrical load is sourced in the ESS, while the remaining electric power is sourced in the L-WHRS motor drive. This power flow case simulates an operational condition wherein the waste thermal power at the locomotive stack was sufficient to start the L-WHRS drive (e.g., locomotive operations transitioning from idling to medium-low notch settings) but insufficient to provide the full power rating demand at the DC power grid.

For all power flow test case configurations, outputs were gathered from the real-time display outputs of the CUI. Each subsystem is represented by a numbered module associated with the power management system block diagram shown in Figure 38, with the CUI displaying operating information in real time. The CUI display contains the following subsystem modules, also identified by color coded dashed lines as shown in Figure 38:

- Module 1 – ESS connection state, errors, and battery stack data
- Module 2 – Low-side DC bus connection status and voltage, current, and power measurements
- Module 3 – Bidirectional DC-to-DC converter status, errors, and operating mode
- Module 4 – High-side DC bus connection status and voltage, current, and power measurements
- Module 5 – Load DC-to-DC converters connection status
- Module 6 – Motor drive status, errors, operating data, and motor data

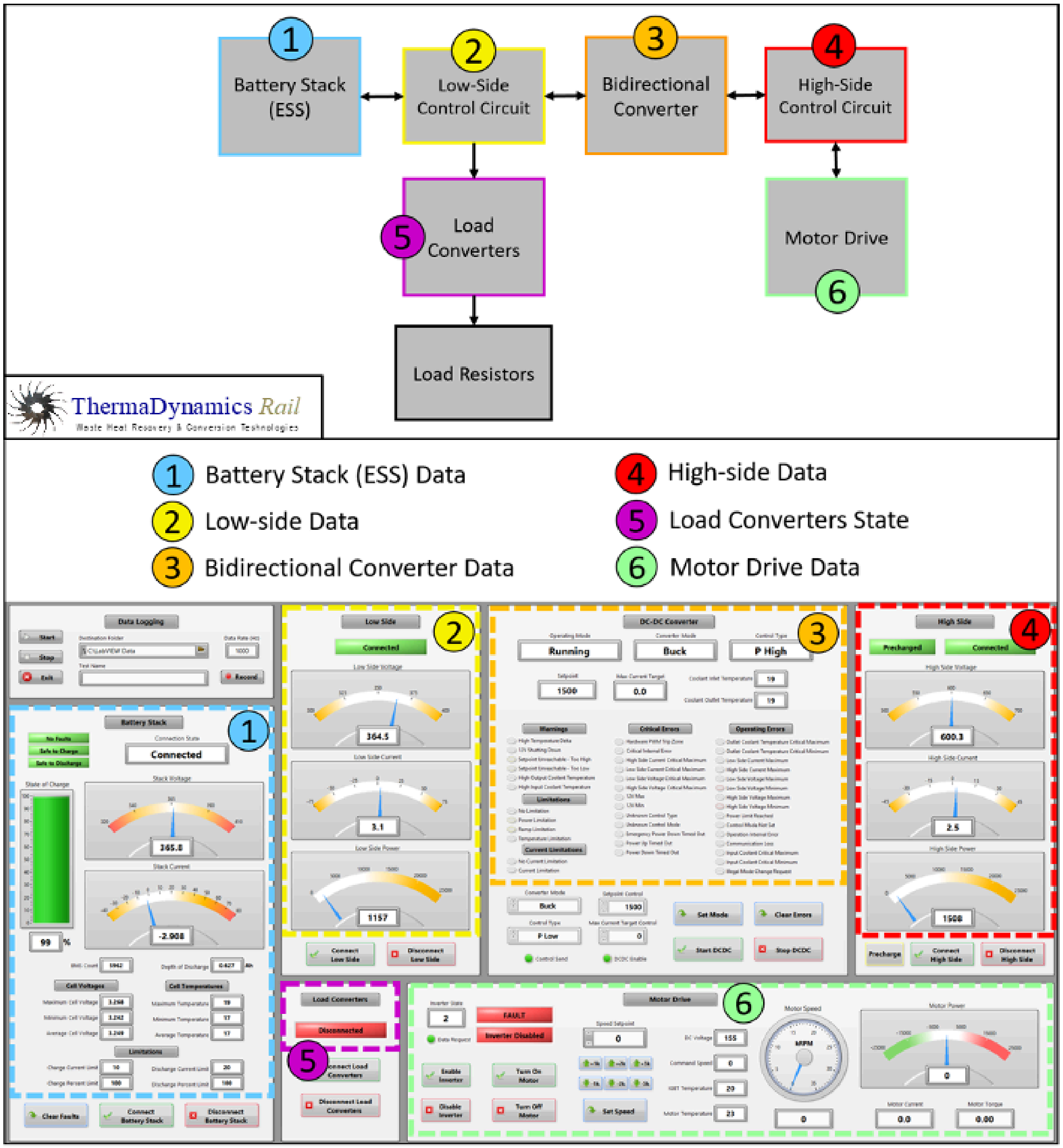
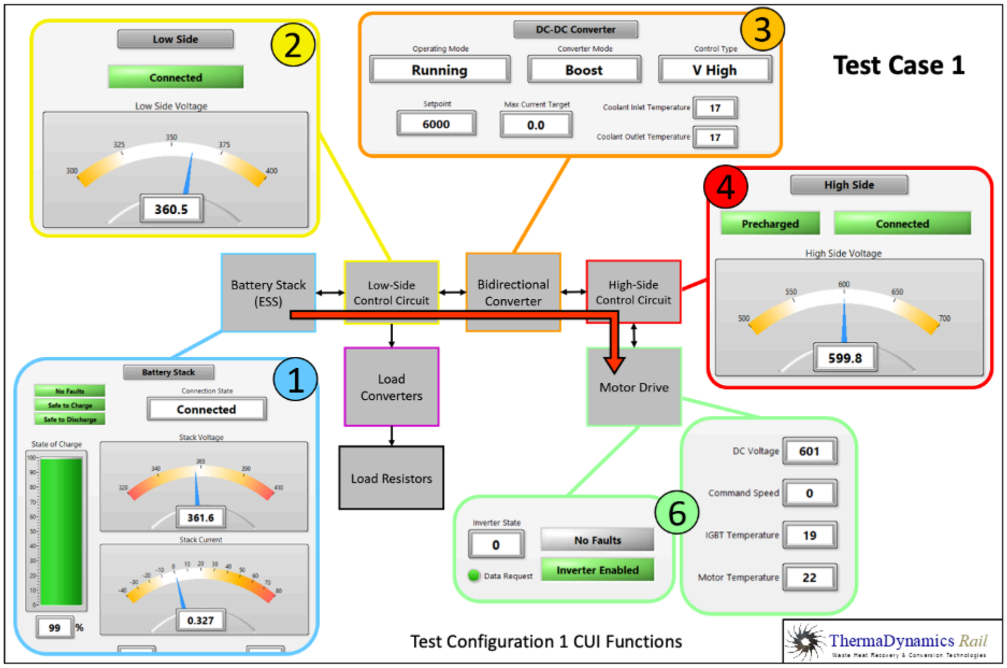


