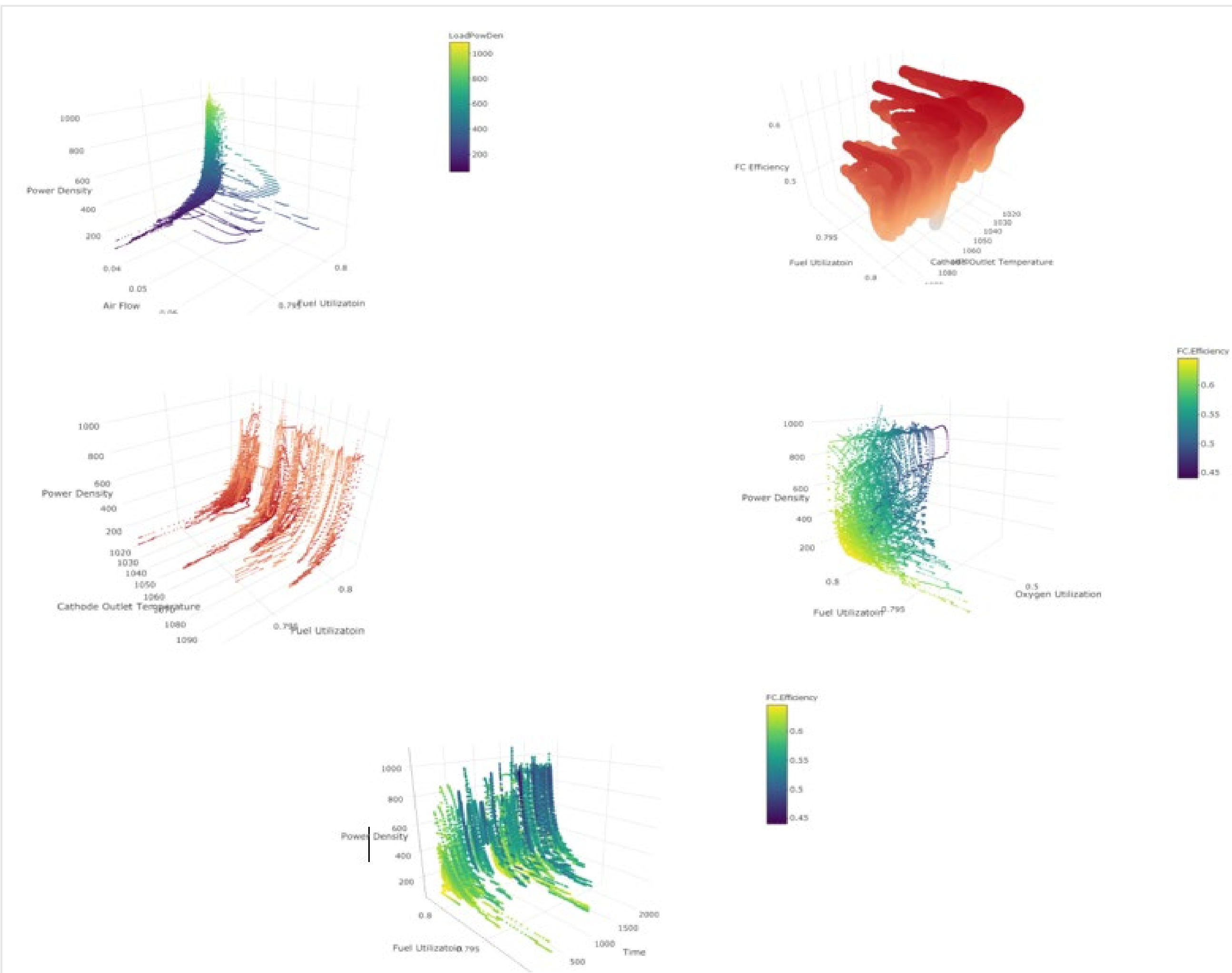
U.S. Department of Transportation

Federal Railroad Administration

Prototype Design and Evaluation of Hybrid Solid Oxide Fuel Cell Gas Turbine Systems for Use in Locomotives

Office of Research, Development and Technology
Washington, DC 20590



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13. ABSTRACT (Maximum 200 words)

Hybrid solid oxide fuel cell-gas turbine (SOFC-GT) systems are among the most efficient and lowest emitting power generation systems conceived for use in locomotives. Their superiority was proven in stationary power applications with near-zero (natural gas operation) to zero (hydrogen operation) pollutant emissions. However, the feasibility and dynamic operation of these systems for use in locomotives has not been extensively investigated. In this report, a new system based on existing National Fuel Cell Research Center (NFCRC) control methods was developed by NFCRC at the University of California, Irvine (UCI) for these types of systems. These control strategies enable the hybrid SOFC-GT system for locomotive engines to follow dynamic power demands while keeping all of the components and system operating variables within acceptable limits of performance under fuel utilizations between 75 and 80 percent. A detailed economic analysis of potential SOFC-GT locomotive production and operation costs in comparison to other low pollutant emitting alternatives (e.g., diesel-electric, battery electric, catenary-electric) was accomplished. The economic analyses show that SOFC-GT systems are likely to cost more and lead to higher costs for delivering goods per ton-mile than the diesel-electric alternative which has higher emissions. SOFC-GT locomotives are likely to produce lower operating costs compared to the catenary-electric alternative, and significantly lower operating costs compared to the battery-electric alternative.

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Solid oxide fuel cell-gas turbine, SOFC-GT, hybrid fuel cell system, National Fuel Cell Research Center, NFCRC, fuel cell, gas turbine, prototype design, locomotive engine

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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)

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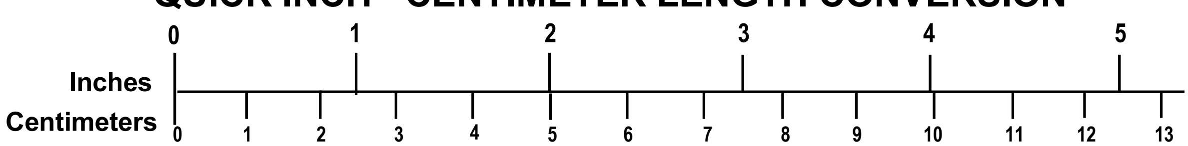
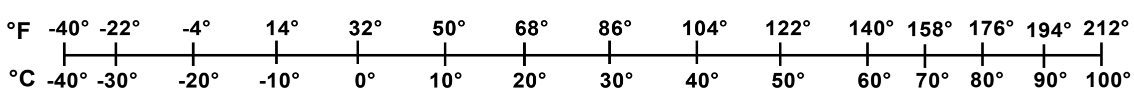


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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

The National Fuel Cell Research Center (NFCRC) at the University of California, Irvine (UCI) developed a 500-kW dynamic computer model of a hybrid fuel cell gas turbine (FC-GT) system component for locomotive engine applications. The researchers demonstrated that the C-200 Capstone® micro gas turbine integrated into a 500-kW hybrid solid oxide fuel cell-gas turbine (SOFC-GT) system is a viable option for locomotive applications. UCI performed the research with funding from the Federal Railroad Administration (FRA) between September 7, 2016, and December 31, 2017. NFCRC identified partners for the development of a prototype SOFC-GT locomotive power system. The partners included FuelCell Energy, Inc. (FCE), the world-leading manufacturer of carbonate fuel cell systems and leading developer and manufacturer of state-of-the-art solid oxide fuel cell (SOFC) technology for stationary power, military, aerospace, and other applications. The other major partner identified is Capstone Turbines (Capstone), the world-leading manufacturer of micro-turbine generator (MTG) technology that is in the size class of the system requirements needed for the prototype system. FCE and Capstone worked together previously in the development and demonstration of hybrid FC-GT technology including previous efforts that have included the NFCRC.

NFCRC researchers also developed a prototype design based upon the specifications of technology that FCE and Capstone can respectively produce and integrated into the first locomotive prototype hybrid SOFC-GT system. This prototype design is in the 200 kW – 1 MW size class, which is consistent with the step-by-step development concept (prototype to switcher to short-haul to long haul) developed in Phase I of the research effort, presented in the FRA Technical Report, "Thermodynamic and Dynamic Assessment of Solid Oxide Fuel Cell Hybrid Systems for Use in Locomotives."[1]

NFCRC researchers then searched for test platforms with several railroad companies and railroad engine manufacturers and determined that the testing of the first prototype system should be in the laboratory, followed by installation and testing of the prototype on an actual rail platform. Burlington Northern Santa Fe Railway (BNSF) was one of the platforms considered for this application of the SOFC-GT technology; BNSF expressed interest in working with the team (i.e., NFCRC, FCE, and Capstone) to develop and test the prototype system. NFCRC then developed a test protocol outline for the prototype system planned for application in both the laboratory platform and the rail platform experiments. This test protocol includes subjecting the system to the dynamic operation requirements of both switcher end-use and long-haul locomotive end-use.

Based upon previous dynamic SOFC-GT system simulation capabilities developed in the MATLAB/Simulink platform, NFCRC proceeded to analyze the first prototype of the hybrid SOFC-GT system on the BNSF route from Bakersfield, CA, to Mojave, CA. This modeling process is divided into two sections, modeling of the switch engine and modeling of the long-haul locomotive. The switch engine model was used to develop the first commercial system, which will follow demonstration of the prototype system in the step-by-step development process of Phase I.

[1] Federal Railroad Administration. (2019). *Thermodynamic and Dynamic Assessment of Solid Oxide Fuel Cell Hybrid Systems for Use in Locomotives*. Technical Report No. DOT/FRA/ORD-19/16. Washington, DC.

In the current study, the control strategy of the SOFC-GT was modeled based on the eight notches of the locomotive power system. One of the designs evaluated was a 1 MW-class switcher similar to EMD RS 1325 model. A single vehicle kinematic model is developed in the MATLAB/Simulink platform. The basis of the calculation of the total distance traveled on a typical rail yard is the double integration of traction force. The net force on the locomotive is calculated using rolling resistance, air and axle resistance and the switcher weight.

The basis of the system development for the locomotive is two main components of vehicle dynamics and notch calculations. The notch system takes speed of the locomotive, grade of the route, acceleration and traction/brake force as inputs. Several assumptions were made in implementing the notching locomotive control algorithm: 1) the maximum desired train velocity was set to 60 mph, 2) the minimum desired train velocity was set to 10 mph, 3) the power notching progressed by only one notch at any given time step (increasing or decreasing), which decision is typically made by the locomotive driver, 4) notching does not alternate rapidly from time step to time step, and 5) the sign of the grade has an effect on the decision making. The findings showed that this control strategy was able to safely operate the SOFC-GT locomotive, and was able to do so through the test protocol duty cycles for a switcher and long haul (using the Bakersfield to Mojave route through the Tehachapi Loop).

Even though, the prototype design and control strategy showed that an SOFC-GT system could safely fulfill the requirements for dynamic operation in both switcher and long-haul locomotive operating conditions within acceptable bounds of operation, several of the SOFC and locomotive manufacturers that the team engaged were concerned about the highly dynamic operation that was required. As a result, the performance of a separate study took place that evaluated the potential for adding some battery energy storage to the prototype SOFC-GT system design. The findings showed that even a small battery storage system could significantly reduce the dynamic operating requirements of the SOFC-GT system while still successfully meeting traction requirements even in the demanding duty cycle of the Bakersfield to Mojave route.

Finally, working with the President of Empowered Energy, the team conducted a thorough set of economic analyses of potential SOFC-GT locomotive production and operation costs in comparison to other low pollutant emitting alternatives (e.g., diesel-electric, battery electric, catenary-electric). The economic analyses show that SOFC-GT systems are likely to cost a bit more and lead to higher costs for delivering goods per ton-mile. However, the conventional diesel electric engine has a much higher emissions rate. SOFC-GT locomotives are likely to produce lower operating costs compared to the catenary-electric alternative, and significantly lower operating costs compared to the battery-electric alternative.

1. Introduction

The University of California, Irvine (UCI) performed research for the Federal Railroad Administration (FRA) between September 7, 2016, and December 31, 2017, that focused on investigating the feasibility of solid oxide fuel cell - gas turbine (SOFC-GT) system to power locomotive engines for lowered emissions and higher engine efficiency. Hybrid SOFC-GT technology has the greatest potential to be designed for locomotives and operated on a fuel with sufficient energy density such as natural gas (also known as NG), and is proven to have near-zero criteria pollutant emissions and high efficiency Integrated hybrid systems have the potential to operate at higher efficiency than a fuel cell or gas turbine alone. The Solid Oxide Fuel Cell (SOFC) is electrochemical devices that convert the chemical energy contained in fuel directly to electrical energy through electrochemical reaction. The SOFC power plant was proven as an alternative power generation technology in electric utility and for domestic, industrial and commercial applications. These types of power generation plants have been presented in both locomotive and stationary applications. SOFC systems have operated on various types of fuels such as carbon monoxide (CO), natural gas, hydrogen (H_2), propane (C_3H_8), landfill gas, diesel and jet propulsion fuel (JP-8).

Typically, the operating temperature of SOFC is higher than the other types of fuel cells such as proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC) and molten carbonate fuel cell (MCFC). Higher operating temperatures of SOFC enables them to directly reform natural gas. SOFC converts the reformed hydrogen through electrochemical reaction and produces electrical power and high grade waste heat for a combined heat and power (CHP) system. SOFC power generation systems have operated in the power production range of 250 kW to 20 MW to date. Hybrid fuel cell gas turbine (FC-GT) systems provide clean energy at high efficiency. The only conventional device that has been previously tested for hybrid fuel cell systems is micro-gas turbine generator (MTG). MTG has been shown to be amenable to integration with a high temperature SOFC. FC-GT hybrid power systems posses the highest efficiency and the cleanest emissions of all fossil fueled power plants. Today, SOFC-GT hybrid systems are known as one of the most promising technologies that could meet the U.S. Department of Energy's (DOE) demands: 1) to achieve a higher energy efficiency, 2) minimization of environmental pollution, 3) electricity production at a competitive cost, and 4) investigation of carbon dioxide (CO_2) capture and sequestration strategies.

