Appendix C

Technical Support Document: Zero Emission Locomotive Conversion

Contents

I. Background

On September 20, 2022, CARB released the Initial Statement of Reasons for the Proposed In-Use Locomotive Regulation, which included a Technology Feasibility Assessment for the Proposed In-Use Locomotive Regulation. The technology feasibility assessment focused on currently available technologies and the state of cleaner locomotive technologies commercially available or under development.

This technical support document examines a related question: conversion of existing (non-new) diesel-electric locomotives to zero emission (ZE) locomotives and ZE capable locomotives. ZE capable locomotives are locomotives that can be operated in a zero emission configuration or operated on a fuel that produces emissions. After examining duty cycle information and options for conversion to zero emission, this report concludes that it is feasible to convert diesel-electric locomotives currently in use to ZE locomotives or ZE capable locomotives. This document analyzes the conversion of diesel-electric locomotives to ZE or ZE capable locomotives by locomotive owners and operators.

There are various ways to convert a diesel-electric locomotive to a ZE locomotive or ZE capable locomotive. For example, the following options are available.

- ZE locomotives or ZE capable locomotives
    - ZE locomotives: Remove the existing diesel engine entirely, thereby intending to use the locomotive only in a zero emission configuration.
    - ZE capable locomotives: Keep the diesel engine and operate the locomotive in some configuration using multiple power sources, alternating between zero emission, diesel emission, or both.
- ZE power source
    - Hydrogen fuel cell, battery-electric, or some combination.
    - Overhead catenary or a third rail.

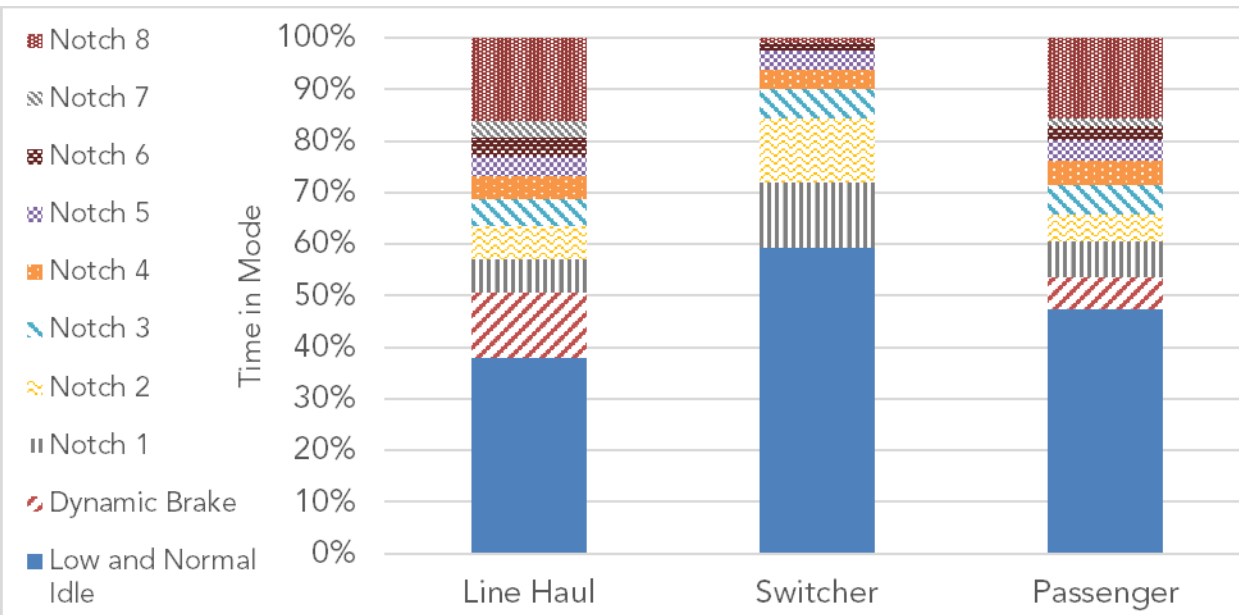
This document is not intended to comprehensively list all possible configurations but is intended to show the fundamentals for selected methods and application examples in locomotives. This document focuses on the removal of the existing diesel engine and is then replaced by a zero emission power source. Staff assess that this option is more difficult than keeping the diesel engines and alternating the power sources between zero emission, diesel emission, or both. This document also does not discuss catenary or third-rail power, because that power option is well-established, well-studied and has been in use for more than 100 years.

II. United States Environmental Protection Agency Duty Cycles for Locomotives

Understanding the duty cycle of the given locomotive is a key first step to determining how best to convert the locomotive to zero emission operation. Locomotive duty cycles are established by evaluation of characteristic operating cycles, by reviewing average activity patterns for locomotive operations.

The operational duty cycles of line haul locomotives are characterized by a longer time in higher power notch settings[1] (i.e., Notches 5-8), when traveling cross country on main rail lines. When line haul locomotives operate within railyards (e.g., to trim railcars to form trains or receive fuel, service, or maintenance), they typically operate in idle or lower power settings (i.e., Notches 1-3). Idle time represents about 40 percent of their line haul operational time. The switcher duty cycle assumes locomotives primarily operate in lower locomotive power notch settings (i.e., Idle-Notch 2) for about 84 percent of the time. Passenger locomotive emission levels are calculated using the line haul duty cycle because of their similarity. However, there are slight differences between the two. Figure 1 and Table 1 show the locomotive duty cycle published by United States Environmental Protection Agency (U.S. EPA).

Figure 1: U.S. EPA locomotive duty cycle of line haul locomotives, switchers, and passenger locomotives shown in average time in mode.



[1] Locomotives are often controlled by eight discrete power settings called "notches." Notch 1 is the lowest power setting, and notch 8 is the highest power setting. In addition, there are idle and dynamic brake settings.

Table 1: U.S. EPA Locomotive duty cycle of line haul locomotives, switchers, and passenger locomotives shown in average time in mode.

Test Mode Percent	Line Haul[2]	Switcher[2]	Passenger[3]
Low and Normal Idle	38%	58.8%	47.4%
Dynamic Brake	12.5%	0%	6.2%
Notch 1	6.5%	12.4%	7.0%
Notch 2	6.5%	12.3%	5.1%
Notch 3	5.2%	5.8%	5.7%
Notch 4	4.4%	3.6%	4.7%
Notch 5	3.8%	3.6%	4.0%
Notch 6	3.9%	1.5%	2.9%
Notch 7	3.0%	0.2%	1.4%
Notch 8	16.2%	0.8%	15.6%
Total	100%	100%	100%

III. Diesel-Electric Locomotive Powertrain

A. Overview

Locomotives are generally equipped with diesel-electric power unit(s) that are specifically designed to meet certain power requirements. Different types of locomotives, line haul, switch, and passenger, may all have different power requirements and can have individualized power requirements.

Power units are often electronically controlled, self-diagnostic diesel engines that are fixed to an alternator with an associated rectifier unit.[4] In older locomotives, diesel engines are fixed to a generator, and in both cases, the output from the power unit is direct current (DC). Figure 2 shows an overview of a diesel-electric locomotive.

[2] 40 CFR 1033.530 Duty cycles and calculations. (weblink: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1033#1033.501). Accessed: January 6, 2023.

[3] U.S. EPA Locomotive Emission Standards: Regulatory Support Document, 1998. (weblink: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100F9QT.PDF?Dockey=P100F9QT.PDF).

[4] A rectifier is a device that converts occulting two-directional alternating current (AC) into a single-directional direct current (DC).