Figure 38. ThermaDynamics rail power management system diagram

Each module enables the activation or de-activation of controlled interfaces and obtains real-time power flow data via the virtual gauges populating the CUI. Developing TDR CUI to simulate design basis power flows between the locomotive electrical system and the L-WHRS, ESS, and selected electrical loads will greatly facilitate the design and programming of a microprocessor-based TDR controller interface in subsequent phases of the project. The microprocessor-based controller will automate the operations made by an operator and will also be coupled to a user interface display integrated with the locomotive cabin instrumentation, enabling the crew to monitor the L-WHRS-ESS performance and disconnect these systems in case of emergency or to execute maintenance activities.

6.3.1 Test Cases, CUI Configurations and Outputs

Power Flow Case 1, which was shown in Figure 31 as a block diagram and modules interactions, is now shown in Figure 39 within the context of the CUI modules. This test scenario represented L-WHRS black-start conditions and mimics the locomotive operational conditions in which sufficient waste thermal energy is produced by the locomotive engine to enable the L-WHRS electric power generation. In this scenario, the CUI shows that the ESS is connected (Module 1) and provides power through the connected low- and high-side control circuits (Modules 2 and 4). The converter boosts the voltage to a setpoint of 600 VDC (Module 3), which powers the motor drive and enables the inverter (Module 6).