Siemens-Westinghouse Power Corporation developed the first pressurized (3 atm) hybrid SOFC-GT system that generated 220 kW of electrical power at a net electrical efficiency of 55 percent. FuelCell Energy, Inc. (FCE) and Capstone Turbine (Capstone) built a 250 kW hybrid MCFC-GT system that achieved 57 percent net electrical efficiency. Recently, Mitubishi Heavy Industries demonstrated a 250 kW hybrid SOFC-GT system in Japan that operated for more than 4100 hours without noticeable degradation. The current study intends to provide a compressor stall/surge insight into a similar power rated hybrid SOFC-GT system.

Among the features that allow the integration of gas turbine with SOFC, the following points can be emphasized: 1) SOFC exhaust temperature and GT inlet temperature are well-matched; 2) GTs operate at relatively lower pressure ratios that makes integration easier; 3) GTs often use recuperation in order to improve the system efficiency; 4) GTs allow fuel cells to operate under higher pressures which improves the cell performance; 5) thermal energy amount and quality (temperature) contained in the SOFC exhaust is sufficient for gas turbine inlet conditions to produce compressor power (for the fuel cell pressurization) and an electric power generator (that produces additional electricity).

Initial work at the National Fuel Cell Research Center (NFCRC) on the feasibility of using SOFC-GT systems in locomotive applications showed that the technology can possibly fit into the locomotive platform and produce sufficient power and dynamic power for long-haul applications. This NFCRC work was supported by the California Air Resources Board (CARB) and the South Coast Air Quality Management District (SCAQMD) to investigate the feasibility of using ultra-high efficiency and ultra-low emissions SOFC technology in locomotives. In previous research, the NFCRC determined that hybrid SOFC-GT systems can be designed to power a locomotive and can be controlled and operated in a manner that can power locomotives in typical service. FRA supports the current work to take the next steps to advance hybrid SOFC-GT technology for use in locomotives. The goal of the proposed effort is to conduct prototype design analyses, identify, and work with technology partners to plan and prepare for prototype testing of the hybrid SOFC locomotive concept.

1.1 Background

According to a 2007 report from the CARB, exposure to criteria pollutants, especially fine $PM_{2.5}$, above the state standard leads to 5,400 premature deaths, 2,400 hospitalizations, 140,000 cases of asthma and other lower respiratory problems, and 980,000 lost work days per year in the South Coast Air Basin (SoCAB) alone.[2] A large part of these emissions is attributed to the movement of goods via freight railway to and from the ports of Los Angeles and Long Beach in California. Therefore, developing locomotives with higher efficiencies and lower pollutant emissions will not only slow down climate change globally, but also significantly reduce the impacts on the local population in a place like the SoCAB.

Long-haul locomotive transportation is one of the most prevalent methods of shipping goods in the United States. An exploratory committee formed in 2002 at the Center for Transportation Research at Argonne National Laboratory, under the guidance of the U.S. Department of Energy (DOE), reported that in 1997, locomotives consumed 4 billion gallons of diesel fuel in the United States. This amount represents 10 percent of all diesel used for transportation and 2.3 percent of all transportation fuels. For the rail operators, this represents an annual cost of $2 billion, contributing 7 percent of their total operating expenses. Today, the situation is not much different, as the consumption of petroleum in freight rail represented 2.1 percent of the total national transportation fuel use in 2005, thereby consuming 571.4 trillion BTUs of fuel. Thus, fuel use for long-haul locomotives is continually of economic interest to both government and industry, and represents a field with much potential for increasing energy independence.

In addition to these motivating factors, the use of diesel fuel in railway applications presents a significant environmental concern. Although the nationally averaged emission signature of locomotives nationwide appears low (in 2001, locomotive-sourced nitrogen oxide (NOx) was only 5 percent of the national total), locomotives are responsible for much of the emissions, especially diesel particulate matter (PM), in the areas where they are stationary. At classification rail yards, locomotives are responsible for 96 percent of PM emissions; at intermodal rail yards,

[2] California Environmental Protection Agency, "Diesel Particulate Matter Exposure Assessment Study for the Ports of Los Angeles and Long Beach," California Air Resources Board, Sacramento, 2006

the contribution is 39 percent. The public living near these stationary rail operations is most affected by these emissions, and improvements in locomotive emission signatures can enhance the air quality for this subset of the population.

Moreover, in California, the center of rail operations tends to be in areas that have difficulty achieving air quality standards due to high source concentration and stagnating meteorological conditions; thus, the additional burden is placed on those living in areas already known to have poor air quality. Similar to passenger vehicles and diesel freight trucks, locomotives have thus been assigned a progressively limiting tier-based schedule of emissions standards. This tier system requires substantial ongoing reductions in the emission of NOx, CO, hydrocarbons, smoke, and particulates.[3] Therefore, developing locomotives with higher efficiencies and lower pollutant emissions will not only slow down climate change globally, but also significantly reduce the impacts on the local population in a place like the SCAB.

1.2 Objectives

The following research objectives were accomplished:

- Selected partners for development and testing of the hybrid SOFC prototype
- Designed the hybrid SOFC prototype
- Selected an experimental test platform
- Designed the hybrid SOFC prototype test protocol and test matrix
- Conducted economic analysis
- Established prototype demonstration budget, approach, schedule, and partners

1.3 Overall Approach

The overall approach of this research is to work with manufacturing partners to develop a prototype design, to prepare for evaluation of the prototype by developing a test protocol, to develop and demonstrate control systems for SOFC-GT hybrid systems that are required to pass a 1 MW switcher locomotive through a switcher locomotive load profile and a 3 MW long-haul locomotive through the Bakersfield to Mojave route, and to evaluate the economics of such hybrid SOFC-GT systems.

For the control systems developed, implementation of typical proportional integral differential controllers control the revolutions per minute, compressor inlet guide vanes, fuel cell fuel flow rate and fuel cell power. Specific gains for these controllers pass the switcher through the route. Due to the highly dynamic nature of the power duty cycle, the control systems are required in order to follow the power demand in the short periods of times. The highly dynamic power cycle is due to the algorithm that keeps the switcher at constant speed during the whole route. The

[3] United States, "Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression-Ignition Engines less than 30 Liters per Cylinder," in *Federal Register 6*, Environmental Protection Agency, 2008, pp. 25098–25146.

implementation of other algorithms took place to produce a less dynamic profile of the power duty cycle at which the controllers have better performance in following the power demand.

1.4 Scope

This report covers the integration and development of a hybrid SOFC-GT system in 1 MW switcher locomotive. The report addresses prototype system development for this type of switchers. Also, a test railroad route (i.e., Bakersfield to Mojave) was chosen to analyze the SOFC-GT performance on the route. Parametric studies were accomplished to find the optimal design of the system that can effectively meet the power demand profile.

The efficacy of the SOFC-GT to improve efficiency and offer zero or near zero emissions is dependent on the dynamics of the locomotive duty cycle and route. This was investigated in the current effort for an SOFC-GT system that can be used in a prototype design and demonstration that is on the path for eventual development of long-haul hybrid fuel cell gas turbine locomotive systems.

The current model of the SOFC-GT system works based on natural gas as the main source of fueling.

1.5 Organization of the Report

This report is organized into the following sections each describing a major element of the research accomplished in this study:

- Section 1: Introduction including the Background, Objectives, Overall Approach, and Scope
- Section 2: Development Partners, Experimental Platform and Test Protocols
- Section 3: Prototype design and evaluation
- Section 4: Prototype Development
- Section 5: Economic Analyses
- Section 6: Conclusion
- Appendix A: A Market Potential for Non-Diesel Electric Locomotives

2. Development Partners, Experimental Platform and Test Protocols

If the SOFC-GT system application for a locomotive is going to be introduced in the foreseeable future, then several steps beyond system design and simulation are required. First, negotiation with partners who will provide the fuel cell and gas turbine systems for testing a prototype is required. Moreover, the usage of both stationary and railcar testing platforms needs to be planned, which includes creating a steady-state and a dynamic test protocol.

2.1 SOFC-GT System Development Partners

The NFCRC has identified partners for the development of a prototype hybrid SOFC-GT locomotive power system. The partners include FCE the world-leading manufacturer of carbonate fuel cell systems and leading developer and manufacturer of state-of-the-art SOFC technology for stationary power, military, aerospace, and other applications. The other major partner identified is Capstone, the world-leading manufacturer of MTG technology that is in the size class of the system requirements needed for the prototype system. FCE and Capstone worked together previously in the development and demonstration of hybrid fuel cell gas turbine technology including previous efforts that have included the NFCRC.

Working with these partners, NFCRC researchers have developed a prototype SOFC-GT locomotive engine design based upon the specifications of technology that FCE and Capstone can respectively produce. This prototype design, which could well be integrated into the first locomotive prototype hybrid SOFC-GT system, is described in a later chapter of this report. This prototype design is in the 200 kW – 1 MW size class, which is consistent with the step-by-step development concept (prototype to switcher to short-haul to long haul locomotive platforms) developed in Phase I of this effort.

2.2 Prototype Experimental Platform

NFCRC researchers searched for test platforms with several railroad companies and railroad engine manufacturers and determined that the first prototype system should first be tested as a stationary system in the NFCRC laboratory, followed by installation and testing of the prototype on an actual rail platform. This step-by-step experimental evaluation will allow for required modifications and enable the team to address shortcomings and challenges that arise well before integration into a railroad application occurs. Each of these testing platforms are described in the sections below.

2.2.1 Stationary Testing Platform

The NFCRC site has multiple places in which the prototype SOFC-GT system can be tested via connection to controllable loads. One of the locations is the High-Bay Fuel Cell Systems Laboratory depicted in Figure 1. This laboratory space supports the operation and testing of large fuel cell and fuel processing equipment. The second NFCRC space that is amenable to the thorough evaluation of the SOFC-GT prototype system is the Distributed Generation Testbed. This outdoor testbed space has been used over the years for pre-commercial testing and demonstration of distributed energy technologies from a few watts to 500 kW with combined cooling, heating and power (CCHP). One of these two sites will provide the first testing platform for the prototype SOFC-GT locomotive system.

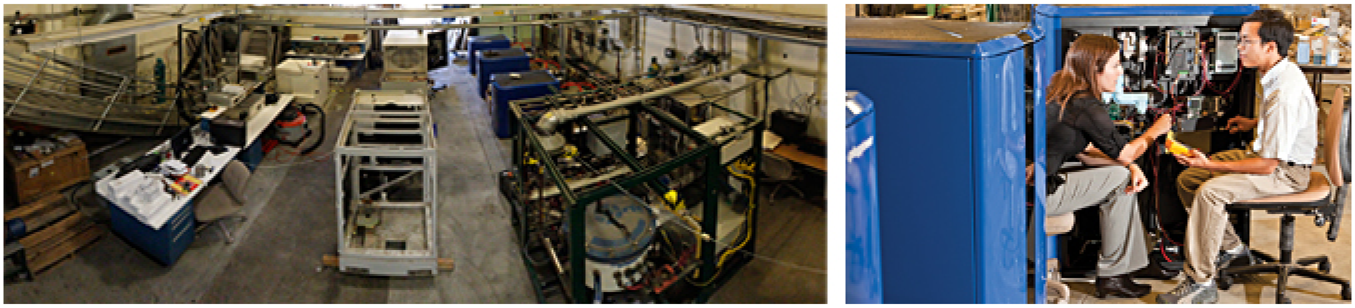

Figure 1. Photographs of the High Bay Fuel Cell Systems Laboratory of the NFCRC

Figure 2. Photographs of the Distributed Generation Testbed of the NFCRC

Note that these stationary testing platforms of the NFCRC include significant measurement and performance verification expertise and capabilities such as potentiostatic and galvanostatic measurements, electrochemical impedance spectroscopy (EIS), and degradation/failure analysis. The NFCRC is constantly expanding the number of the in-house proprietary analytical procedures and electrochemical performance measurement standards which are prepared to perform for this proposed effort. The development of the custom and in-house proprietary analytical procedures were due to the deep knowledge and experience of the NFCRC and the team in electrochemical performance measurement. Electrochemical measurements can be conducted using existing ceramic cell testing station, the most advanced versatile Ceramic Cell fixture ProboStat® as shown in Figure 3. The electrochemical testing can be performed on a Solartron® model 1260 and 1480 8-Channel AC Impedance Spectrometer, the cell operating temperature is controlled by an applied test system single zone multi-sample split tube furnace and the electrode-electrolyte interface environments are controlled by Brooks® MFCs. The performance tests that the NFCRC laboratory capable to perform include but not be limited to: 1) conductivity under various temperatures and various oxygen partial pressures; 2) thermal/chemical compatibility of the electrode-electrolyte material sets; 3) oxygen permeability; 4) stability and degradation rate test; and 5) impedance spectra of the electrode-electrolyte interfaces under various temperature and oxygen partial pressures.