Figure 2: **Overview of a diesel-electric locomotive.**

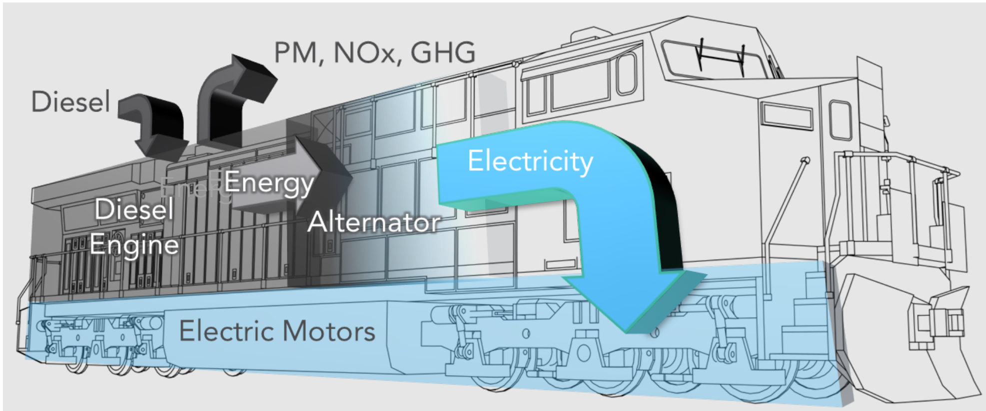
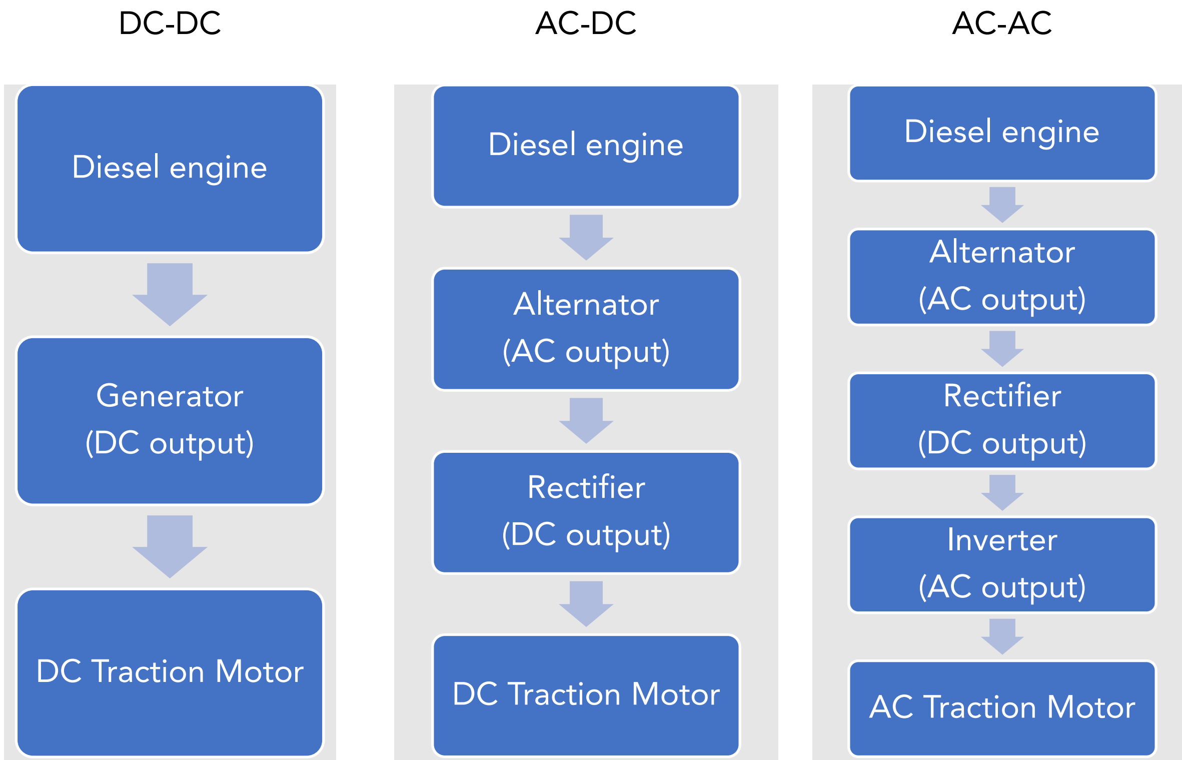


Figure 3 shows different types of diesel-electric locomotive powertrains and some key components. The output from the power unit drives either DC or alternating current (AC) traction motors on each of the locomotive trucks.[5] Because power units supply DC to the traction motors, locomotives using AC traction motors will have inverters that transform DC to AC. At a high level, the power electronics controller transforms the DC or AC from the power unit appropriately to control traction motors. The traction motors convert electrical power to mechanical energy.

[5] "Truck" is a general term that includes the parts that comprise the structures that support a locomotive body and also provide the attachment of wheels and axles. Most locomotives have two trucks.

Figure 3. Different types of diesel-electric locomotive powertrains and key components.



B. Operator Interface

In a conventional diesel-electric locomotive, the operator has eight discrete power settings (called "notches") to control power to the traction motors, in addition to idle and dynamic brake settings. When a locomotive operator sets the power setting to one of the eight notches, various operating parameters of the engine and the generator/alternator are adjusted to supply the traction motor the power demanded for the notch set by the locomotive operator. While modern power electronics are not limited to only eight notch settings, this is still used to enable backwards compatibility between modern locomotives and legacy locomotives for operators.

C. Traction Motor

Locomotives use either DC or AC traction motors, which require either DC or AC power input. DC traction motors are controlled by changing the current applied to them, and AC traction motors are controlled by changing the voltage and frequency of the AC.

Controlling AC motors by changing voltage and frequency was difficult to accomplish without modern electronics. Inverters use microprocessors to transform DC to three-phase AC. As modern microprocessor-based controllers became common, AC traction motors became frequently used in transportation applications such as locomotives and on-road vehicles.

Note that both DC and AC motors have DC at some point between the diesel engine and the motor. DC motors require DC as the input, but AC motors also use DC from a rectifier, followed by an inverter. This is important because batteries and fuel cells provide DC that can be conditioned for either DC or AC traction motors.