Operating Mode Running

Converter Mode Boost

Control Type V High

Setpoint 6000

Max Current Target 0.0

Coolant Inlet Temperature 17

Coolant Outlet Temperature 17

Connection State Connected

Inverter State 0

DC Voltage 601

Command Speed 0

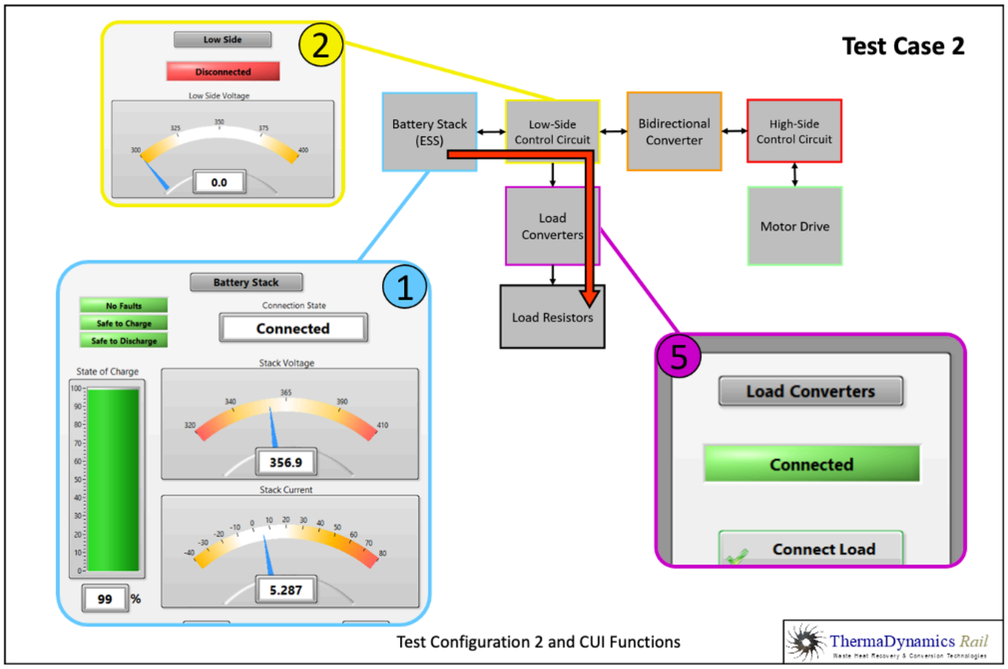
IGBT Temperature 19

Motor Temperature 22

Figure 39. L-WHRS black-start configuration

The block diagram describing Power Flow Case 2 (Figure 32) is integrated with the CUI modules to illustrate their functions (Figure 40). This test represents a scenario in which the selected locomotive load is powered (e.g., cabin crew set the HVAC system to "ON" via the switch shown in Figure 20), but conditions are unfavorable for the L-WHRS startup to convert waste thermal energy to electricity. This operational scenario may be represented by the locomotive engine not providing sufficient waste thermal energy (e.g., engine shut-down, idle, or operated at low notch settings).

Module 1 (Figure 40) represents the battery stack (ESS) and is connected and provides power through part of the low-side DC bus control circuit; however, the bidirectional converter (part of Module 2) remains disconnected, while power flows through the connected load converters (Module 5) and is dissipated in the load resistors. As the L-WHRS is not generating power and there is insufficient thermal energy at the locomotive stack, there is no power flow from or to the L-WHRS.