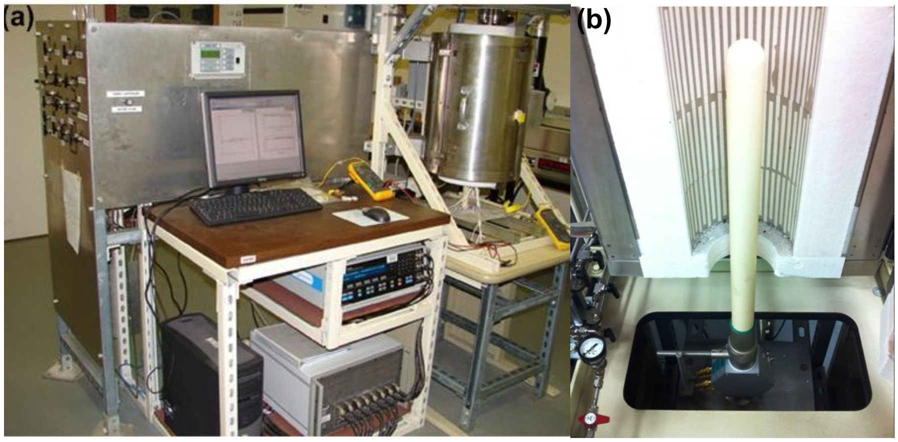

Figure 3. (a) Ceramic cell testing station and (b) Ceramic cell fixture by ProboStat®

The NFCRC maintains a wide array of state-of-the-art test facilities and research measurement capabilities for fuel cell and other energy conversion devices. These facilities and capabilities allow detailed measurements and analyses of fuel cell components and systems including an investigation of overall performance, internal component performance, and materials and subcomponent characteristics. The NFCRC maintains an extensive laboratory with 14 test bays dedicated to fuel cell, hybrid fuel cell gas turbine, and combustion-based energy conversion device research. The testing facilities are designed to accommodate conventional testing and measurements as well as advanced solid state electrochemical testing and laser diagnostic methods. Most test bays feature traversing of the hardware required to map out aspects of interest including fuel distribution, velocity, and scalar fields. In addition, several analyses capabilities including those that support computational fluid dynamics, steady state and dynamic cycle analyses, chemical kinetics, and stress analyses are also available.

The NFCRC research facilities have the capability of providing a large flow of high-pressure air to support high throughput experiments. Three 300 horsepower electric air compressors can provide 2,400 SCFM of air at 140 psig, and a booster air compressor can provide 450 SCFM at 450 psig. In addition, the NFCRC is set up to provide a significant flow of natural gas at high pressures as well as a variety of natural gas-based or carbon monoxide and hydrogen based simulated landfill and digester gases and synthesis gases. Below is a summary of most of these verification measurement capabilities.

- Air Factory:
    - 4 lb/sec at 8 ATM
    - 1 lb/sec at up to 30 ATM
- Fuel Delivery:
    - Natural Gas to 0.2 lb/sec, 500 psia
    - Liquid Fuels to 80 gpm, 1,000 psia
    - Hydrogen and Hydrogen/Nitrogen mix flows
    - Fuel Variation Simulation Facility
        - Natural gas

        - Biomass gases
        - Landfill/digester gas
        - Synthesis/process gases
- Conventional Diagnostics:
    - Extractive Emissions (e.g., flame ionization detector [FID], nondispersive infrared [NDIR], infrared [IR])
    - Gas Chromatography (GC)
    - Mass Spectrometry (MS)
    - Atomic Absorption (AA)
    - Temperature
    - Soot
    - High Speed Video
- Energy System Testing Equipment:
    - High pressure/temperature single cell
    - High temperature button cell
    - High temperature/pressure stack
    - Low pressure/temperature PEMFC cell test
    - PEMFC stack testing
    - Reformer testing
    - Integrated SOFC system testing
    - Integrated hybrid SOFC/GT system tests
    - Integrated PV fuel cell testing
    - Electrolyzer and reversible FC testing
    - Hydrogen refueling test/evaluation
    - Load banks
- Optical Diagnostics:
    - Laser Anemometry
    - Digital Particle Image Velocimetry
    - Coherent Anti-Stokes Raman Scattering
    - Planar Laser Induced Fluorescence
    - Laser Rayleigh
    - Laser Diffraction
    - Phase Doppler Interferometry

- Chemiluminesence
- Differential Absorption
- Transient Grating Spectroscopy

Figure 4 presents some photographs of the test stands and measurement resources. These facilities and capabilities include: (a) atomic absorption spectroscopy for measuring atomic composition; (b) particulate analyzer for emissions assessment; (c) impedance spectrometer for determining electrochemical losses; (d) high temperature ceramic cell test-stand for independent measurement of SOFC cells; (e) fuel/air delivery systems for control and measurement of inlet fuel and air; (f) a low temperature fuel cell test-fixture; (g) integrated high temperature and pressure ceramic test-stand, for pressurized measurement of SOFC cells and short stacks; and (h) a fuel cell emissions analyzer for measurements of all criteria pollutants at ultra-low levels expected from the SOFC-GT prototype system.

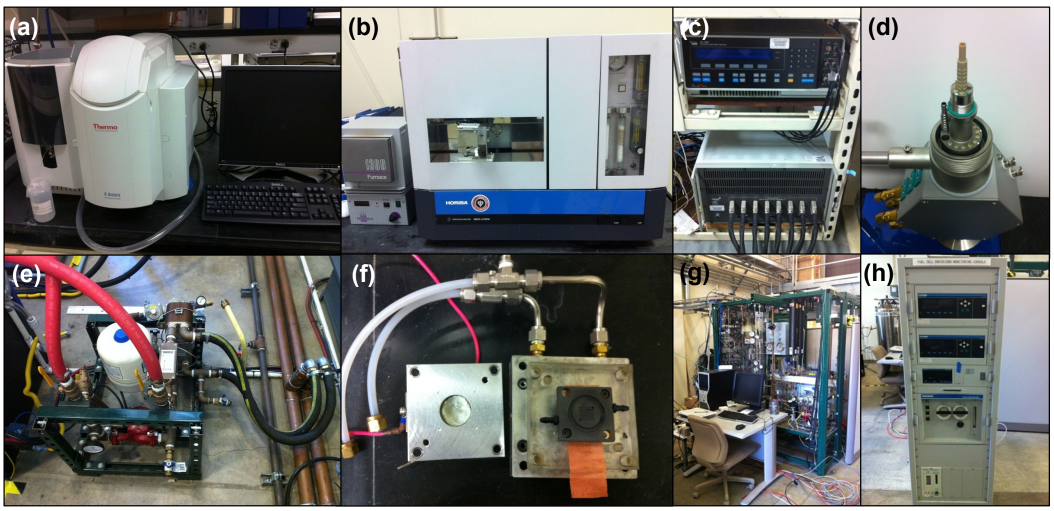

Figure 4. Photographs of various test-stands and model verification measurement equipment (a) Atomic absorption (b) Particulate analyzer (c) Impedance spectrometer (d) High temperature ceramic cell test-stand (e) Fuel/air delivery system (f) Low temperature fuel cell test-fixture (g) Integrated high temperature and pressure ceramic test-stand and (h) Fuel cell emission analyzer

2.2.2 Railcar Testing Platform

One of the platforms that is to be considered for evaluation of the prototype SOFC-GT system is that which could be provided by BNSF, a railroad company that has expressed interest in working with the team (i.e., NFCRC, FCE, and Capstone) to develop and test the prototype system. BNSF has not yet committed to an agreement to have NFCRC use their test platform, but, they have expressed sincere interest. Figure 5 and Figure 6 depicts the platform provided by BNSF in photographs. This experimental railroad locomotive platform was used by BNSF in previous evaluations of hydrogen powered fuel cell engines. This platform is that of a shunting locomotive that served as a testbed for hydrogen fueled proton exchange membrane fuel cell (PEMFC) technology that BNSF evaluated in Topeka, KS.

Figure 5. 1st Photograph of the BNSF test platform for potential use in evaluating the prototype hybrid SOFC-GT system

Figure 6. 2nd Photograph of the BNSF test platform for potential use in evaluating the prototype hybrid SOFC-GT system

2.3 Development and Test Protocols

NFCRC developed a test protocol for the prototype system planned for application in both the laboratory platform and the rail platform experiments. This test protocol included two separate sets of tests to determine: (1) steady state operating performance characteristics, and (2) dynamic operating performance characteristics. In each case, the hybrid SOFC-GT system will be subjected to a set of parametric variations as described in the following subsections.

2.3.1 Steady State Test Protocol

The steady state test protocol assumes that the specifications for both the fuel cell and the turbine are unknown and can be used to evaluate each of the components to determine an optimal steady state integration (operating strategy) for any given set of fuel cell and turbine specifications. The test protocol includes sensitivity analysis conducted for each of the major SOFC-GT system performance features. The test protocol provides a consistent estimate of performance while the integrated system adheres to required performance specifications and constraints. This section presents the major parameters that are varied for the steady state evaluation and an example of one parametric variation that provides an example regarding how results can be presented during the testing. The major parameters that must be varied in the steady state evaluation are:

1. Fuel cell temperature gradient
2. Fuel cell operating power density
3. Fuel cell fuel utilization
4. Air pre-heating effectiveness
5. Peak compressor/turbine efficiency
6. System operating pressure
7. Fuel cell Positive-Electrolyte Negative (PEN) average operating temperature

The value of each parameter must span the range of the available technology for the specific SOFC stack and turbine technology considered. The method of determining optimal hybrid performance with the specified constraints is comprised of the following steps as outlined in Figure 7.

- Specify the FC type, physical dimensions, geometry, and electrochemical properties. These parameters can be calibrated to a real system or taken from the literature, and are then held constant through the design process.
- Specifying 4 of the following 8 conditions. Solve for the remaining 4 by simulating the steady-state fuel cell; air flow, fuel flow, cell power, voltage, inlet temperature, average temperature, temperature gradient, fuel utilization.
- Simulate the balance of plant components using the outlet conditions specified by the fuel cell simulation. Depending on the precise hybrid configuration, different design parameter will be available for modification. In the design studied 5 of the following 10 parameters needed to be specified; net system power, FC stack size, GT mass flow, FC air flow, FC inlet temp, recirculation, pre/post-combustor fuel, fuel/air pre-heater size, turbine inlet temperature (TIT). The five specified were net system power, FC air flow

and inlet temperature (from FC simulation), and the amount of additional fuel supplied to a pre- and post-FC combustor (zero).

- Combine the dynamic fuel cell and dynamic balance of plant components into a single model with the sizing and operating conditions specified by their respective individual models, and confirm that the steady behavior arrives at the desired operating temperature and power output.

Apply a control strategy to physical inputs such as valves, fuel flow, and blowers to test the dynamic response to perturbations including ambient temperature, fuel content, and load changes.

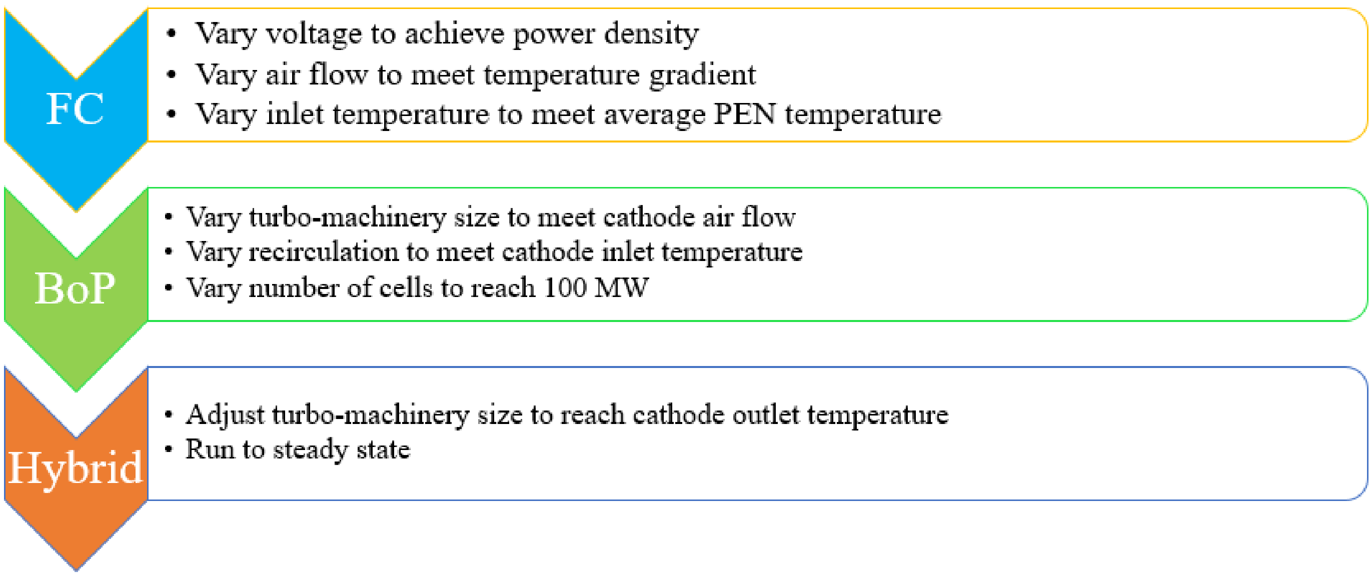

Figure 7. Methodology for parametric evaluation of FC-GT cycle performance

An important design feature of the SOFC topping cycle studied is the size of the air pre-heater. A larger heater reduces the amount of cathode recirculation, which increases efficiency, but lowers the TIT which reduces system efficiency. The combined effect depends on the part-load efficiency of both the blower and turbine. Use of a heat exchanger with a bypass loop at this point of the cycle allows for substantial controllability. The heater bypass generates increased air flow at constant temperature by cooling the heater exhaust and relying on additional recirculation heating of the cathode inlet stream. Table 2 presents a comparison of design operation with different heater sizes for 80 percent fuel utilization, 200 °C gain across the stack, and a power density of 500 mW/cm^2. The 200 °C of pre-heating represents the baseline design to which the figures of this section have been normalized. Note the ultra-high, >70%, fuel to electric efficiency using existing SOFC and GT technology.