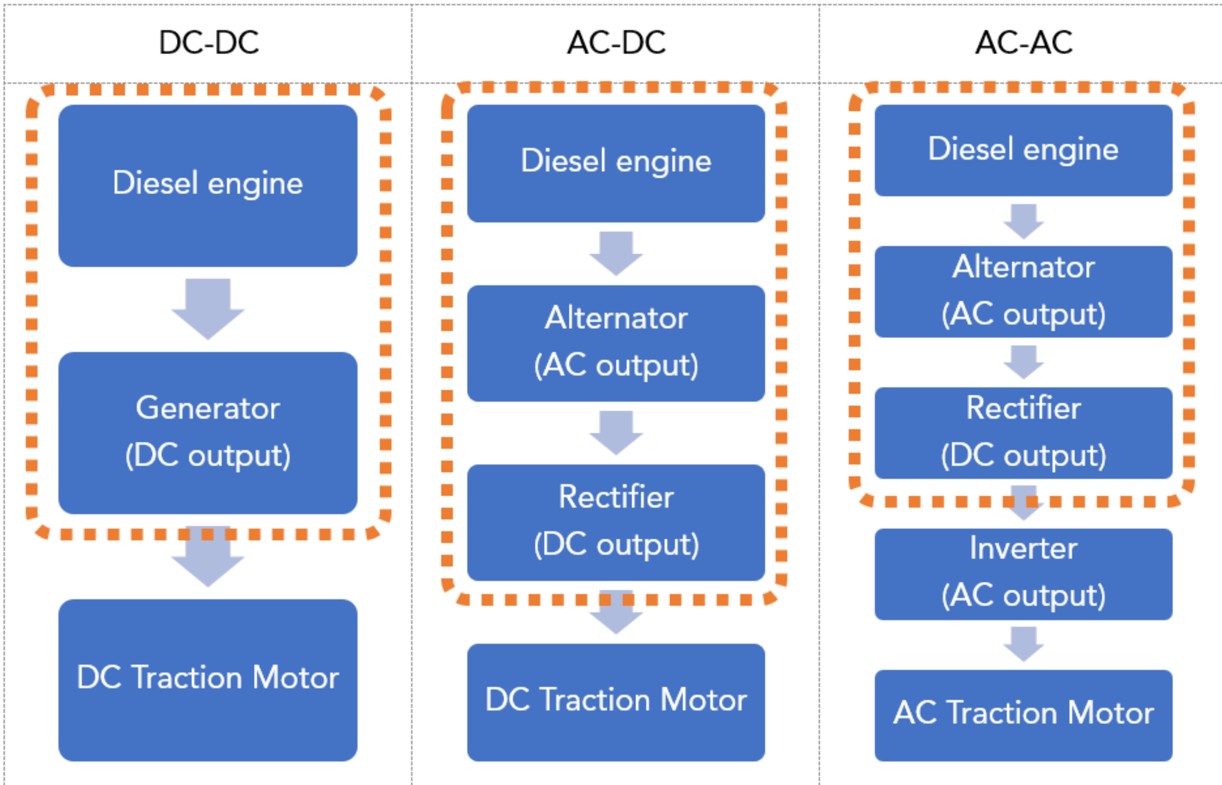
IV. Zero Emission Locomotive Conversion

A. Overview

Zero emission power sources such as fuel cell stacks and batteries produce DC. Diesel-electric locomotives produce DC to power traction motors using a combination of a diesel engine and generator, or a diesel engine, alternator, and rectifier (Figure 4). To convert a diesel-electric locomotive to ZE operation, a ZE power source must be provided, and the diesel engine and generator/alternator must be bypassed. The orange dotted lines in Figure 4 show the components in diesel-electric locomotives that produce the DC that eventually powers traction motors—it is these components that would be bypassed or removed for ZE operation. One option is to “hybridize” the locomotive by making it ZE capable locomotive, using a toggle switch to alternate between the diesel power and the ZE power.

If the intention is to convert a diesel-electric locomotive to ZE-only operation, then the operator could achieve better efficiency by replacing the diesel engine and generator/alternator with a ZE power source, because the diesel engine and generator/alternator would no longer be needed.

Figure 4. Different types of diesel-electric locomotive powertrain, and components that can be replaced by a ZE power source (outlined in orange dotted line).



Once the diesel engine and generator/alternator are bypassed or replaced with a ZE power source, the ZE power source needs to generate power suitable for the locomotive truck. Power electronics controllers transform DC from the ZE power source appropriately to control the traction motors. Control of DC and AC motors using power electronics controllers is common in industrial and transportation applications.

ZE power sources can effectively replace the diesel-electric powertrain when it generates DC voltage and current similar to what the diesel-electric powertrain would have generated at the same notch. This will enable reusing as many components from the original diesel-electric locomotive as possible in the ZE conversion. Depending on the level of retrofit, it may be more effective to replace existing control modules with a modern microprocess-based power electronics controller.

B. How to use a ZE power source for traction motors

The electrical energy flow from the ZE power source to the traction motors is managed by a power electronics controller. Diesel-electric locomotives are also equipped with power electronics controllers to control their DC or AC motors, although the level of sophistication and complexity will vary based on age of the controller.

DC traction motors are controlled by changing voltage and current to the motor, whether the DC comes from a diesel-electric powertrain, a fuel cell system, or batteries. Modern power electronics controllers can control DC motors more efficiently than what may be equipped in the diesel locomotive, and it may be simpler and more advantageous to replace the original power electronics controllers with a new one. However, the original power electronics controllers may be used if the ZE power source was designed to effectively mimic the DC output from the diesel engine and generator.

AC traction motors are controlled by changing voltage and frequency to the motor. It is likely that microprocessor-based power electronics controllers are already used for diesel locomotives with AC traction motors due to complex algorithms to change the voltage and frequency of AC. It is possible that the existing power electronics controller can be either reused or replaced case-by-case depending on factors such as cost and ease of integration.

Microprocessor-based power electronics controllers use methods such as pulse width modulation (PWM) to control both DC and AC motors. Numerous manufacturers worldwide supply motor controllers, such as Siemens, Allen-Bradley, and ABB. In addition, an operator or an engineering firm can program the overall power electronics controllers as evidenced in a fuel cell switcher conversion project announced in 2021. In this project, the University of British Columbia Okanagan School of Engineering (UBCO) will design the control module and integrate it into the locomotive.[6] UBCO also projected that numerous engineering firms will offer services to design control modules for similar projects in the future.

Commercial availability of battery-electric locomotives,[7] a working fuel cell locomotive prototype,[8] and commercial availability of both battery-electric and fuel cell on-road vehicles leave no doubt that modern power electronics controllers can control motors using ZE power sources in transportation applications. In addition, a locomotive owner or operator will have an option to either use one of numerous power electronics controller manufacturers or engineering firms for the design, manufacture and integration, or do the design, manufacture and integration themselves.

C. Battery-Electric

1. Overview

Due to relatively low energy density of batteries compared to diesel or hydrogen, battery tenders connected to a locomotive may be an option to provide longer

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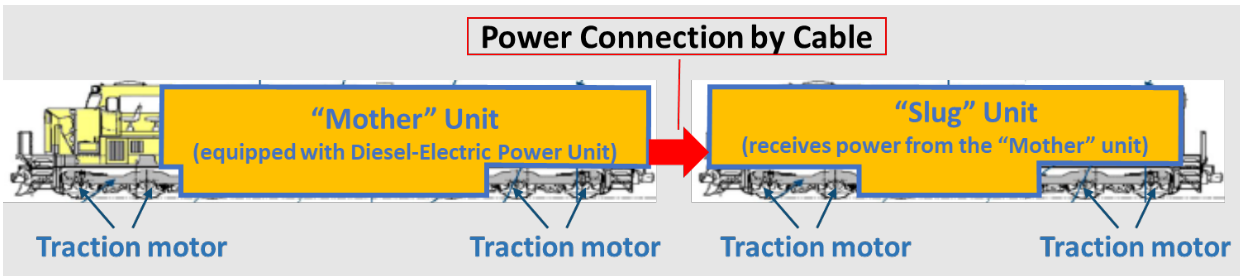
[6] Minutes of the CARB-UBCO Fuel Cell Switcher Conversion Project Discussion, January 10, 2023.

[7] California CORE, Railcar Movers and Switchers (weblink: https://californiacore.org/equipment-category/railcar-movers-switchers/). Accessed: January 25, 2023.

[8] Trains, Canadian Pacific's hydrogen-powered locomotive makes first revenue run, November 15, 2022 (weblink: https://www.trains.com/trn/news-reviews/news-wire/canadian-pacifics-hydrogen-powered-locomotive-makes-first-revenue-run/). Accessed: January 25, 2023.

operational range. Battery tenders are railcars that are filled with batteries. Battery systems can be installed in available railcars without modification. Battery tenders can be connected to locomotives through power cables similar to ones used in a mother-slug configuration. Mother-slug configurations consist of a "mother" unit equipped with diesel-electric powertrain, and a "slug" unit with traction motors but no engine (Figure 5). Diesel-electric power from the mother unit also powers the slug unit connected to it. The mother-slug configuration has been used since the 1940s in applications where a single engine can provide sufficient power, but additional tractive effort is desired to pull heavy loads at slow speed.[9]

Figure 5. Overview of Mother-Slug Configuration.



Many applications may be satisfied with on-board batteries on the locomotive without a battery tender as energy density of batteries continues to increase. For example, the Progress Rail EMD Joule SD70J is commercially available with up to 8.0 megawatt-hours (MWh) of on-board battery capacity.[10]

Lithium-ion, nickel-metal hydride, and lead-acid are some of the most widely used battery chemistries. While lead-acid batteries have been widely used, even in some early battery-electric railcar movers and prototype locomotives, lithium-ion batteries have been more commonly used in recent years due to their greater power and energy density.