Test Case 2

Low Side: Disconnected

Low Side Voltage: 0.0

Battery Stack: No Faults, Safe to Charge, Safe to Discharge

Connection State: Connected

State of Charge: 99 %

Stack Voltage: 356.9

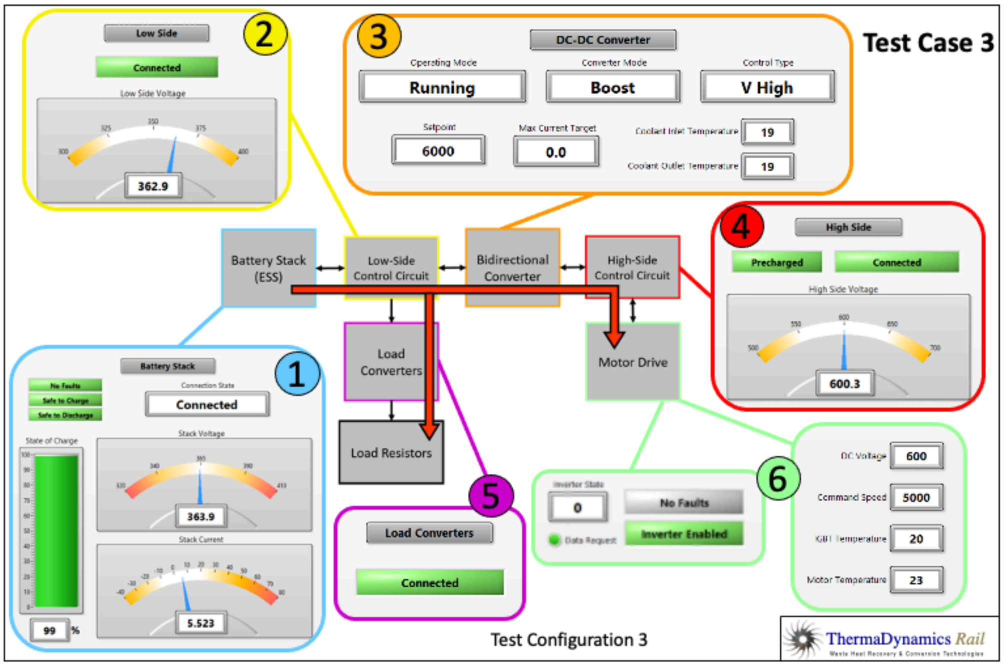
Stack Current: 5.287

Load Converters: Connected

Connect Load

Figure 40. Locomotive electric load supplied by the ESS

Power Flow Case 3 shows the CUI functional modules (Figure 41). This power flow case represents a scenario where the selected locomotive load is powered and the L-WHRS is powering up, but power generation from waste heat recovery has not occurred yet. This power flow simulates the operational condition in which the L-WHRS transitions from black-start to power generation.


Test Case 3

Low Side: Connected

Low Side Voltage: 362.9

DC-DC Converter

Operating Mode: Running

Converter Mode: Boost

Control Type: V High

Setpoint: 6000

Max Current Target: 0.0

Coolant Inlet Temperature: 19

Coolant Outlet Temperature: 19

High Side: Precharged, Connected

High Side Voltage: 600.3

Battery Stack: No Faults, Safe to Charge, Safe to Discharge

Connection State: Connected

State of Charge: 99 %

Stack Voltage: 363.9

Stack Current: 5.523

Load Converters: Connected

Inverter State: 0

Data Request

No Faults

Inverter Enabled

DC Voltage: 600

Command Speed: 5000

IGBT Temperature: 20

Motor Temperature: 23

Figure 41. ESS powering locomotive electrical load and the L-WHRS motor drive

The ESS is connected (Module 1) and provides power through the connected low- and high-side control circuits (Modules 2 and 4). The converter boosts the voltage to a setpoint of 600 VDC (Module 3), which powers the motor drive and enables the inverter (Module 6). This case assumes the Cabin HVAC is switched on, so that electrical power flows through the connected load converters (Module 5) and is dissipated in the load resistors.

Power Flow Case 4 (Figure 42) represents an operational scenario in which the L-WHRS is generating power, the selected locomotive load is powered on, and the ESS is disconnected (Module 1). The power supply, which simulates the L-WHRS motor drive, is set to 600 VDC and provides power through the connected high- and low-side control circuits (Modules 2 and 4) to the connected load converters (Module 5). Power is dissipated in the load resistors. In this power flow case, the converter bucks the voltage to a setpoint of 350 VDC (Module 3) on the low-side, with a power reading of 1,904 W (as shown in the bottom display of Module 2).

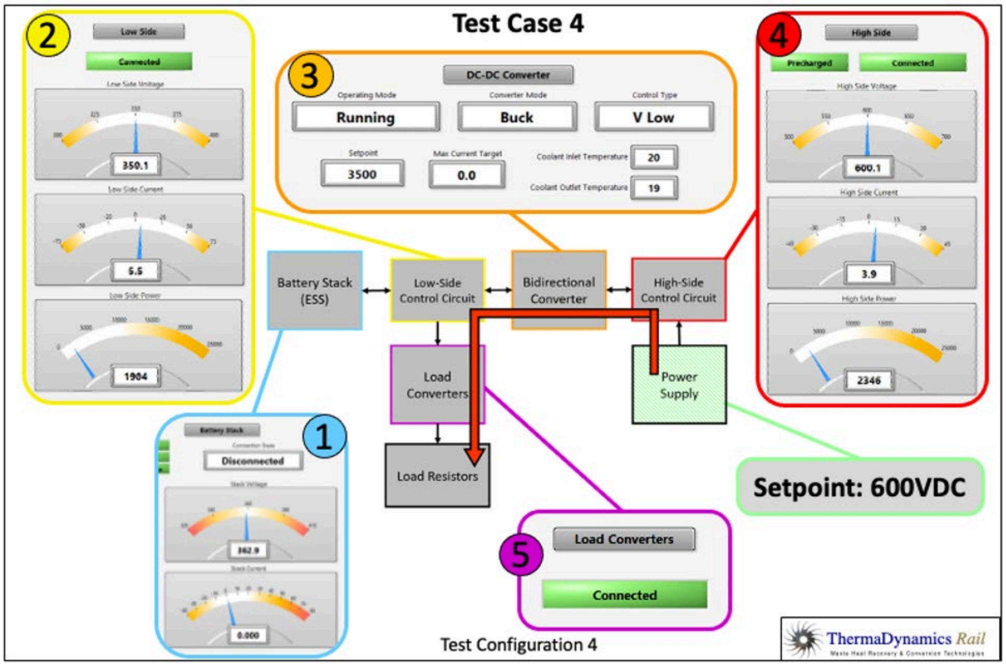


Figure 42. L-WHRS motor-drive (simulated by DC high-voltage power supply)