Table 1. Design Impact of Regenerative Air Heater

Air Pre-Heat		0 °C	100 °C	200 °C
Stack Power	MW	84.1	83.5	83.4
Gen Power	MW	16.6	17.1	17.0
Blower Power	MW	0.70	0.55	0.40
Efficiency	%	67.1	68.6	70.7
Turbine %	%	16.5	17.0	17.0
Air Heater	plates	0	891	2762
Turbine Inlet	°K	1,332	1,220	1,095
Recirculation	%	64.09	55.54	42.28

Example Parametric Variation: Stack Temperature Rise

Stack temperature gradient plays a determining role in system efficiency and durability. Manufacturers often specify a maximum thermal stress sustainable by the system to be met at design and during off-design performance. Intuitively a greater temperature rise across the stack requires less air flow, and thus smaller turbo-machinery, resulting in higher system efficiency. The model supports this, but to a lesser extent than expected. A sensitivity analysis of 13 important design variables are evaluated as either better or worse than the baseline system design; Figure 8. Higher values indicate improvements in efficiency, voltage, compressor size, turbine percent power, stack power, generator power, and TIT, whereas lower values indicate improvement in recirculation, blower power, stack and heat exchanger sizes, and PEN temperature gradient. The sensitivity of each output is scaled to its maximum deviation during the course of the parameter study. Reducing the temperature gradient across the cell 5 °C/cm improves durability and resulted in an overall system efficiency only 0.3 percent lower. The reduction in efficiency is due to offsetting impacts of a larger turbine and additional recirculation used to pre-heat the cathode stream.

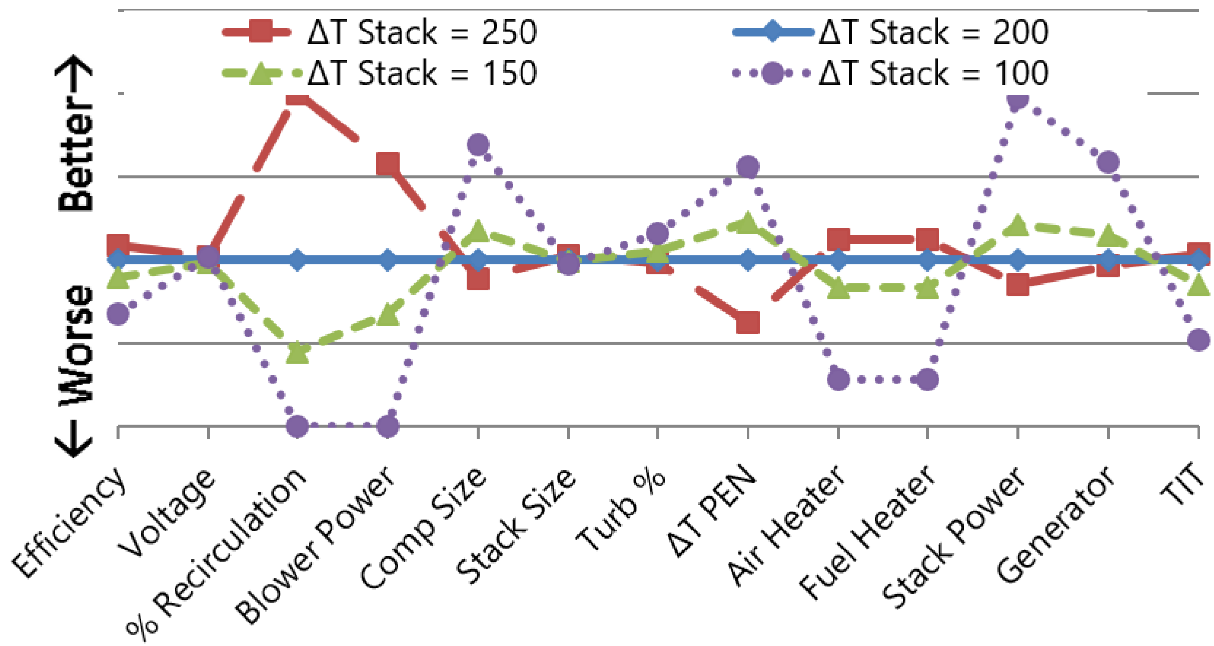

Figure 8. Design impact of stack temperature profile

2.3.2 Dynamic Test Protocol

Locomotive traction and dynamic braking have evolved over many years. In diesel locomotives, eight notches for the throttle control emerged based on a three-valve fuel control. It should be noted that, more modern locomotives have different numbers of notches and levels of dynamics braking. In the current study, the control system modeled eight notches.

The dynamic test protocol for the SOFC-GT locomotives is established for both evaluating the simulated performance of various SOFC-GT designs and for evaluating the first prototype SOFC-GT system. The test protocol includes subjecting the system to a dynamic load profile that is typical of use in a switcher locomotive (as shown in Figure 9), and a separate dynamic load profile that is typical of a long-haul locomotive that travels through a challenging mountainous route, such as from the ports of Los Angeles and Long Beach to Barstow, or from Bakersfield to Mojave through the Tehachapi Loop. Figure 10 presents such a long-haul locomotive duty cycle.

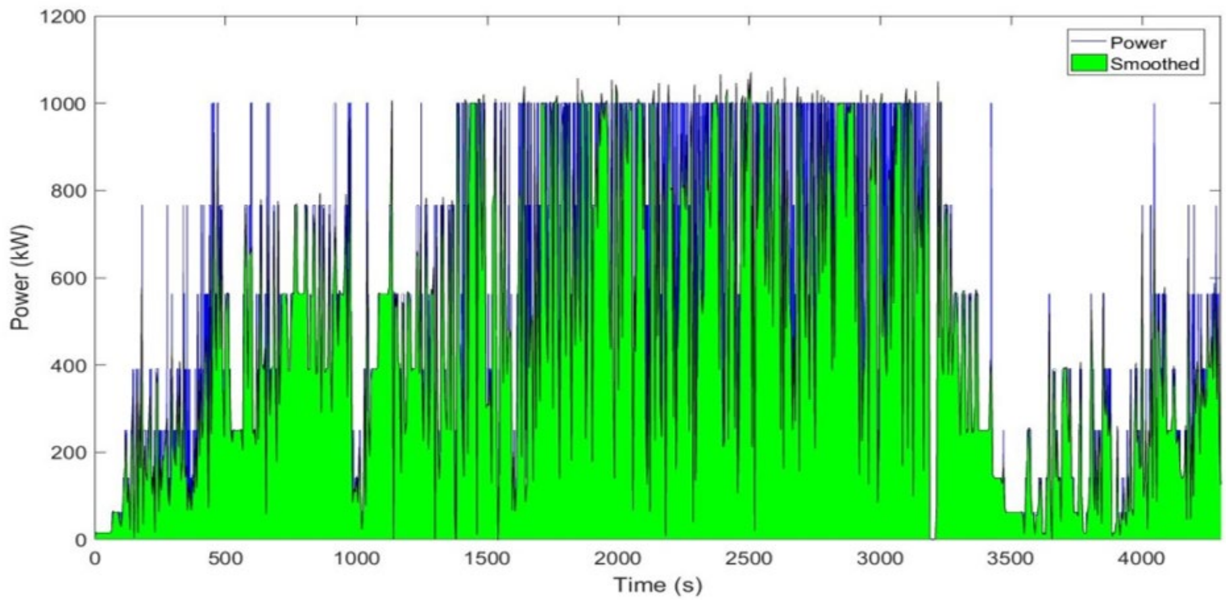

Figure 9. Power duty cycle of a 1 MW switcher locomotive

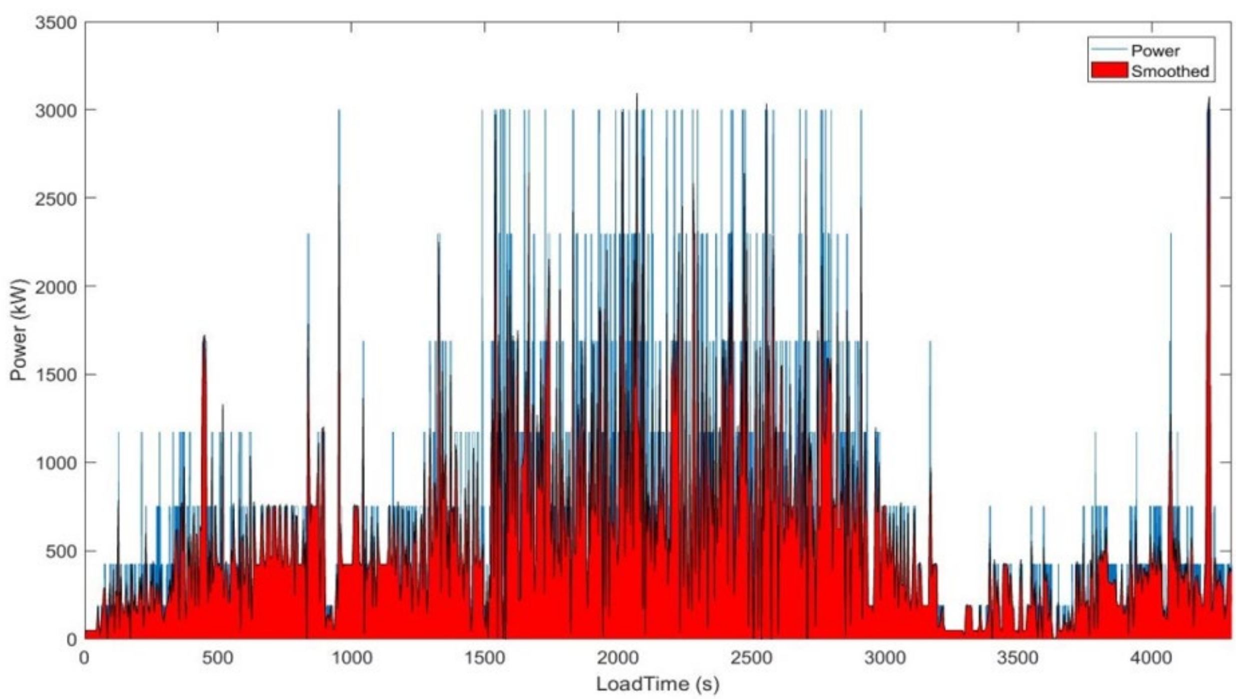

Figure 10. Power duty cycle of a 3 MW long-haul locomotive

3. Prototype Development

This section includes a presentation of dimensions and weight of a 280-kW gross stack module building block. Additionally, a process cell model framework and various characteristics and operating parameters are presented to begin a prototype system process design study and mechanical layout assessment.

3.1 SOFC System Selection—FuelCell Energy Compact Stack Architecture

This section of the report presents initial design and operating parameters for a conceptual FuelCell Energy SOFC stack module design. The design presented is based upon a new stack platform termed Compact SOFC Architecture (CSA) stack. This stack platform has high volumetric and gravimetric power density leading to these characteristics carrying-over to the stack module. Thus, a CSA stack module is believed to be suitable for mobile SOFC product applications.

3.1.1 Compact SOFC Architecture Stack

The CSA stack (shown in Figure 11) is a next generation SOFC stack, which is suitable for various fuel cell (and electrolysis) applications. Table 3 summarizes the CSA stack operating parameters.

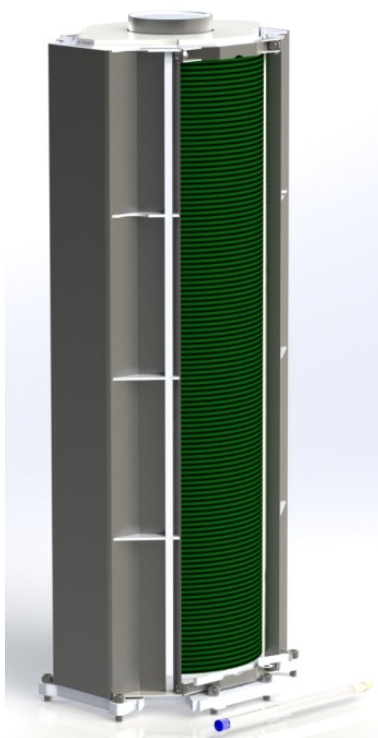

Figure 11. FuelCell Energy CSA stack design

Table 2. CSA Stack Operating Parameters

Selected Operating Parameters	Nominal	Units	Max	Min	Comment
Power Density	250	mW/cm^2	350	0	Atm. pressure operation
Current Density	290	mA/cm^2	440	0	Atm. pressure operation
Area Specific Resistance	~0.3	$\Omega - cm^2$	0	0	Function of T and P, see Equation 3 below for P effect
Stack Fuel Utilization	65	%	80%	60%	Generally anode recycle desired for water independence and attainment of high system fuel utilization
Cell Operating Temperature	725	°C	650	800	N/A

For the purposes of a high-level process design investigation, a description of a basic cell performance model is as follows:

$$V_{cell} = V_{OCV-avg} - ASR \; x \; i_d \qquad \text{Equation 1}$$

Where V_{cell} is the predicted operating cell voltage, $V_{OCV-avg}$ is the average cell open circuit voltage based on the temperature, pressure, equilibrium fuel in/out compositions, and oxidant in/out condition. ASR is area specific resistance (Ω-cm^2) and i_d is the current density (A/cm^2). Assuming that the process-modeling tool calculates the anode side oxygen partial pressure for any fuel inlet composition equilibrium, $V_{OCV-avg}$ can be calculated efficiently utilizing:

$$V_{OCV-avg} = Average\left(\frac{RT}{4F}\ln\left(\frac{P_{O2-Cathode\ In}}{P_{O2-Anode\ In}}\right), \frac{RT}{4F}\ln\left(\frac{P_{O2-Cathode\ Out}}{P_{O2-Anode\ Out}}\right)\right) \qquad \text{Equation 2}$$

Where R is the ideal gas constant, T is temperature and F is Faraday's constant. At pressure, cell performance could improve via both the Nernst shift as well as better cell operation, which translates to ASR reduction. Equation 2 found the Nernst improvement, while Equation 7 describes the core cell improvement:

$$ASR = -0.023 \ln P_{total} + 0.325 \qquad \text{Equation 3}$$

Where P_{total} is described in units of atmosphere valid up to 10 atm. Table 4 shows sample V-j data for stack operating at 65 percent stack fuel utilization, 725 °C operation, 40 percent oxygen utilization and a non-equilibrium stack module fuel inlet composition of 5 percent CH_4, 34 percent H_2, 9 percent CO, 28 percent H_2O, and 1 percent N_2.