In 2013, TransPower, a California company offering energy-related products and services, developed a concept for a fully integrated battery system that would be installed in a standard railcar or tender. In this concept, referred to as the "Rail-Saver," electricity from the 6.2 MWh battery tender would be transmitted via a cable to the locomotive to power the traction motors. TransPower estimated the battery cost to be $3 million in 2015 and $1 million in 2030. Assuming additional $800,000 for the battery subsystem and $1.2 million for the railcar and connections, the battery tender was estimated to cost $3 million in 2030.[11]

[9] Trains, 'Slugs' for extra tractive effort, May 1, 2006. (weblink: https://www.trains.com/trn/train-basics/abcs-of-railroading/slugs/). Accessed: January 12, 2023.
[10] California CORE, EMD Joule SD70J. (weblink: https://californiacore.org/equipment/emd-joule-sd70j/). Accessed: Dec 30, 2022.
[11] CARB, Technology Assessment: Freight Locomotives, November 2016. (weblink: https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf).

Significant advances in battery technologies have occurred in the last 10 years, leading to battery pack cost decreases of approximately 85 percent, reaching $143/kilo-Watt-hour (kWh) in 2020.[12] Volumetric energy density of lithium-ion batteries increased by more than eight times between 2008 and 2020, to 450 Watt-hours per liter.[13]

A 50-foot standard railcar has approximately 5,238 cubic feet capacity.[14] Assuming only 30 percent of capacity is available for batteries due to the battery management system and other necessary components,[15] a 50-foot standard railcar has 1,571 cubic feet capacity for batteries. Using the 450 Watt-hours per liter estimate from above, a standard railcar could still fit 20 MWh of lithium-ion batteries. Using $143/kWh, the 20 MWh battery will cost about $2.86 million. This is similar to the cost estimate from 2013 by TransPower even with over three times the battery capacity. As battery cost falls and their energy density increases, staff estimates that the cost of a battery tender could be around $3–5 million depending on the required battery capacity.

2. Battery Capacity

Required battery capacity for a battery-electric locomotive can be calculated through analyzing its projected operation, such as duty cycle and charging pattern. For example, the battery capacity required for a switcher following the duty cycle shown in Table 1 can be calculated with the following additional assumptions:

- Rated power of the switcher is 2,000 horsepower (hp) (=1,491 kW).[16]
- At each notch, power levels are expressed as a percentage of the rated power as shown in Table 2.

[12] U.S. Department of Energy, Energy Storage Grand Challenge Roadmap, 2020, Page 48. (weblink: https://www.energy.gov/sites/default/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf).

[13] U.S. Department of Energy, FOTW #1234, April 18, 2022: Volumetric Energy Density of Lithium-ion Batteries Increased by More than Eight Times Between 2008 and 2020. (weblink: https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy-density-lithium-ion-batteries). Accessed: January 25, 2023.

[14] CSX, Railroad Equipment. (weblink: https://www.csx.com/index.cfm/customers/resources/equipment/railroad-equipment/). Accessed: December 30, 2022.

[15] Energy density of lithium-ion battery packs was 140 Watt-hours per liter in 2013 (Department of Energy, FOTW #1234, April 18, 2022: Volumetric Energy Density of Lithium-ion Batteries Increased by More than Eight Times Between 2008 and 2020. (weblink: https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy-density-lithium-ion-batteries). Accessed: January 25, 2023). At this density, a 50-foot standard railcar with 5,238 cubic feet can hold about 21 MWh of battery packs. Transpower concept is based on 6.2 MWh battery capacity suggesting that about 30 percent of the available space is used for the battery packs.

[16] Switchers are locomotives with rated power of 2,300 hp or less (40 CFR 1033.901 "Switch locomotive", (weblink: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1033/subpart-J/section-1033.901). Accessed: January 13, 2023. Common switcher models such as GP38 and GP38-2 have rated power of 2,000 hp.

- The switcher operates 16 hours between being fully charged.[17]
- The switcher does not have regenerative braking capability, consequently braking does not charge the batteries.
- A maximum 80 percent of the battery capacity is usable to prevent battery damage from excessive discharging.[18]
- The switcher has a parasitic load of 100 hp (=75 kW) from the air compressor, cooling system, etc.[19]

Table 2. Standard Notch Power Levels Expressed as a Percentage of Rated Power[20]

Notch	Percent
Normal Idle	0.0
Dynamic Brake	0.0
Notch 1	4.5
Notch 2	11.5
Notch 3	23.5
Notch 4	35.0
Notch 5	48.5
Notch 6	64.0
Notch 7	85.0
Notch 8	100.0

Combining the switcher duty cycle from Table 1 and the power levels from Table 2, the switcher operates at 8.3 percent of its rated power, or on average 165 hp (=123 kW). Adding the parasitic load of 100 hp (=75 kW), the switcher operates at 265 hp (=198 kW) power on average. During its 16-hour shift, it uses 3.2 MWh of energy that requires 4 MWh battery capacity to limit the maximum discharge to 80 percent.

In 2022, battery-electric locomotives with battery capacity up to 8 MWh are commercially available.[21] The above example analysis shows that battery-electric locomotives could meet a representative 16-hour duty cycle of a switcher between being fully recharged. As battery capacities continue to increase, battery-electric locomotives may be able to move beyond switcher duties in railyards to operating in

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[17] Staff assumption for a representative switcher working two shifts per day, with up to 8 hours for recharging.
[18] Massachusetts Institute of Technology, Lithium Ion Battery Safety Guidance, Page 13, March 2017. (weblink: https://ehs.mit.edu/wp-content/uploads/2019/09/Lithium_Battery_Safety_Guidance.pdf).
[19] Staff estimate based on off-the-shelf air compressor for locomotives. (Wabtec, 3CW Compressor. (weblink: https://www.wabteccorp.com/locomotive/air-generation-and-treatment/compressors) Accessed: January 13, 2023.
[20] 40 CFR 1033.530 Duty cycles and calculations. (weblink: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1033#1033.501). Accessed: January 6, 2023.
[21] California CORE, EMD Joule SD70J. (weblink: https://californiacore.org/equipment/emd-joule-sd70j/). Accessed: Dec 30, 2022.

short regional line haul operations. A hybridization approach, in which the diesel engine is kept in the locomotive and augmented by a battery tender car along with regenerative braking, would be a viable option for longer line-haul operations in the near term.

D. Fuel Cell

1. Overview

Fuel cell systems are widely used technology in stationary as well as transportation applications. Various types of fuel cell exist depending on the fuel and structure. However, the most used fuel cell type in transportation applications is a hydrogen PEM (proton-exchange membrane, or polymer electrolyte membrane) fuel cell. A single fuel cell produces less than one volt, which is insufficient for most applications. Individual fuel cells are typically combined in series into a fuel cell stack.[22]

Just like diesel engines that are manufactured by specialized manufacturers even when integrated into custom equipment, staff projects that fuel cell systems will be manufactured by specialized manufacturers for use in locomotives. The fuel cell system manufacturers will provide fuel cell stacks as well as auxiliary components.