In Power Flow Case 5 (Figure 43), the L-WHRS is generating power and the ESS is charging, while the electrical load is disconnected. In this test, the power supply is set to 600 VDC and provides power through the connected high- and low-side control circuits (Modules 2 and 4) to the connected and charging ESS (Module 1). The converter bucks the voltage to not exceed 1,500 W (a test-specific programmable value) on the high-side (Module 3), which is verified by the high-side power measurement (Module 4). The negative ESS current (shown in Module 1, bottom display) indicates that current is flowing into the battery stack for charging. This configuration mimics an operational scenario in which the HVAC dial shown in Figure 20 is set to the "OFF" position. If other locomotive electrical loads are considered, Power Flow Case 5 represents a scenario in which none of the locomotive electrical loads are connected to the DC power grid coupled to the L-WHRS, while the locomotive is operated at medium-to-high notch settings and the ESS is not fully charged. In this configuration, the HVAC or other selected locomotive electrical loads could still be powered by the locomotive DC power bus, the electric energy source of which is supplied by the OEM locomotive alternator-rectifier system. The locomotive DC electric supply system supplies power to the Cabin HVAC depending on the configuration of the OEM locomotive interface breakers (Figure 19) as the locomotive crew follows the configurations steps described in Section 4.5. Power Flow Case 6 describes a scenario wherein the locomotive crew sets the L-WHRS as the source of DC power for the Cabin HVAC system, as described in the following paragraph.

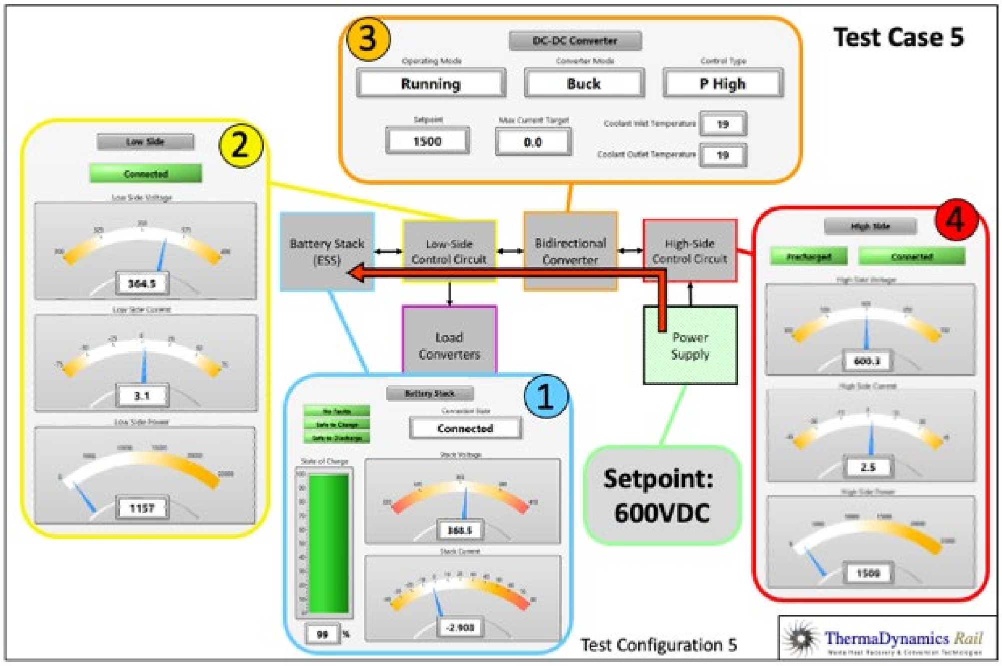


Figure 43. Power Flow Case 5 – L-WHRS charging ESS & powering the electrical load

Power Flow Case 6 (Figure 44) represents a scenario wherein the L-WHRS is generating power, the ESS is charging, and the selected locomotive load is powered on.