Table 3. Sample FuelCell Energy SOFC V-j Performance

	Atmospheric Pressure	Atmopsheric Pressure	5 Atmospheric Pressure	5 Atmospheric Pressure
	Current Density [A/cm^2]	Average Cell Voltage [V]	Current Density [A/cm^2]	Average Cell Voltage [V]
Open Circuit	0.00	0.985	0.00	1.010
Rated Output	0.29	0.850	0.29	0.890

Based on a more refined and concise understanding of the proposed locomotive application cell/stack operating conditions, an improved predictive cell model could be developed.

3.1.2 CSA Stack Module

Based on the CSA stack described in this section, a compact stack module is conceivable for ambient pressure operation (Figure 12) or pressurized operation (Figure 13) while contained in the horizontal pressure vessel. Multiples, or groups of these modules are possible for higher power outputs such as MW-level utilizing four stack modules. Other characteristics and operating parameters are as shown in Table 5.

The stack module consists of the following: CSA stacks (with integrated mechanical compression), radiant heat transfer capability for stack thermal management, thermal insulation, hot electrical connections, temperature and voltage instrumentation, gas manifolding, piping and bellows. Necessary interfaces include piping connections, electrical connections, and instrumentation connections.

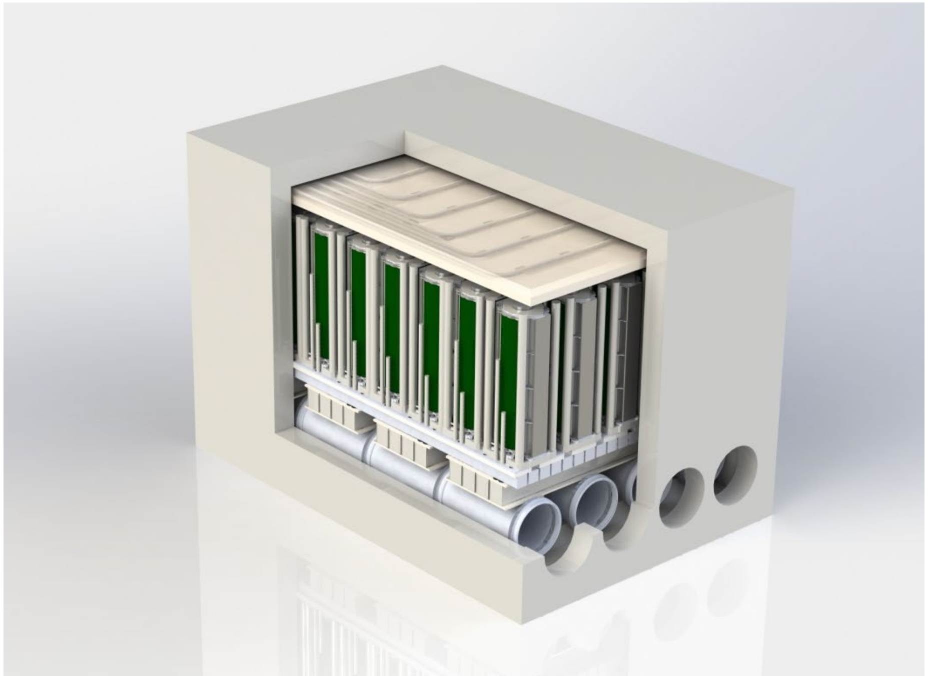

Figure 12. CSA stack module (simple)—stacks, manifolding, and thermal insulation—non-pressure rated

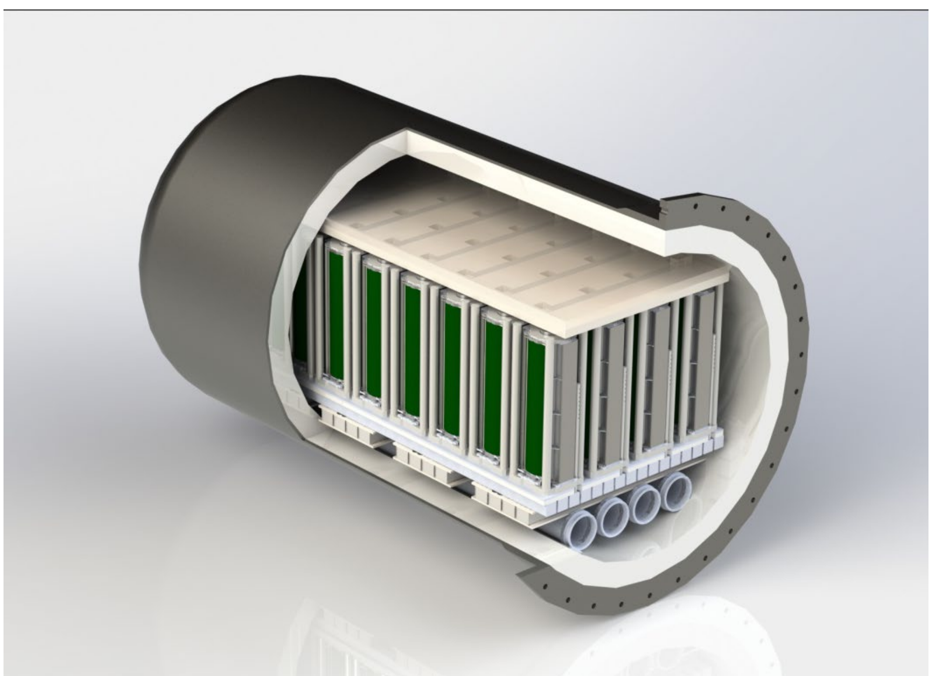

Figure 13. CSA stack module (simple)—stacks, pressure vessel, manifolding, and thermal insulation—pressure-rated

Table 4. CSA Stack Module Characteristics and Operating Parameters

Selected Characteristics	Nominal	Units	Max	Min	Comment
Total Active Area	1,134,000	cm^2			
Module Height – Atm.	107	cm			
Module Foot Print – Atm.	107 x 152	cm x cm			Non-pressure rated
Module Weight – Atm.	1,300	kg			
Module Height – Pressurized	122	cm			
Module Foot Print – Pressurized	122 x 192	cm x cm			Pressure rated, 48" diameter
Module Weight - Pressurized	2,300	kg			
Selected Operating Parameters	Nominal	Units	Max	Min	Comment
Module Power	280	kW			Gross, atmospheric pressure operation
Module Current - Total	470	A	700		Atm. pressure operation
Module Voltage	+ / - 298 *595 V diff*	V			Atm. pressure operation
System Level Fuel Utilization	85	%	90	80	Assumes anode recycle
"In-Module" Level Reforming (including stack)	100	%	100	0	Assumes anode recycle
Anode and Cathode dP—Module	0.05	Atm	0.07	0.01	Operating at pressure or higher utilizations will reduce nominal dP
Flush Configuration	Cathode Inlet				Module internal pressure equalized to cathode inlet
Oxygen Utilization	40	%	60	20	
Module Fuel In Temp	600	°C	725	400	Parameters can be varied to maintain stack module thermal management in conjunction with fuel composition, stack degradation, etc.
Module Air In Temp	625	°C	725	400	
Module Air/Fuel Out Temp	725	°C	750	675	
Heat Loss	5.0	kW			

3.1.3 Process Design Discussion

Figure 14 presents a FuelCell Energy baseline SOFC system design. As the turbine-hybrid process design will likely lead to a different and more integrated design, a more concise and simple stack module (shaded purple) was selected for this document and the presented stack module requirements.

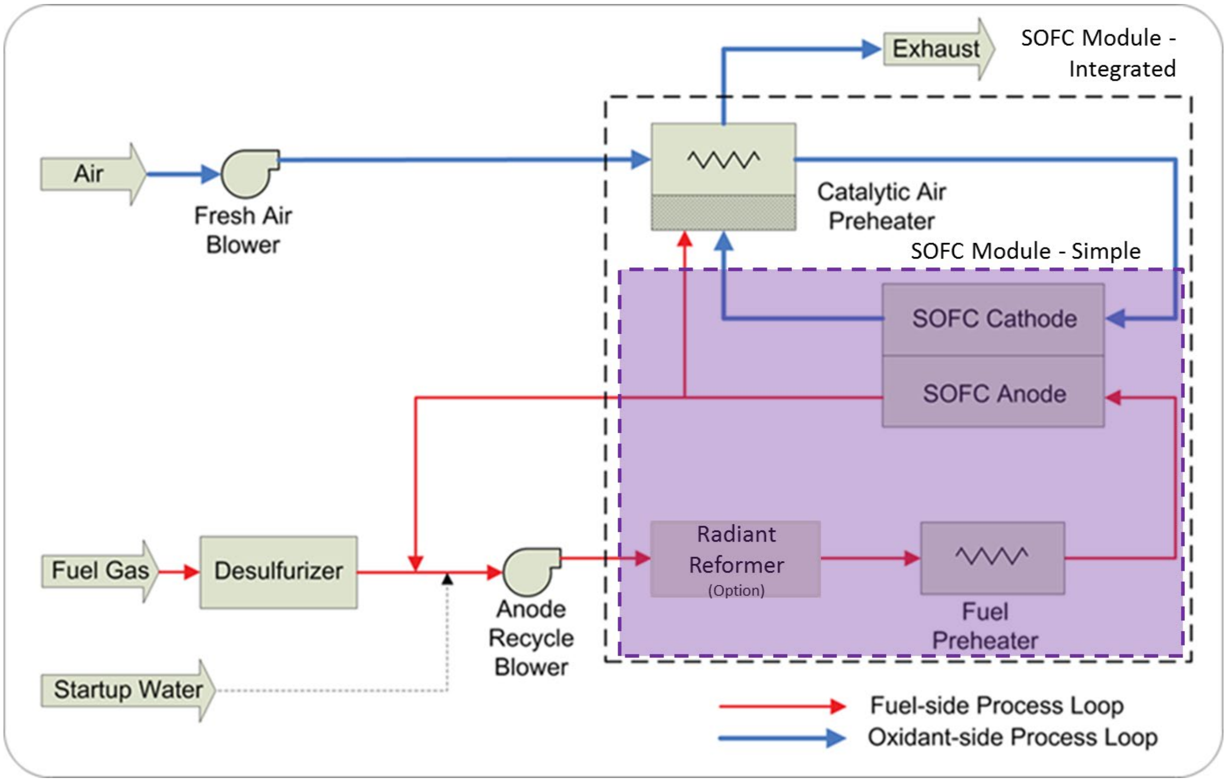

Figure 14. SOFC system design—FCE baseline

3.2 Gas Turbine System Selected—Capstone Turbines

The other major partner identified is Capstone, the world-leading manufacturer of MTG technology that is in the size class of the system requirements needed for the prototype system. FCE and Capstone have worked together previously in the development and demonstration of hybrid fuel cell gas turbine technology including previous efforts that have included the NFCRC.

3.2.1 Capstone® Turbomachinery in C-65, C-250, C370LP-spool

Without scaling, changes to the fuel cell operating condition produce noticeably different trends, while the turbine remains similar. Table 6 presents the specification of the Capstone® line of micro-turbines. The resulting performance map for the C-250 engine, shown in Figure 15, better demonstrates the de-rate in power at reduced heating rates. The operating window of the C-250 turbine appears to be at heating rates between 250 and 800 kW to produce between 50 and 250 kW of electric power. It is worthwhile to note that the micro-turbines were found to exhibit poor emissions performance at low power during tests at UCI; however, this would not be an issue when hybridization replaced the combustor with clean electrochemical oxidation.

Table 5. Various Capstone Micro-turbine Specifications

Specification	C-65	C-250	C-370 LP spool
Mass Flow (lb/s)	1.08	3.44	3.2
Compressor Outlet (°F)	424	469	397
Compressor Outlet (psig)	40	58.8	49
Recuperator Outlet(°F)	1,050	1,097	960
Turbine Inlet (°F)	1,720	1,788	1,550
Efficiency (%)	3,1.2	33.25	34.5

Figure 15. Capstone C65 micro-turbine

3.3 Hybrid SOFC-GT Prototype Design

Several prototype system design concepts were considered in the current study. These included all the configurations depicted schematically in the following figures. Figure 16 presents a schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration. Figure 17 presents a schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration with a cathode bypass and associated valve added. Figure 18 presents a schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration with an auxiliary combustor added. Figure 19 presents a schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration with both cathode bypass and auxiliary combustor added. Figure 20 presents a schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration with recuperator bypass added. Finally, Figure 21 presents a schematic of the directly fired (pressurized) SOFC-GT system configuration. Because the CSA design of FuelCell Energy is capable of being pressurized, the hot module design of FCE's CSA design includes anode tail-gas oxidation. This results in the system configuration being comprised of fewer parts; therefore, the hybrid system design selected is the pressurized design depicted in Figure 21.