In 2022, numerous fuel cell manufacturers exist, such as Ballard, Plug Power, Fuel Cell Energy, etc. Fuel cell systems have been integrated into locomotives. For example, Sierra Northern Railway is integrating two Ballard FCmove-HD+ modules into a switcher demonstration project funded by a California Energy Commission grant. The FCmove-HD+ module is one fuel cell module Ballard offers for transportation applications,[23] and these fuel cell modules have been utilized in locomotive retrofit projects in the U.S., Europe, and China.[24] Canadian Pacific, a Class I railroad, is converting three locomotives to fuel cell locomotives, each using up to six Ballard fuel cell modules.[25]

2. Hydrogen Capacity

Compared to battery technology, more energy can be stored as hydrogen with the same volume and mass. Hydrogen has a gravimetric energy density of 120 megajoules

[22] U.S. Department of Energy, Fuel Cell Systems. (weblink: https://www.energy.gov/eere/fuelcells/fuel-cell-systems). Accessed: January 24, 2023.
[23] Ballard, Heavy Duty Modules. (weblink: https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/motive-modules). Accessed: January 5, 2023.
[24] Ballard, Powering the Future of Rail with Hydrogen, March 2021 (weblink: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Finfo.ballard.com%2Fhubfs%2FReports%2FBallard_Rail_Presentation_-_Heavy_Duty_Motive_modules.pptx). Accessed: January 11, 2023
[25] Canadian Pacific, Hydrogen Locomotive Program, Biogas West 2022.

per kilogram (MJ/kg), and liquid hydrogen has a volumetric energy density of 8 (megajoules per liter) (MJ/L).[26]

Compressed hydrogen tanks are used in commercial light duty vehicles such as the Toyota Mirai and Honda Clarity, as well as in some Class 8 truck demonstration projects. In the Sierra Northern Railway project, the hydrogen tanks are an existing product from Hexagon Purus.[27] The project is using compressed hydrogen tanks to carry 222 kilograms (kg) of gaseous hydrogen, equivalent to 7.4 MWh of energy. Assuming the fuel cell has 60 percent energy efficiency,[28] 4.4 MWh is available for the locomotive to use between refueling. As shown in Chapter IV.C.2. Battery Capacity of this document, 4.4 MWh is enough to meet the representative 16-hour duty cycle of a switcher.

Hydrogen fuel tenders are railcars carrying hydrogen connected to locomotives to provide the locomotives fuel in addition to the on-board locomotive fuel storage. The hydrogen fuel tenders enable fuel cell locomotives to operate in line haul applications by extending operation range between refueling. Cryogenic liquid hydrogen may be a preferred solution for applications requiring fast refueling time and higher volumetric energy density, such as line haul locomotive application. Cryogenic liquids can be transported by rail, and specifications for cryogenic liquid tank cars already exists.[29] One Class III railroad in Florida operates liquid natural gas (LNG) locomotives with a container style LNG fuel tender connected to them.[30] Based on the design and the overall size, an LNG tender has a capacity of 11,000 to 28,000 gallons.[31] If liquid hydrogen tenders have a similar capacity and carry 11,000 to 28,000 gallons, they can carry around 2,800 to 7,100 kg of hydrogen. Fuel cell locomotives have 30 percent or higher efficiency than diesel-electric locomotives.[32] One hydrogen tender can provide

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[26] U.S. Department of Energy, Hydrogen Storage. (weblink: https://www.energy.gov/eere/fuelcells/hydrogen-storage). Accessed: January 4, 2023.

[27] Institute of Gas Technology dba Gas Technology Institute, Sierra Northern Hydrogen Locomotive Project, California Energy Commission GFO-20-604 Hydrogen Fuel Cell Demonstrations in Rail and Marine Applications at Ports (H2RAM), October 8, 2020.

[28] U.S. Department of Energy, Fuel Cells. (weblink: https://www.energy.gov/eere/fuelcells/fuel-cells). Accessed: January 11, 2023

[29] Title 49, Code of Federal Regulations, Subpart F - Specification for Cryogenic Liquid Tank Car Tanks and Seamless Steel Tanks (Classes DOT-113 and 107A). (weblink: https://www.govinfo.gov/content/pkg/CFR-2011-title49-vol3/pdf/CFR-2011-title49-vol3-part179-subpartF.pdf).

[30] Chart Industries, LNG on the Rails- Precursor to LH2 on the Rails? 2018. (weblink: https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-nason-larson.pdf).

[31] Chart Industries, DOT-113 Tank Cars for LNG, September 20, 2021. (weblink: https://www.nationalacademies.org/documents/embed/link/LF2255DA3DD1C41C0A42D3BEF0989ACAECE3053A6A9B/file/D5ED320EE9C57511EA8CA605804C041648401B9B1E04).

[32] R. K. Ahluwalia, D. Papadias, and X. Wang, Rail and Maritime Metrics, U.S. DOE Hydrogen and Fuel Cells Program 2020 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., May 19-21, 2020. (weblink: https://www.hydrogen.energy.gov/pdfs/review20/ta034_ahluwalia_2020_o.pdf).

operation range equivalent to about 3,300 to 8,300 gallons of diesel.[33] A typical fuel tank capacity of a line haul locomotive is 5,000 gallons, so a single fuel tender can provide enough operational range equivalent to a conventional diesel line haul locomotive. Staff estimates a hydrogen tender cost to be approximately $1 million.[34]

3. Fuel Cell Power

Typical switcher locomotives have diesel engines rated around 2,000 to 2,300 hp (=1.5 to 1.7 MW), and line haul locomotives have diesel engines rated around 4,000 to 4,400 hp (=3.0 to 3.3 MW). These rated powers represent peak power of the engines, and fuel cell systems in transportation applications achieve the equivalent power with battery augmentation.

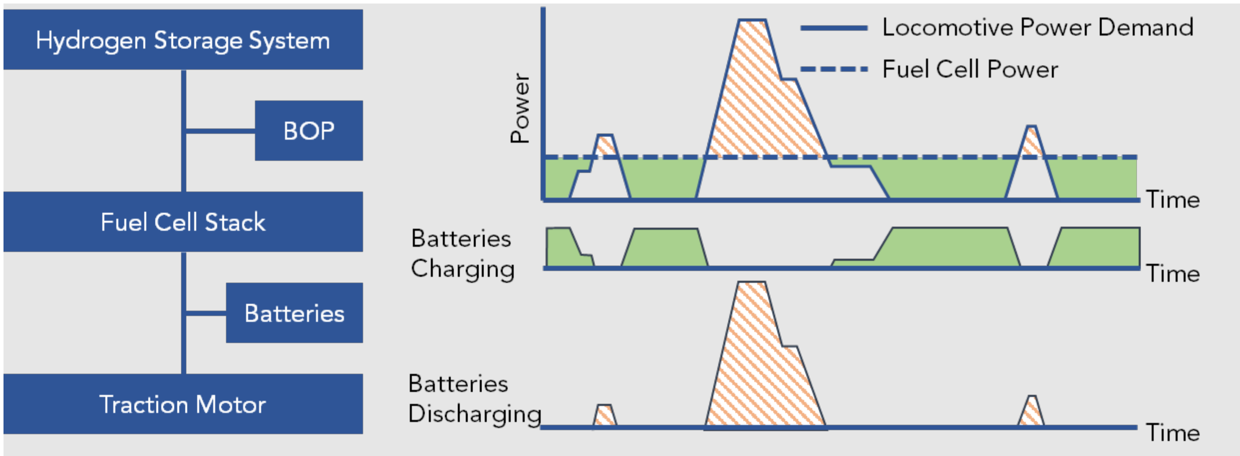
Fuel cell systems in transportation applications are almost always augmented with batteries, making them fuel cell battery hybrid systems. Hybridization has two advantages for transportation applications. One, a fuel cell system can meet the application with a fuel cell stack with lower rated power than the peak power demand. Two, hybridization also allows the operator to respond to power demand faster, because batteries have faster response time than fuel cell stacks.

Figure 6 shows how fuel cell battery hybrid systems use a low power fuel cell stack to meet the base load of the application and keep the battery charged, while the batteries provide peak power. The fuel cell stack meets average power demand (dotted line), and batteries are used to meet power demands exceeding what the fuel cell stack can provide (orange hashed region). The fuel cell charges the batteries when the power demand is lower than its power output (solid green region). The fuel cell battery hybrid systems diagram shows the storage system, fuel cell stack, batteries, and balance of plant (BOP). The BOP is group of auxiliary components that support the system, such as air blowers, humidifiers, and thermal management systems.

[33] U.S. Department of Energy, Alternative Fuels Data Center Fuel Properties Comparison. (weblink: https://afdc.energy.gov/files/u/publication/fuel_comparison_chart.pdf). Accessed: January 4, 2023

[34] CARB, Proposed In-Use Locomotive Regulation Standardized Regulatory Impact Assessment (SRIA), May 26, 2022. (weblink: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appb.pdf).

Figure 6. An overview of a fuel cell battery hybrid system (left), and how batteries are used to meet peak power demands (right).