For this specific test, the high-voltage DC power supply (Figure 29) simulates the motor-drive of the L-WHRS during power generation with voltage set to 600 VDC. As shown in Figure 44, the high-voltage DC power supply provides power through the connected high- and low-side control circuits (Modules 2 and 4) to the connected ESS (to charge the battery stack comprised by Module 1) and to the connected load converters (Module 5). For the purposes of this test, electric power is dissipated in the load resistors. The converter bucks the voltage to not exceed 3,000 W on the high-side (Module 3), which is verified by the high-side power measurement (Module 4).

The negative ESS current, shown by the bottom right display in Module 1, indicates current flowing from the L-WHRS motor drive into the battery stack for charging.

This simulation mimics an operational scenario in which the locomotive was idling or at low notch settings and the locomotive crew selected the L-WHRS DC power grid as the source of power for the Cabin HVAC. As waste thermal power was insufficient for the L-WHRS motor-drive to generate power, the ESS gradually discharged while supplying power to the HVAC unit. As the locomotive transitions from idling to medium to high notch settings (while the HVAC unit is always energized), sufficient thermal power is converted into electricity for the L-WHRS to supply power to the HVAC unit and, at the same time, to the ESS to recharge the battery stack.

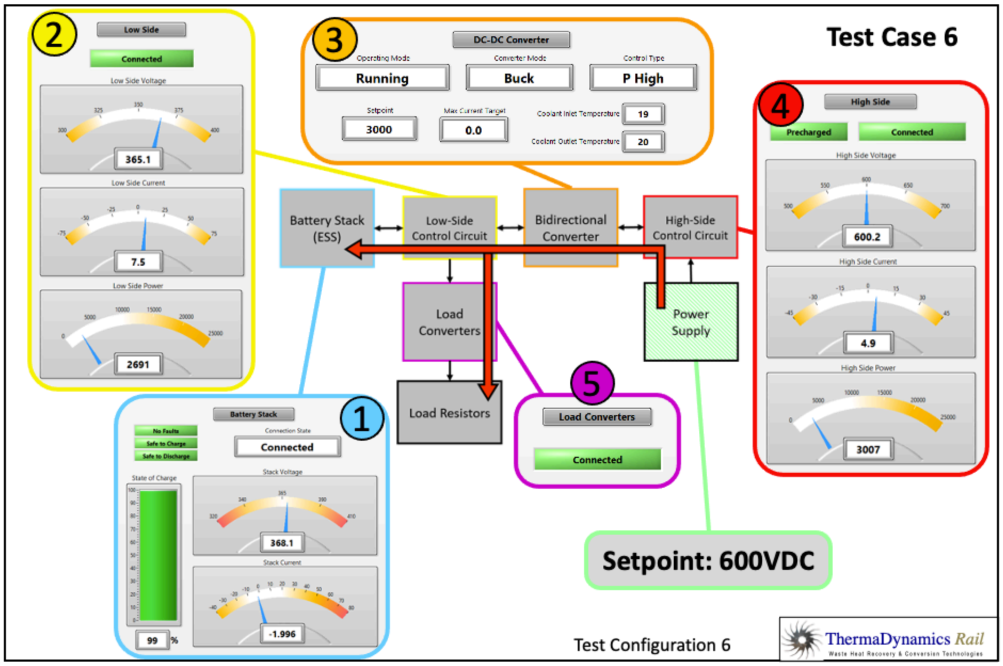


Figure 44. Power Flow Case 6: L-WHRS charging the ESS and powering the electric load

Power Flow Case 7 is shown in Figure 45. In this scenario, the L-WHRS is generating power, but not enough to power the selected locomotive load. Therefore, the ESS is discharging while contributing the matching power required to supply the electrical load.