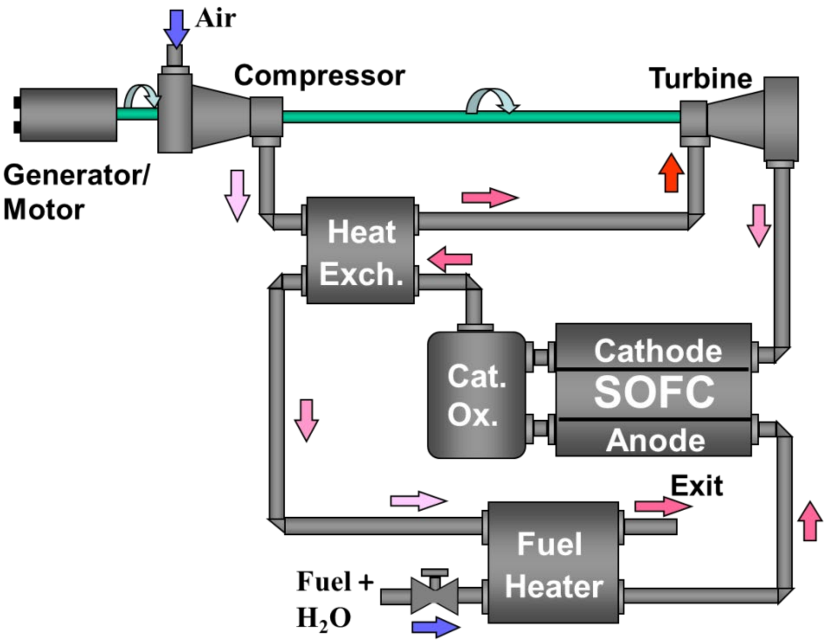

Figure 16. Schematic of the indirectly fired (atmospheric pressure) SOFC-GT design concept

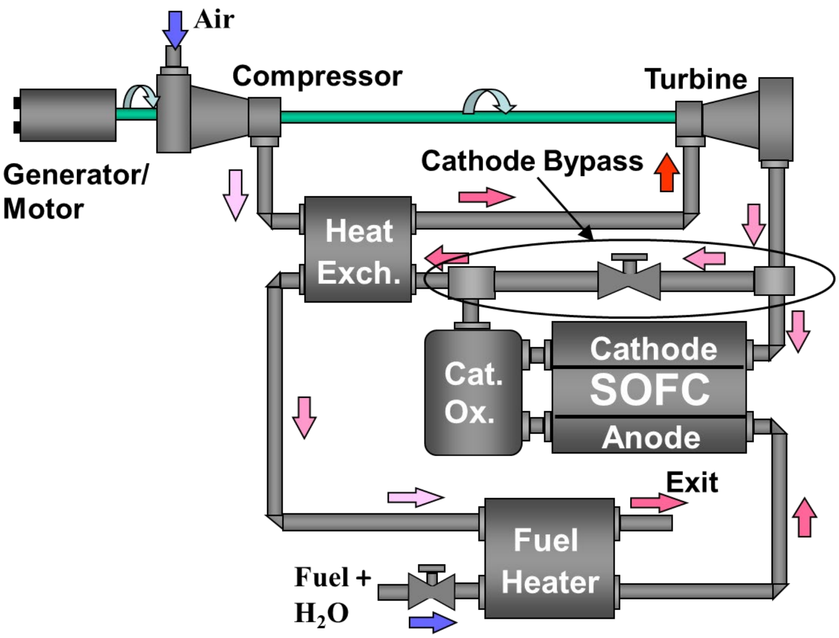

Figure 17. Schematic of the indirectly fired (atmospheric pressure) SOFC-GT design concept with cathode bypass

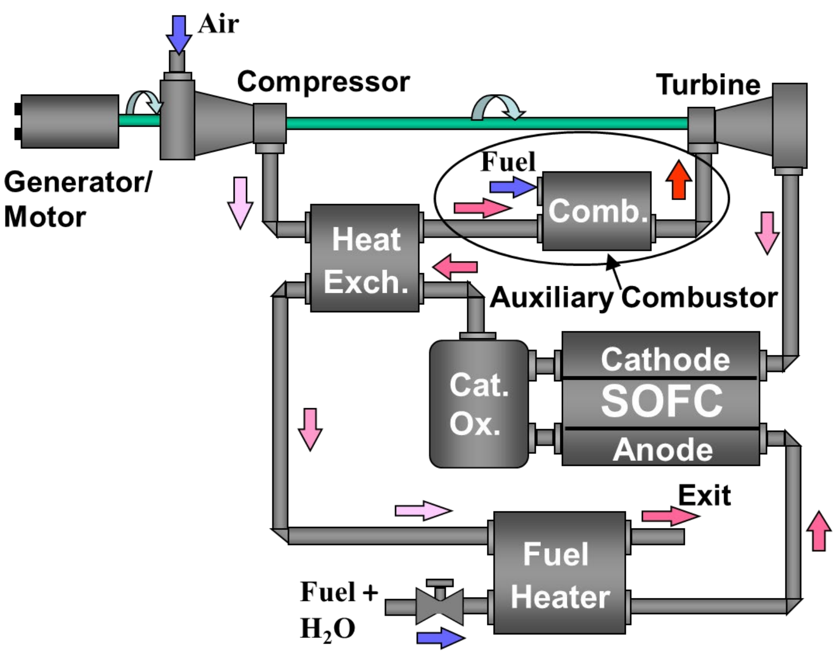

Figure 18. Schematic of the indirectly fired (atmospheric pressure) SOFC-GT design concept with added auxiliary combustor

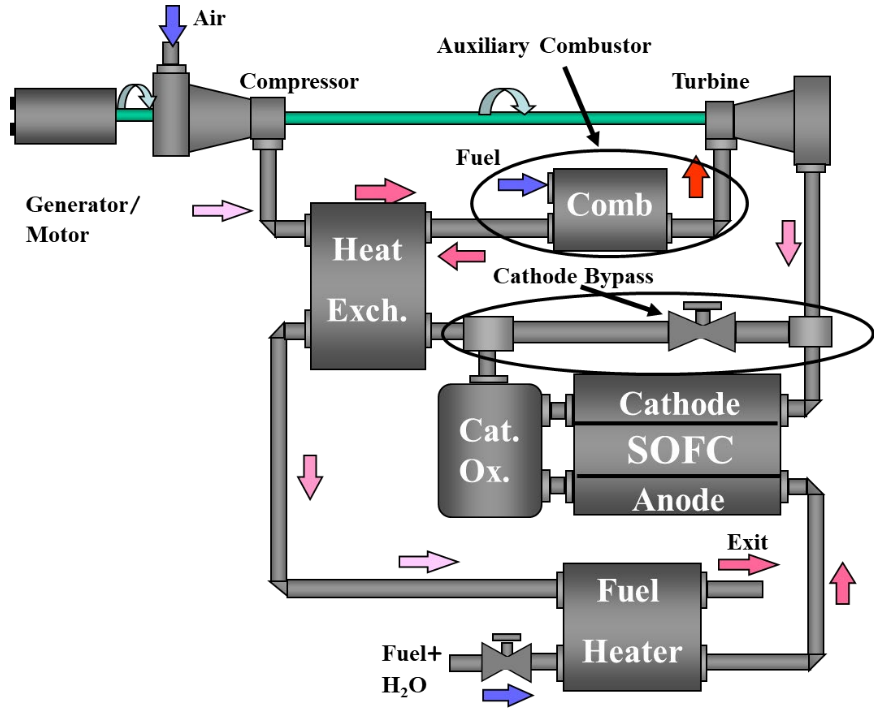

Figure 19. Schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration with a cathode bypass and auxiliary combustor

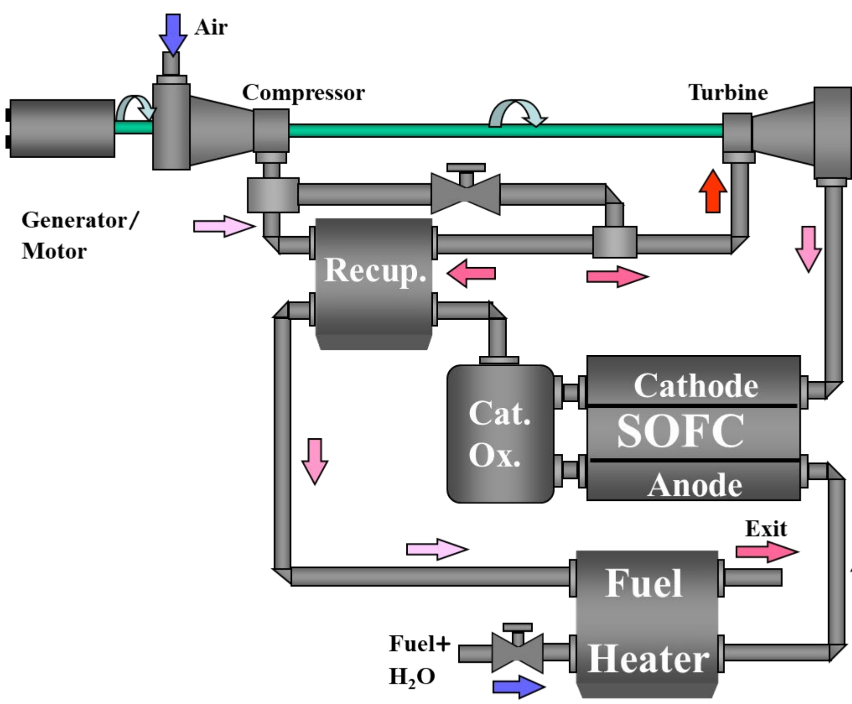

Figure 20. Schematic of the indirectly fired (atmospheric pressure) SOFC-GT system configuration with recuperator bypass

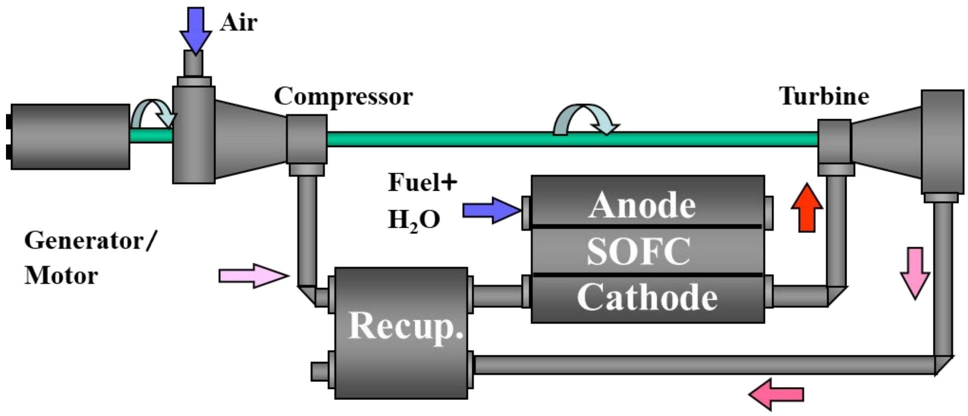

Figure 21. Schematic of the directly fired (pressurized) SOFC-GT system configuration with a cathode bypass and auxiliary combustor

3.3.1 Turbo-machinery Design Impacts

The Capstone® micro-turbines presented in Figure 15 above employ variable speed generators to maintain high efficiency at reduced load by reducing the rotational speed. This reduces the airflow to maintain turbine exhaust temperature, and thus retains the same effectiveness in the regenerative heat exchanger. Since pressure ratio decreases with speed, the turbine inlet temperature is lower despite the fixed exhaust temperature. This operating strategy causes the regeneration to provide a greater portion of the heat addition to the high-pressure air, making the lower mass flow inherently more efficient.

The opposite is true for the axial flow turbine, which does not utilize a regenerative heat exchanger, Figure 22, as reduced airflow corresponds to lower efficiency. Axial flow turbines operate synchronous with the electric grid. It cannot use variable speed generators and thus employ inlet guide vanes to reduce the mass flow and maintain high operating temperatures at reduced load. The guide vanes reduce the compressor efficiency and operating pressure resulting in a substantial impact on efficiency at reduced load. The achievable range of inlet guide vane manipulation without stalling the engine limits the operating regime of large turbines to between 70–100 percent rated output. The wider operating range of a micro-turbine is more suitable to a hybridization and hybrid control strategies.