As described in Chapter IV.C.2. Battery Capacity, the average power of a switcher duty cycle is 8.3 percent of the rated power. Using the same method as described in Chapter IV.C.2. Battery Capacity, the average power of a line haul duty cycle is 27 percent of the rated power and the average power of a passenger duty cycle is 24 percent of the rated power. With battery augmentation, fuel cell systems can potentially meet all locomotive duty cycles with fuel cell stacks with rated power less than 30 percent of the diesel engine they are replacing. Batteries provide additional power for the peak power output of the system, such as going uphill, during acceleration, or pulling heavy loads. Analyzing the duty cycle intended for the locomotive will determine required power of the fuel cell stacks and battery capacity. In general, higher average power will require fuel cell stacks with higher power, and continuous operation at high power will require larger battery capacity. Whereas, low average power and infrequent high-power operation lasting only short periods, which is a typical switcher duty cycle, can be completed with low power fuel stacks and small battery capacity.

The Sierra Northern Railway fuel cell switcher project uses fuel cell modules with a total rated power output of 200 kW (=268 hp), and Canadian Pacific fuel cell line haul locomotive projects uses fuel cell modules with a total rated power output of 1.2 MW (=1,609 hp). With battery augmentation, these fuel cell locomotive projects replace diesel engines that have 2 to 8 times higher rated power.

In 2019, heavy duty vehicle fuel cell technology was estimated to cost $190/kW at 1,000 units per year manufacturing volume.[35] For a switcher using 200 kW fuel cell modules with 500 kWh battery capacity, staff estimates the cost of the system to be $109,500.[36] While duty cycle analyses can determine appropriate fuel cell module

[35] U.S. Department of Energy, DOE H2 Heavy Duty Truck Targets, January 21, 2020. (weblink: https://www.energy.gov/sites/prod/files/2020/02/f71/fcto-compressed-gas-storage-workshop-2020-adams.pdf).

[36] The battery costs $71,500 assuming $143/kWh, consistent with Chapter IV.C. Battery-Electric.

power and battery capacity, staff assumes the cost of the system for a line haul locomotive to be about six times greater than the switcher. This is based on the average power of the line haul duty cycle being about six times greater than the average power of the switcher duty cycle, and the Canadian Pacific fuel cell line haul locomotive project using a fuel cell system six times larger than the Sierra Northern Railway fuel cell switcher project.[37] Based on this assumption, the cost of the fuel cell battery hybrid system for a line haul locomotive is estimated to be $657,000. In the Standardized Regulatory Impact Assessment published on September 20, 2022, with the Initial Statement of Reasons, staff estimated a new fuel cell line haul locomotive will cost $4.25 million whereas a diesel-electric locomotive costs $3.1 million.[38] This suggests that a fuel cell conversion may be accomplished with less cost than purchasing a new fuel cell locomotive.

E. Locomotives with Multiple Power Sources

A ZE powertrain can be added to a conventional diesel-electric locomotive to allow it to operate using either the diesel-electric powertrain or the ZE powertrain based on operator needs. The structure of a multiple power source locomotive will share similarities with a conventional diesel-electric locomotive, a battery-electric locomotive, and a fuel cell locomotive. Figure 7 shows, at a high level, two potential structures of a hybrid locomotive. In the structure shown on the left, batteries power the traction motors and an additional power source keeps the batteries charged. This configuration adds batteries to a diesel-electric locomotive with an optional fuel cell to charge the batteries. In the structure shown on the right, the diesel engine and generator/alternator configuration is identical to a conventional locomotive, and either batteries or a fuel cell system are connected in parallel to the existing diesel-electric power source. In both cases, ZE operation is achieved by shutting off the diesel engine, and powering the traction motor with batteries that are charged by an optional fuel cell system. With a modern microprocessor-based power electronics controller, switching between two power sources will be feasible. Concepts developed by TransPower in 2013 included options to operate solely on batteries or operate using the diesel engine, as well as the potential of adding a fuel cell system to extend the battery range.[39]

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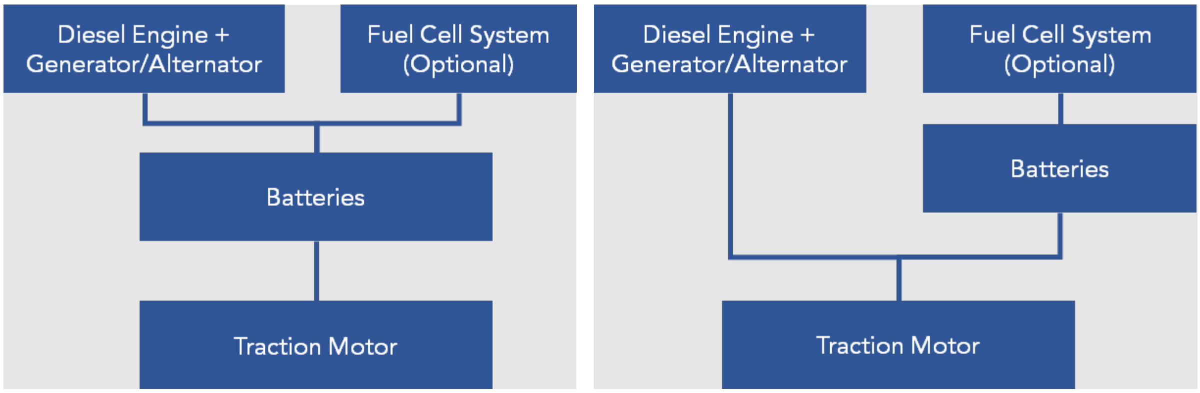
[37] The average power of a 4,400 hp locomotive using the U.S. EPA line haul duty cycle is 1,183 hp. This is 6.2 times the average power of a 2,300 hp locomotive using the U.S. EPA switcher duty cycle (190 hp). This is also consistent with on-going projects where a switcher uses a 200 kW fuel cell system (Sierra Northern Railway Switcher Project) and a line haul locomotive uses a 1,200 kW fuel cell system (CP project). Battery capacity is assumed to be proportional to the fuel cell power.

[38] CARB, Proposed In-Use Locomotive Regulation Standardized Regulatory Impact Assessment (SRIA), May 26, 2022. (weblink: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appb.pdf).

[39] Rail-Saver Zero-Emission Locomotive Technology, Response to South Coast Air Quality Management District Request for Information Zero- And Near-Zero Emission Locomotive Technologies RFI# 2012-01, TransPower.

Figure 7. Two potential high-level structure of a locomotive with multiple power sources.