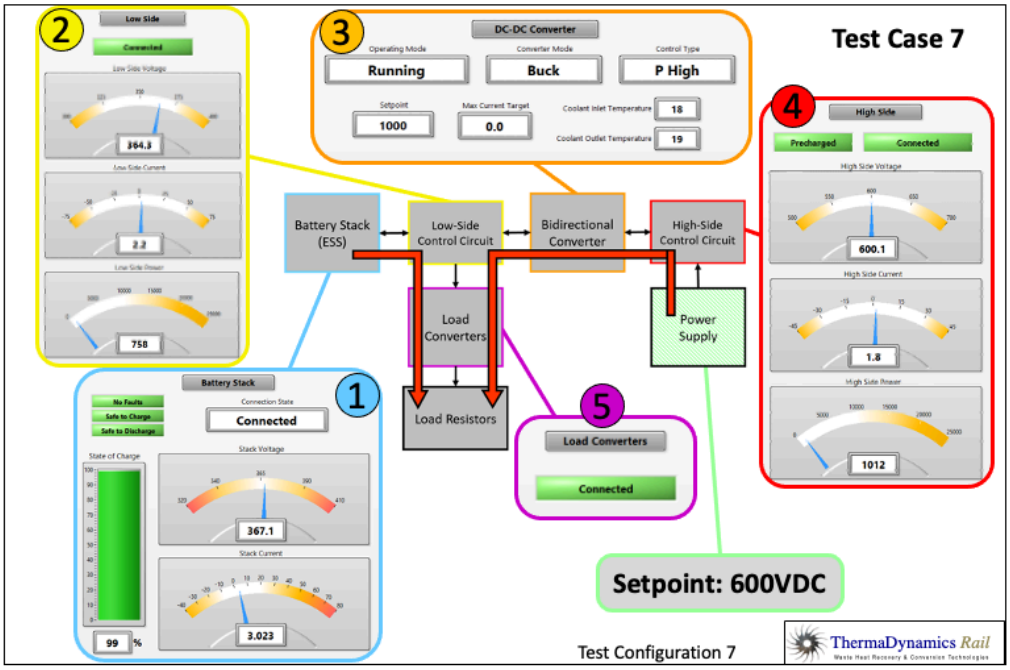


Figure 45. ESS & L-WHRS supply power to the electrical load

In this test scenario, the L-WHRS simulated power supply is set to 600 VDC, provides power through the connected high- and low-side control interfaces (Modules 2 and 4) to the connected load converters (Module 5), and is dissipated in the load resistors.

The converter bucks the voltage to not exceed 1,000 W on the high-side (Module 3), which is verified by the high-side power measurement (Module 4). As these L-WHRS operating conditions do not provide enough power to match the dissipation power of the load resistors, the ESS is connected and supplies the make-up power required by the electrical load(s) and starts discharging the battery stack (as shown by Module 1 displays).

Overall, the seven test cases include all operating condition combinations that can manifest as electric demand at the electric bus and interfaces of the DC microgrid, represented by the L-WHRS, the ESS, and the electrical loads. For the execution of these simulations, and as the CUI and interfaces represented a "first-of-a-kind" power system coupled to an active multi-kW power battery stack, the power rating selected for the validation of multi-directional power flows was kept below 3 kW for safety. As all tests demonstrated reliable control of the interfaces via CUI, the power rating can be increased to maximum ESS discharge power and maximum L-WHRS charging power. Tests at the maximum power rating, with the L-WHRS and interfaces retrofitted on a testing locomotive operated at various operational conditions and environments for extended time durations (e.g., during revenue service operations), are planned for future L-WHRS, ESS, and DC power grid optimization activities.

7. Conclusion

In this project, ThermaDynamics Rail LLC (TDR) integrated the Locomotive-Waste Heat Recovery System (L-WHRS) and interfaced it with an advanced Energy Storage System (ESS) to power selected locomotive electrical loads and demonstrate safe power flows between the onboard DC microgrid formed by the L-WHRS, the ESS, and locomotive interfaces. The ESS was selected with the approval of the Federal Railroad Administration (FRA) and was operated independently of the locomotive original equipment manufacturer (OEM) lead-acid battery.

Battery deep discharges are often induced by locomotive crew operations in combination with the engine shut down induced by the Automatic Engine Stop/Start (AESS) control system. When the locomotive engine is not operational, electrical loads such as the cabin Heating, Ventilation and Air-Conditioning (HVAC), computers, lights and other locomotive hotel loads, normally connected to the lead-acid battery via DC bus, can cause deep-discharging of this component. When the engine is restarted, the lead-acid battery undergoes current surges. Deep discharges combined with fast recharging of these types of batteries results in incremental damage leading to failure of this component, causing costly operational disruptions and premature component replacement. Locomotive electrical loads and their power rating requirements were identified, and the locomotive HVAC unit was selected as a DC electrical load to be supplied by the L-WHRS turbine-generator interface.

As part of this project, the Failure Mode, Effect and Criticality Analysis (FMECA) study conducted in previous research phases was updated to account for modification of the L-WHRS interfacing with the ESS and selected locomotive electrical loads. The FMECA identified the risks associated with the ESS interfaces and included a review of static and dynamic testing of the L-WHRS, with operational data from on-the-road locomotive testing and test data obtained by working with a full-scale locomotive simulator operated at TDR test facilities.

A dedicated Controller and User Interface (CUI) was developed by TDR and coupled to the locomotive simulator to test the power flows between the L-WHRS electrical interfaces when the ESS is charging or discharging and while the L-WHRS and the ESS are also electrically coupled to locomotive electrical loads through a DC power grid. The CUI allowed simulation via testing and validation of various locomotive operational scenarios. The FMECA allowed design modifications to mitigate or eliminate potential challenges to safety due to the inclusion of the ESS components electrically coupled to the L-WHRS and locomotive electric loads.