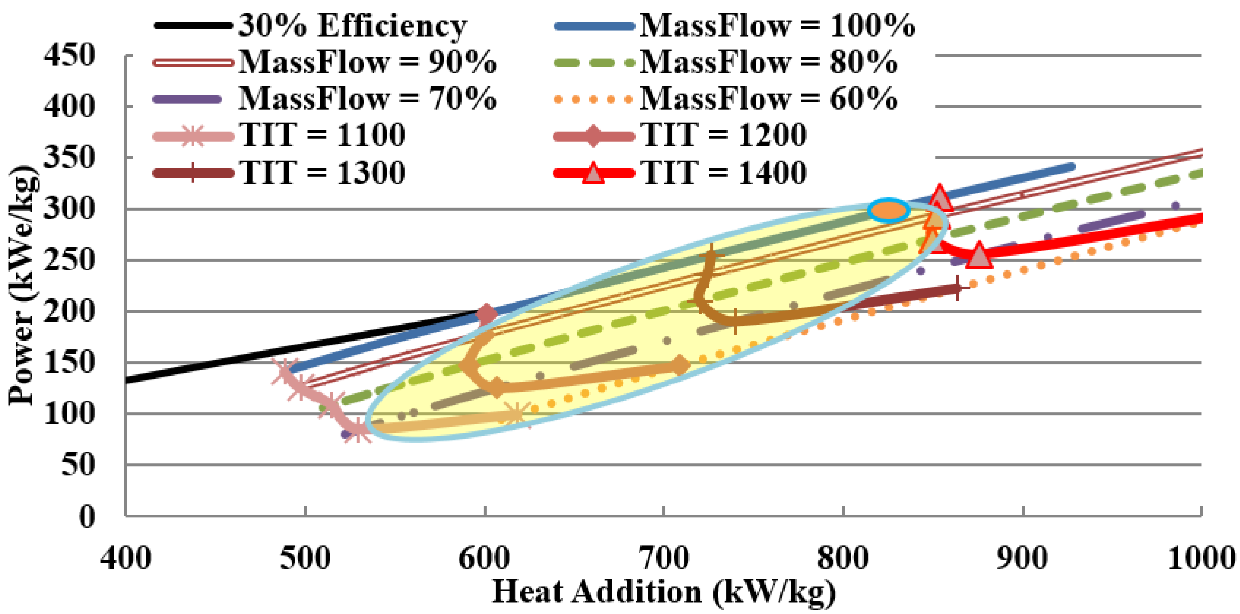

Figure 22. Axial turbine performance map scaled with airflow (kg/s)

The SOFC performance map is similar to that of the MCFC with a few subtle differences due to reduced steam reformation and the associated stack cooling it provides. The DOE Solid State Energy Conversion Alliance (SECA) program target voltage is slightly below that of a FuelCell Energy® DFC unit, thus the nominal operation is slightly below 50 percent efficient. Since additional fuel injection does not provide stack cooling, the airflow requirement is nearly the same at higher fuel flow rates. Some additional power is yielded due to the higher concentration of hydrogen in the anode. The primary impact is the additional heat release in the post-oxidizer, resulting in a more decoupled trend on the power vs. heat release diagram, Figure 23, SECA target and SOFC operating on high hydrogen content coal syngas at 1 atm and 10 atm. The most important difference between the MCFC bottoming cycle and the SOFC topping cycle is the capability to operate the fuel cell at elevated pressure.

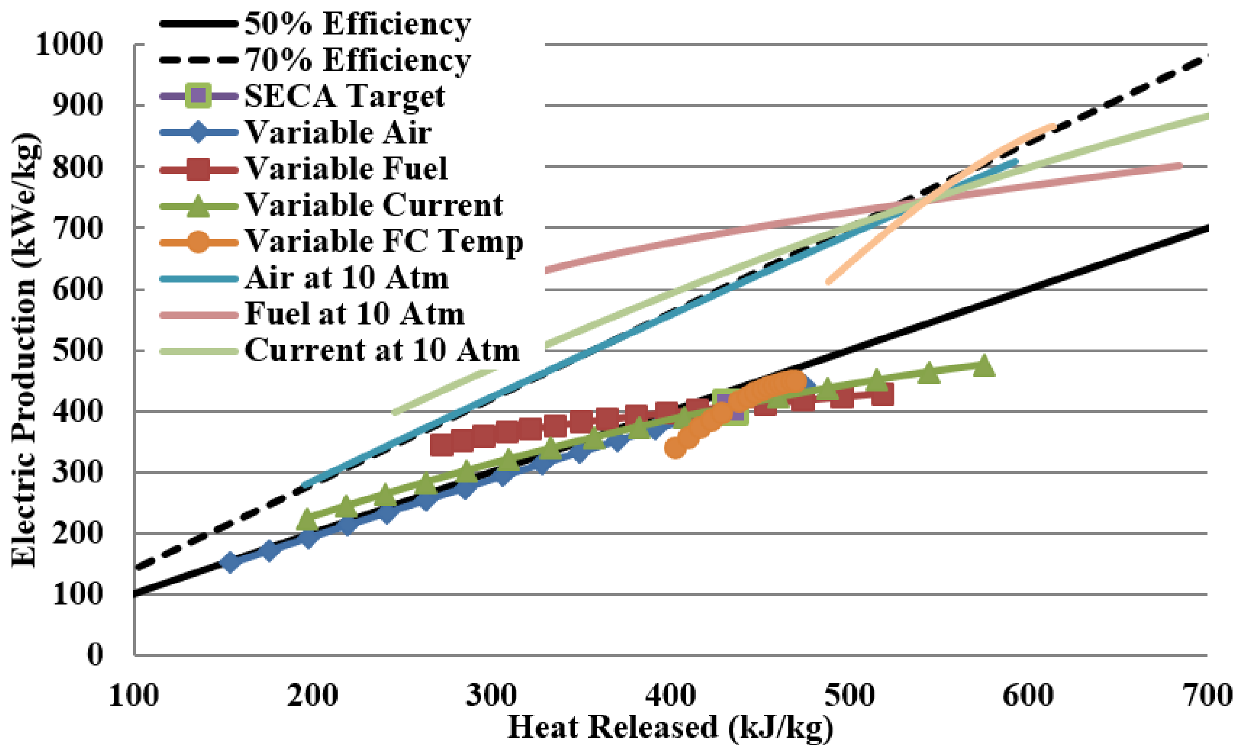

Figure 23. SECA target and SOFC operating on high hydrogen content coal syngas at 1 atm and 10 atm

As in the molten carbonate fuel cell, the post-oxidizer temperature is a function of only the average electrolyte temperature and the specific heating value.

Unlike the radial turbine and molten carbonate fuel maps which indicated relatively compatible specific heating values; these two maps differ greatly. The turbine ranges from 600–900 kJ/kg and the SOFC from 200–500 kJ/kg. This disparity requires cathode recirculation to act as a multiplier of the SOFC heat release. Cathode recirculation increases the specific heating, but also changes the pre-heating requirement and introduces either a parasitic load if a blower is employed or a large pressure loss if an ejector is implemented. Without recirculation, the turbo-machinery could be designed to operate at a pressure, which provides most or all of the air pre-heating for the cathode. Recirculating cathode exhaust provides a substantial amount of cathode heating, replacing that of compression or heat exchange from elsewhere in the cycle. The cathode air supply must be at a lower temperature, lowering the maximum compressor operating pressure unless some form of intercooling is applied. Previous analysis showed that higher pressure resulted in higher efficiency for an SOFC topping cycle, but for a cathode inlet temperature of 650 °C, an upper pressure limit is 15 atm.

With the additional complexity of cathode recirculation, the integration of these two performance maps is less straightforward. The airflow rates for the two devices will be different, thus the application of a conversion factor between the normalized maps is used. The post-oxidizer temperature estimate will be elevated as recirculation increases, Equation 5. The estimate for the hybrid efficiency, Equation 4, does not consider the parasitic losses of a blower or ejector. Depending on the amount of recirculation and pressure drop across the fuel cell the blower parasitic can range from 1–3 percent of the nominal output. Equation 4 will overestimate efficiency by 1–2 percent. Equation 7 can be re-arranged to estimate the necessary recirculation as one minus the ratio of specific heat for the fuel cell exhaust and turbine input.

$$\eta_{hybrid} = \frac{\dot{w}_{FC}+(1-r)\dot{w}_{MGT}}{\dot{w}_{FC}+\dot{q}_{FC}}$$ Equation 4

where, η_{hybrid} is the efficiency of the system, $\dot{w}_{MGT}$ is the specific power and micro gas turbine; r is the cathode recirculation

$$T_{turbine\ inlet} = \frac{1}{(1-r)}(T_{oxidizer} - T_{cathode}) + T_{cathode}$$ Equation 5

where, T is temperature

For the pressurized SOFC and gas turbine of this section a recirculation of 30 percent or greater is necessary. An example of how to apply equations 4 and 6 is shown using the nominal fuel cell condition at elevated pressure (750 kJ/kg electric and 550 kJ/kg of heat) and targeting the nominal turbine operation (275 kJ/kg electric and 800 kJ/kg heat). Using Equation 6 finds recirculation to be 31.25 percent and Equation 4 yields an estimated hybrid efficiency of 72.24 percent. This quick approximation is quite close to the 70.05 percent system efficiency calculated from a detailed simulation of this particular system, explored further in Section 3 and which considers heat losses, heat exchanger ineffectiveness and the parasitic blower load. Application of this estimation method produced similar results for a variety of configurations and fuel cell types.

$$r = 1 - \frac{q_{FC}}{q_{GT}} = 1 - \frac{550}{800} = .3125 * 100 = 31.25\%$$ Equation 6

Where, q is heat of fuel cell or gas turbine

$$\eta_{hybrid} = \frac{\dot{w}_{FC} + (1-r)\dot{w}_{MGT}}{\dot{w}_{FC} + \dot{q}_{FC}} = \frac{750 + (1 - .3125) \cdot 275}{750 + 550} = .7224 * 100 = 72.24\%$$

Exhaust gas heat recovery substantially improves system efficiency of the SOFC topping cycle studied by reducing cathode recirculation and increasing the relative size and output of the turbine. Heat recovery can be applied to the axial turbine model and a new performance map used to determine the hybrid integration. Applying sufficient heat recovery to raise the compressor outlet temperature from 600 °C to 800 °C produces the simulation results of Figure 24. Axial turbine performance map with exhaust heat recovery. The specific power output is the same for each operating condition, but the heat requirement is reduced. An estimation of this map can be found by scaling the x-axis of Figure 23. Axial turbine performance map scaled with airflow (kg/s) does not account for the changing heat exchanger effectiveness at reduced mass flow and exhaust temperature. SECA target and SOFC operating on high hydrogen content coal syngas at 1 atm and 10 atm, results in a recirculation of 18 percent and a net system efficiency of 75 percent. Detailed study of the integration at these conditions determined a net system efficiency of 72.4 percent considering heat losses and parasitic loads.

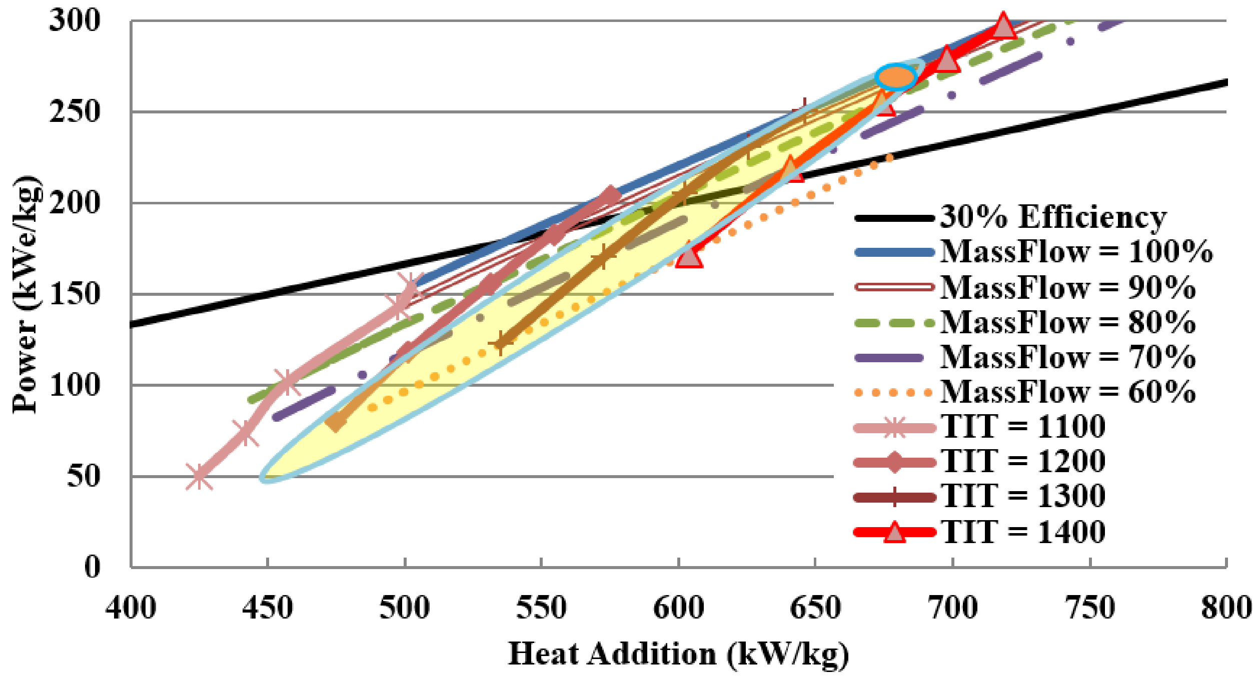

Figure 24. Axial turbine performance map with exhaust heat recovery

3.3.2 Micro-turbine Hybridization, Capstone® C-65, C-250, C370LP-spool

When both the fuel cell and micro-turbine have been specified the same method can be employed using non-scaled performance maps specific to each device. Without scaling, changes to the fuel cell operating condition produce noticeably different trends, while the turbine remains similar. Table 7 presents the specification of the Capstone® line of micro-turbines. The resulting performance map for the C-250 engine, Figure 25, better demonstrates the de-rate in power at reduced heating rates. The operating window of the C-250 turbine appears to be at heating rates between 250 and 800 kW to produce between 50 and 250 kW of electric power. It is worthwhile to note that the micro-turbines exhibited poor emissions performance at low power during tests at UCI; however, this would not be an issue when hybridization replaced the combustor with clean electrochemical oxidation.