V. ZE Conversion Examples

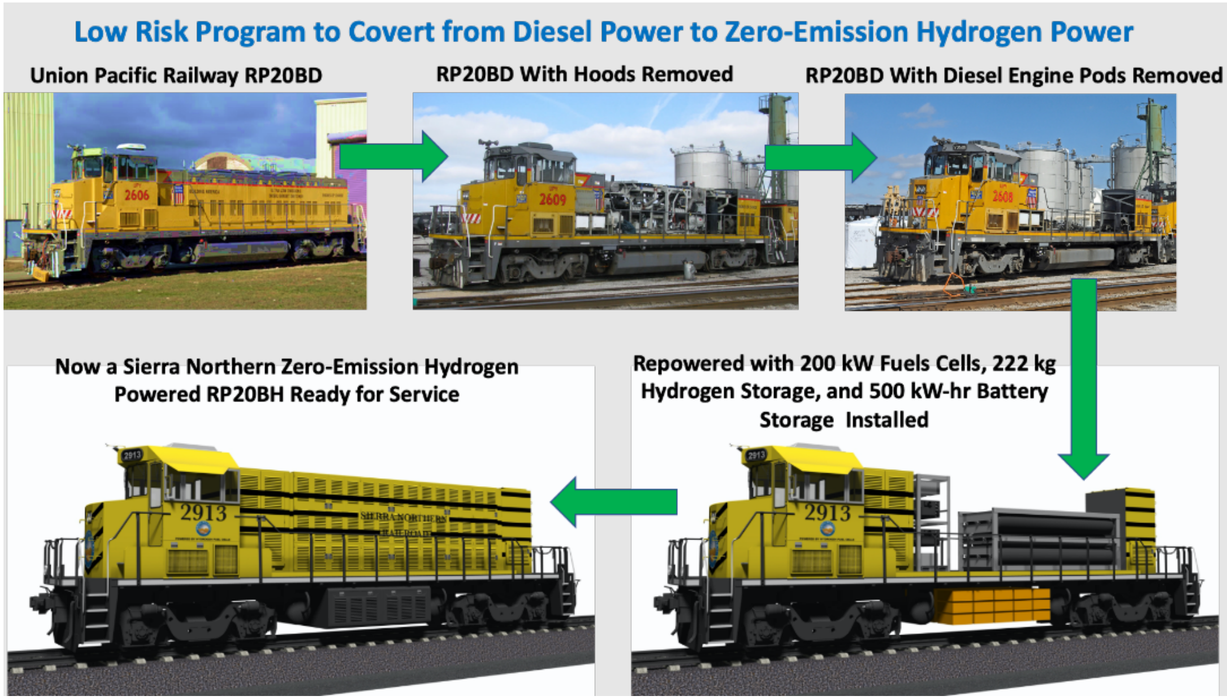
A. Gas Technology Institute (GTI) Hydrogen Fuel Cell Switcher Locomotive

In 2020, California Energy Commission awarded Gas Technology Institute (GTI) $4 million to repower an existing RP20BD with a hydrogen fuel cell powertrain. Following is an overview of the GTI Hydrogen Fuel Cell Switcher Project Narrative.[40]

GTI and Sierra Northern Railway partnered with a diverse team of locomotive and hydrogen experts including Railpower, OptiFuel, Ballard, UC Davis, Frontier Energy, and Valley Vision for this project. This project would involve integration of hydrogen storage, an advanced hydrogen fuel cell, advanced battery, and systems control to convert a diesel-powered locomotive to a hydrogen fuel cell locomotive. Figure 8 shows the overall approach of the repower project.

[40] Institute of Gas Technology dba Gas Technology Institute, Sierra Northern Hydrogen Locomotive Project, California Energy Commission GFO-20-604 Hydrogen Fuel Cell Demonstrations in Rail and Marine Applications at Ports (H2RAM), October 8, 2020.

Figure 8. GTI fuel cell switcher project overall approach.



As stated by GTI in the proposal, conversion of a diesel-powered switcher locomotive to a hydrogen-battery switcher locomotive would be "relatively straight forward." In a diesel-powered locomotive, the diesel engine is connected to a generator that produces DC power and directs it into a DC bus bar. Then the DC bus bar is utilized to power the traction motors, brakes, blowers, lights, and other auxiliary systems. In a hydrogen-battery locomotive, the hydrogen fuel cells are employed to produce the DC power directly from the hydrogen. This produced DC power is then directed into the DC bus bar to provide power for the traction motors and auxiliary systems. A portion of the power produced by the fuel cells is also directed into the battery modules, which support the DC bus bar during peaks (e.g., when high power is needed during short time periods). The fuel cell modules for the switcher locomotive will be Ballard's 7th generation modules that are already used in around 100 fuel cell electric buses operated in the U.S. and Europe. The hydrogen tanks are an existing product from Hexagon Purus. K2 Energy Solutions, a well-established company founded in 2006 to design and manufacture battery systems, will provide the locomotive batteries for this project.

B. Ballard Fuel Cell System Development for Freight Transport Applications

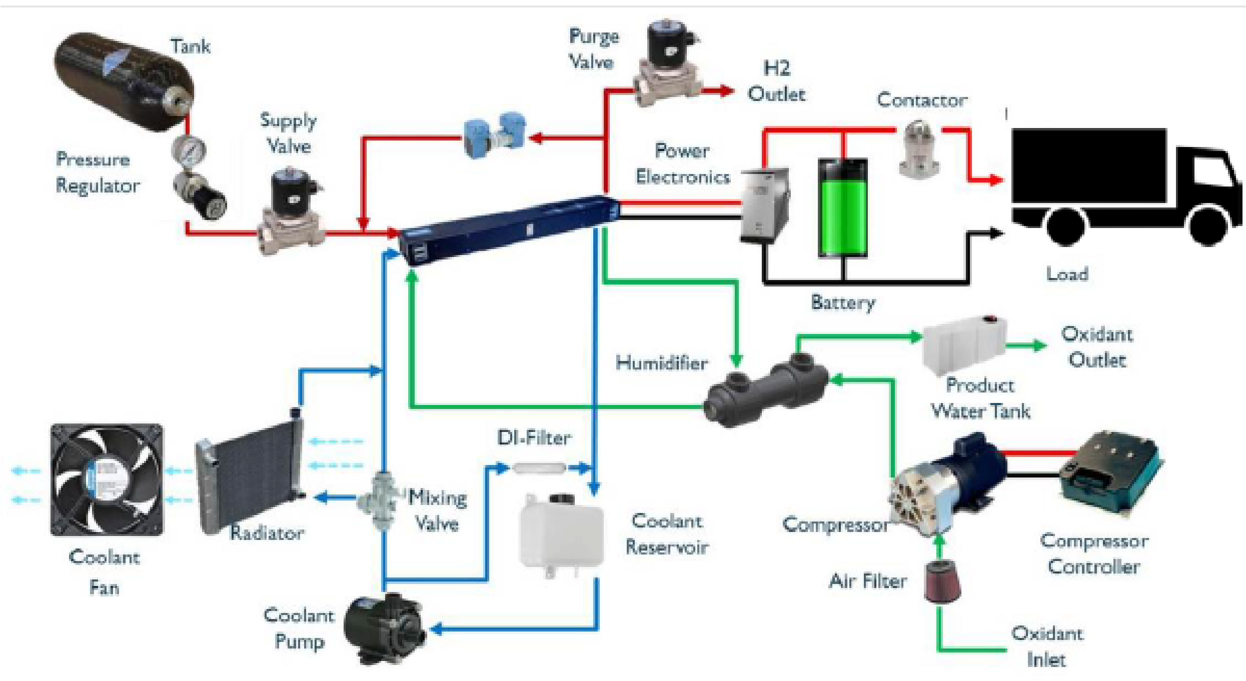
The following is an overview of the Fuel Cell System Development for Freight Transport Applications published by Ballard in 2016.[41]

[41] Ballard, "Fuel Cell System Development for Freight Transport Applications," August 2016.

Ballard, a well-established company, supplied over 10,000 fuel cell stacks to be used in electric lift trucks as of August 2016. Although locomotives are characterized by a higher power and energy requirements, the principles of design, technical knowledge, and implementation developed by Ballard could be modified and customized for fuel cell locomotives as well.

Since the equipment in freight transport applications are constantly starting/stopping and follow a non-uniform duty cycle and usage profile, Ballard recommends using a "hybrid" fuel cell system to meet the usage profile for these applications. In a hybrid fuel cell system, the fuel cell stack and battery are connected in series, and the stacks provide power to the system while the batteries meet the transients and peaks in the usage profile. For the OEMs that are interested in introducing fuel cell-powered freight equipment, Ballard offers the commercially available FCveloCity motive modules with a net power range of 30-200 kW. The FCveloCity motive modules include liquid-cooled FCveloCity -9SSL fuel cell stacks, which makes for straightforward and drop-in integration into the final product. Figure 9 shows the schematics of a typical FCveloCity -9SSL liquid-cooled system.

Figure 9. Schematics of a typical FCveloCity -9SSL hybrid fuel cell system.



C. Rail Propulsion Systems (RPS) Battery Switcher Locomotive

Following is an overview of the Rail Propulsion Systems (RPS) Battery Switcher Locomotive Final Project Report published in 2021.[42]

[42] Rail Propulsion Systems, "Simple Battery Switcher Battery Locomotive Final Project Report," South Coast Air Quality Management District Contract No. 181513, July 2021.