A total of seven power flow test cases conducted in this research included electrical operational scenarios in which the L-WHRS starts from a condition of zero power generation, generates power, charges the ESS, and supplies power to locomotive electrical loads. The cases also included scenarios in which the power recovered by the L-WHRS is insufficient to fully supply the electrical loads and/or charge the ESS. In these operational cases, the ESS is programmed to supply power to the electrical loads until the locomotive operates at medium-high notch settings, and the L-WHRS generates sufficient power to start charging the ESS.

Through the research activities TDR demonstrated that locomotive waste thermal power recovered and conditioned by the L-WHRS can safely be used to charge an advanced ESS, while simultaneously supplying power to locomotive electrical loads.

7.1 Future Activities

TDR's design philosophy is centered on ensuring non-invasive installation of the various L-WHRS components. This requirement enables fast retrofitting of operating locomotive fleets. However, meeting the non-invasiveness requirement comes at the expense of limited waste heat recovery and conversion efficiencies. As part of future activities, TDR will seek cooperation with engine and locomotive manufacturers to execute true ground-up integration with L-WHRS components so as to further decrease locomotive operating costs via lowered fuel consumption and pollutant emissions, while augmenting the locomotive electric power rating.

The criticality of L-WHRS components with respect to locomotive operations and safety can be further minimized since the components forming the L-WHRS represent a completely independent thermodynamic engine executing a closed-loop Rankine power cycle. The dependencies between various locomotive engine interfaces and the L-WHRS components can be constrained, by design, to solely impact thermal and electrical couplings. Locomotive thermal coupling with the L-WHRS via HiPHEXs can be executed so that failures of these components do not lead to locomotive engine failures, even if the HiPHEXs in future applications become permanently integrated with locomotive equipment (e.g., as part of OEM components). Electrical coupling via L-WHRS turbogenerator-converter-ESS can be executed with redundancies and engineered safety features, as adopted by standard high-power electrical equipment connected to multiple electric suppliers (e.g., the locomotive generator and L-WHRS electric generator working in parallel). TDR will continue to optimize the L-WHRS to obtain higher efficiencies in the conversion of waste thermal energy into conditioned electricity.

The CUI developmental work executed in this research paves the way to transition to a fully integrated L-WHRS power management system that is based on a custom-made electronic processor to support mass production of L-WHRS sized and programmable to retrofit different models of locomotive engines. This will allow the conversion of waste thermal energy from the locomotive exhaust gases at a scalable power rating proportional to the total amount of waste energy recovered, ESS capacity, and the power rating requirements of locomotive electrical loads.

8. References

Filippone, C. (2020). *Reliability and Endurance Testing of Locomotive Waste Heat Recovery System*. Technical Report No. DOT/FRA/ORD-20/23. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Simpson, W. (2018). Chapter 6.2: Waste Heat Energy Recovery. In *Diesel-electric locomotives: How they work, use energy, and can become more efficient and environmentally sustainable.* Simmons-Boardman Books, Inc.

Abbreviations and Acronyms

AFE	Active Front End
AC	Alternate Current
AESS	Automatic Equipment Stop/Start
BMS	Battery Management System
CAN	Controller Area Network
CUI	Controller and User Interface
COVID-19	Corona Virus Disease of 2019
DC	Direct Current
EMI	Electro-Magnetic Interference
ESS	Energy Storage System
FMECA	Failure Mode, Effect, and Criticality Analysis
FRA	Federal Railroad Administration
GE	General Electric
HiPHEX	High-Pressure Heat Exchanger
HP	Horsepower
HVAC	Heating, Ventilation, and Air Conditioning
kb	Kilobit
kWh	Kilowatt-hour
kW	Kilowatt
LFP	Lithium Iron Phosphate ($LiFEPO_4$ compound)
Li-NMC	Lithium Nickel Manganese Cobalt
L-WHRS	Locomotive-Waste Heat Recovery System
NI	National Instrument
ORC	Organic Rankine Cycle
OEM	Original Equipment Manufacturer
P&ID	Piping & Instrumentation Diagram
PLC	Programmable Logic Controller
RPM	Revolution per Minute
SEL	System Electric Load
TDR	ThermaDynamics Rail LLC
VAC	Volts of Alternate Current
VDC	Volts of Direct Current
VRLA	Valve Regulated Lead-Acid
W	Watts