RPS, through a contract with the South Coast Air Quality Management District (SCAQMD) assessed and demonstrated design and implementation of a battery electric system, power electronics, and other pertinent subsystems required for conversion of a diesel fueled switcher locomotive to a battery-electric switcher locomotive. RPS completed the design of this project and transitioned to manufacturing phase in early 2019. The integration of the battery system and other subsystems onto the test locomotive was completed in 2020. Following some initial tests pulling up to five railcars in the railyard, the test locomotive, named "Simple Battery Switcher" or "1201", experienced some operational issues resulting in damages to the power electronics in a test with the presence of SCAQMD in December 2020. However, RPS was able to repair the damage, find the root cause of failure, and apply software changes to address this issue. Lastly, RPS successfully completed the performance testing in the railyard in February 2021. The "1201" locomotive ultimately met the performance requirements of this contract with SCAQMD.

The on-site operators chose not to keep this test locomotive in operation, stating that this test locomotive was not adequate for the daily in-use switcher operation due to the simplistic locomotive control system, and the air compressor system not having sufficient capacity for trainline braking operations. None of these issues call into question the underlying battery technology used in the "1201." RPS could redesign and upgrade the "1201" locomotive to address these issues, which would require additional funds beyond the scope of this project.

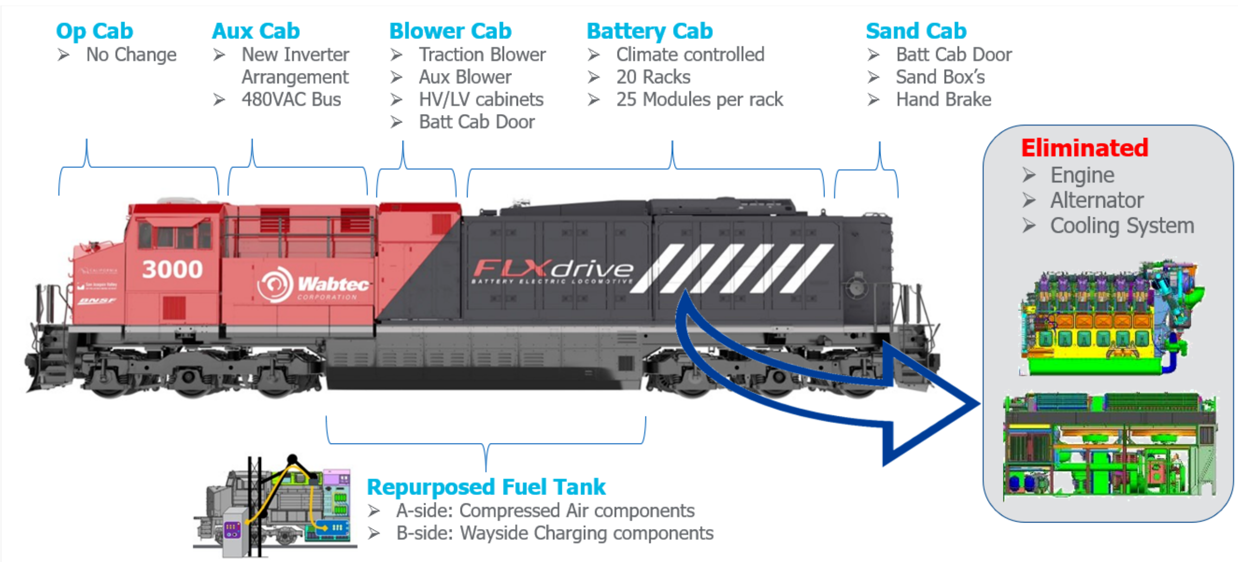
The base locomotive employed as the core for the "1201" locomotive was from the MK1200G locomotives built in 1995. These locomotives were upgraded with a new cab system and an electric air compressor system to provide the necessary platform for replacing the original engine and generator with the battery pack and power electronics. The battery pack was designed to have a usable capacity of 300 kW-hr which is equivalent to the energy generated by consuming 20 gallons of diesel fuel. This capacity would give the battery-electric switcher the energy to pull up to 10 railcars each weighing up to 260,000 lbs. in the daily switcher operation.

RPS employed existing "second life batteries" from EV Grid for economic reasons and to assess usability of these batteries for locomotive applications. Battery modules were equipped to monitor the voltage and temperature. The battery system utilized a closed-loop air circulation system to manage and control the temperature of all the batteries. Regarding the power electronics, the "1201" locomotive possessed two major traction drive modules to control the power flow to the pair of switcher's traction motors. These modules were controlled by a microprocessor control system using the National Instruments Single Board Rio, an off-the-shelf programmable computer built for industrial applications. RPS also replaced the traction motor blower that was originally driven by the diesel engine to provide cooling air while operating at high currents with a new blower system. The new blower system employed a 20-hp AC induction motor, a Chicago Blower Series 62 size 182 centrifugal blower kit, and a Vacon inverter configured to be driven by DC power from the main battery.

D. Wabtec Battery-Electric Locomotive

From 2019 to 2021, Wabtec designed and manufactured a battery-electric line haul locomotive that operated with two diesel-electric locomotives. Figure 10 shows the system changes made to convert an existing locomotive to the battery-electric locomotive.[43] CARB awarded a $22.6 million grant, and a portion of the grant was used to design, manufacture, and commission the battery-electric line haul locomotive.[44]

Figure 10. System changes made to Wabtec Battery-electric locomotive.



E. University of British Columbia Fuel Cell Switcher

In 2021, Loop Energy, a developer and manufacturer of hydrogen fuel cell-based solutions, and Hydrogen In Motion (H2M), a provider of hydrogen storage, announced their plans to collaborate on converting a Southern Railway of BC diesel-electric switcher to a hydrogen electric switcher.[45] The converted switcher will use two 50 kW eFlow fuel cell systems from Loop Energy. The University of British Columbia Okanagan School of Engineering (UBCO) will design the control modules, and they projected that numerous engineering firms will offer services to design control modules for similar projects in the future. The goal of the UBCO is to modularize the fuel cell retrofit kit with a target cost of $1 million.[46]

[43] BNSF Railway, Flexible Solutions for Freight Facilities Final Report, August 15, 2021.
[44] California Climate Investments, Demonstrating Emissions-Reducing Solutions for the Freight Sector. (weblink: https://www.caclimateinvestments.ca.gov/2022-profiles/zanzeff). Accessed: January 25, 2023.
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[46] Minutes of the CARB-UBCO Fuel Cell Switcher Conversion Project Discussion, January 10, 2023.

VI. Conclusion

Locomotives in the U.S. are almost exclusively diesel-electric locomotives, where the diesel engine generates electricity that in turn powers traction motors. To convert a diesel-electric locomotive to ZE operation, only the diesel engine and the generator/alternator need to be bypassed or replaced with a ZE power source, because the traction motors are already powered by electricity. Locomotives use either DC or AC traction motors. Controlling of either motor type with a modern power electronics controller is commonly done in both transportation and stationary applications. Numerous specialized companies offer batteries, fuel cells, and power electronics controllers that an operator may use to convert a non-new diesel-electric locomotive to ZE operation. While individual locomotives have specific duty cycles, using the representative locomotive duty cycles published by the U.S. EPA, staff showed that it is feasible for both battery-electric and fuel cell technology to be used as hybrid power along with diesel or to replace the diesel engine entirely in diesel-electric locomotives.

This document was developed to provide an initial overview of the ZE conversion process, ZE conversion projects, and demonstrate the feasibility. Future ZE conversion projects may use different approaches and may use different processes and technologies. Technical details have been simplified to portray the principles and the feasibility of ZE conversion at a high level. The Proposed Regulation includes two assessments of the progress made in ZE technologies for use with freight line haul, switch, industrial, and passenger locomotives and ZE locomotive conversions will be further evaluated at that time.

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