Table 6. Various Capstone Micro-turbine Specifications

Specification	C-65	C-250	C-370 LP spool
Mass Flow (lb/s)	1.08	3.44	3.2
Compressor Outlet (°F)	424	469	397
Compressor Outlet (psig)	40	58.8	49
Recuperator Outlet (°F)	1,050	1,097	960
Turbine Inlet (°F)	1,720	1,788	1,550
Efficiency (%)	31.2	33.25	34.5

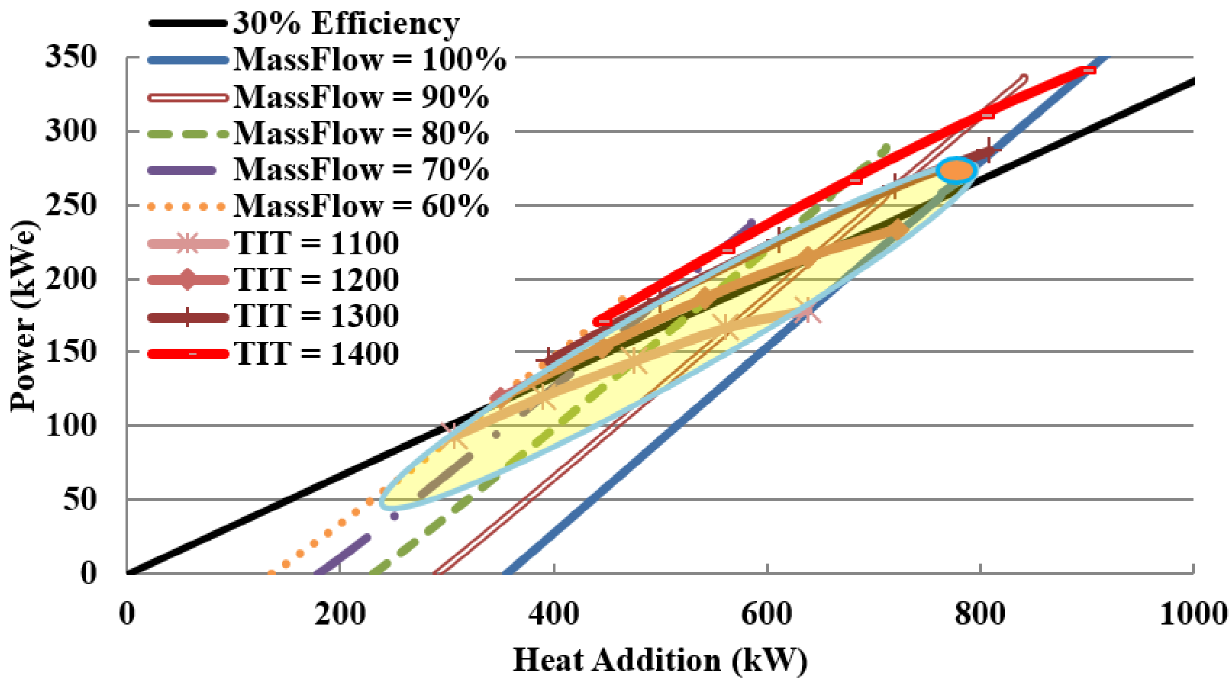

Figure 25. Capstone® C-250 performance map

3.3.3 Hybrid SOFC-GT Locomotive Dynamic Operation

The production of a full dynamic model of the locomotive system occurred at MATLAB/Simulink, to develop the prototype. The power profile in the model is determined via notching algorithm developed in the MATLAB/Simulink platform. The system takes elevation, acceleration and velocity as an input to the notching algorithm and calculates the notch based on constant locomotive speed.

Locomotive traction and dynamic braking evolved over many years. In diesel locomotives, eight notches for the throttle control emerged based on a three-valve fuel control. Note that more modern locomotives have different numbers of notches and levels of dynamics braking. In the current study, eight notches have been modeled for the control system. System of the locomotive is designed for a 1 MW switcher similar to EMD RS 1325. A single vehicle model is developed in MATLAB/Simulink platform. The total distance on the rail yard is calculated based on double integration of traction force. The net force on locomotive is calculated based on rolling resistance, air and axle resistance and the switcher weight. The power duty cycle of a 1 MW and 3 MW switching locomotive engine is shown in Figure 26 and Figure 27, respectively below.

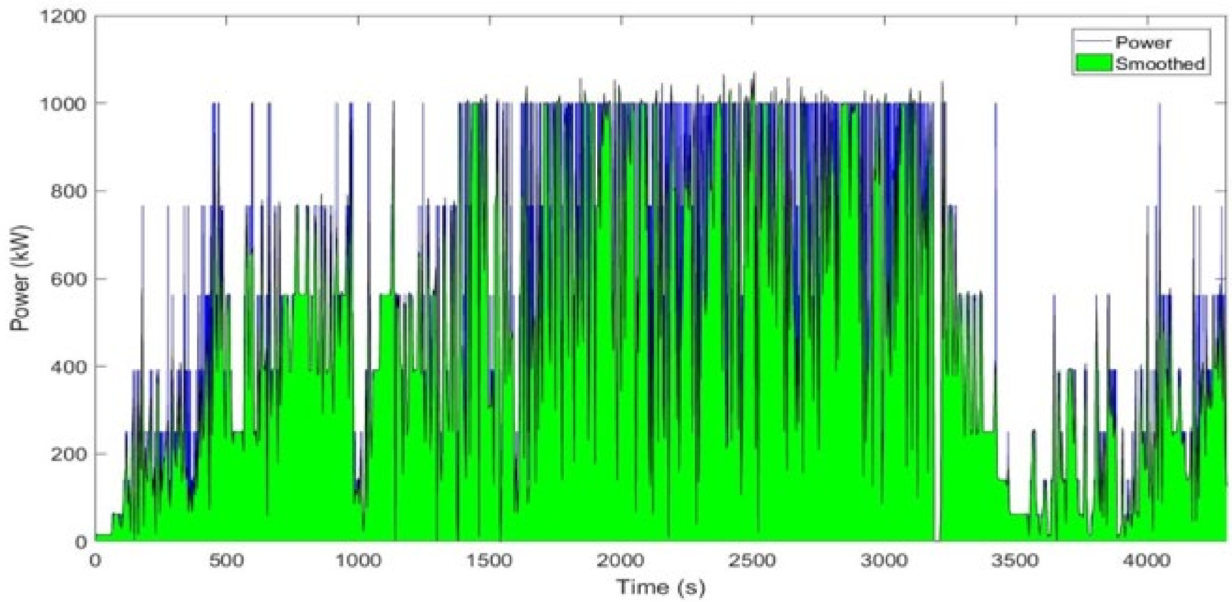

Figure 26. Power duty cycle of a 1 MW switcher locomotive

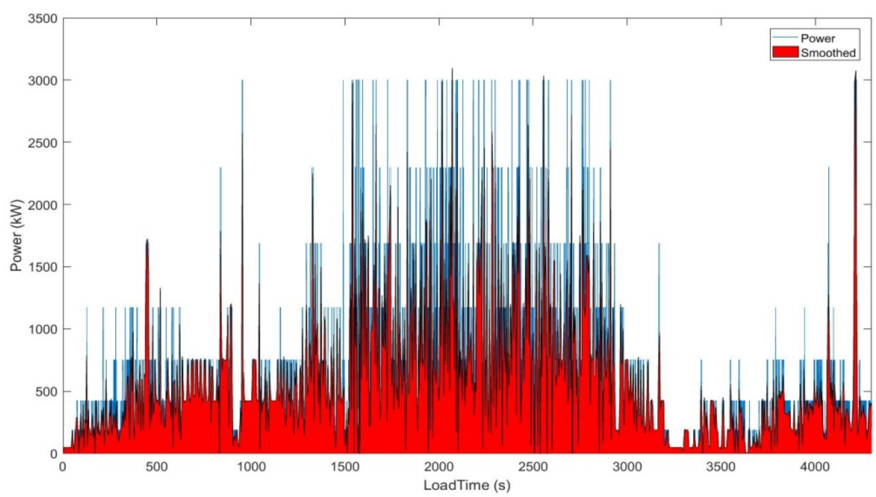

Figure 27. Power duty cycle of a 3 MW locomotive

The calculated dynamic traction force:

$$\text{For } F_{t/db} * v < \left(\frac{N^2}{64}\right) * P_{max},\ F_{t/db} = \left(\frac{N}{8}\right) * Te_{max} - k_f * v$$

$$\text{Else } F_{t/db} = \left(\frac{N^2}{64}\right) * P_{max}/v$$

Where N is the throttle setting in notches, zero through eight; P_{max} is the maximum locomotive traction horsepower in watts; Te_{max} is the maximum locomotive traction force, N and k_f is the torque reduction, N/(m/s).

The system development for the locomotive is based on two main components of vehicle dynamics and notch calculation. The notch system takes speed of the locomotive, grade of the route, acceleration and traction/brake force as an input.

There were several assumptions regarding the implementation of the notching algorithm: 1) the maximum desired train velocity was 60 mph; 2) the minimum desired train velocity was 10 mph; 3) the power notching progressed by one notch at a timestep (increasing or decreasing), (this decision is made by the locomotive driver); 4) notching does not alternate rapidly between the timesteps; and 5) the sign of the grade has an effect on the decision making.

3.3.4 System Optimization

To optimize the system, the research group completed parametric analysis on the fuel cell design. The parameters of PEN average temperature, stack temperature difference, hydrogen and oxygen utilizations, voltage and current densities were varied. Figure 28 shows the parametric study in order to find the optimal fuel cell configuration for the prototype manufacturing of the first hybrid SOFC-GT engine to be used in a 1 MW switcher. Figure 29 shows the parametric analysis for various fuel cell parameters, including power, current, voltage, PEN average temperature, stack temperature difference, and hydrogen utilization and oxygen utilization for the 3 MW prototype system. The figures illustrates the advantage that elevated pressure has on stack performance. The physical characteristics, material properties, and operational power density remain the same, but the increased voltage reduces current and heat generation substantially. The relationship of current, airflow and operating temperature remain similar. As the figures show the linear correlation between power and current, power and voltage, power and stack temperature difference, power and hydrogen utilization, and power and oxygen utilization. As a result, the set-point for hydrogen and oxygen utilization changed to the optimal value that maintains the maximum amount of hydrogen and oxygen utilization and maintains the stack temperature difference in a limited range (the relation between the power and hydrogen utilization, power and oxygen utilization and power and stack temperature difference is positively linear).

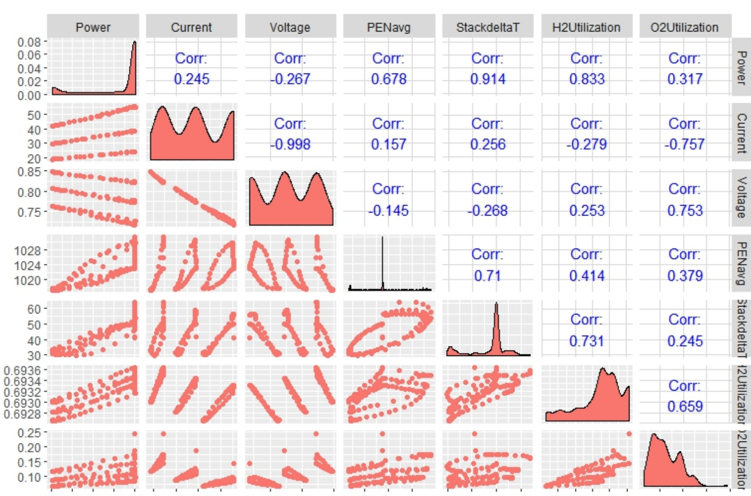

Figure 28. Optimal parametric study of fuel cell stack fo 1 MW prototype switch engine

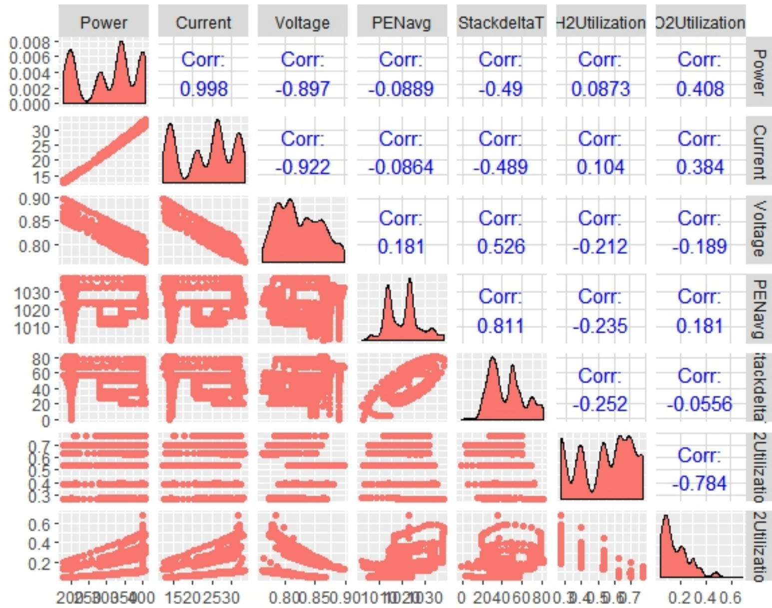

Figure 29. Parametric analysis for performance parameters for 3 MW design

Figure 30 shows the variation of stack temperature difference over time with parameters of fuel utilization and power density. The fuel cell operation shows less variation at higher fuel utilization indicating more stability of performance during transient operation. The more stable performance of fuel cell during transient operation at higher fuel utilization that leads to higher amount of power produced, leads to the optimal value of fuel utilization at 0.8.

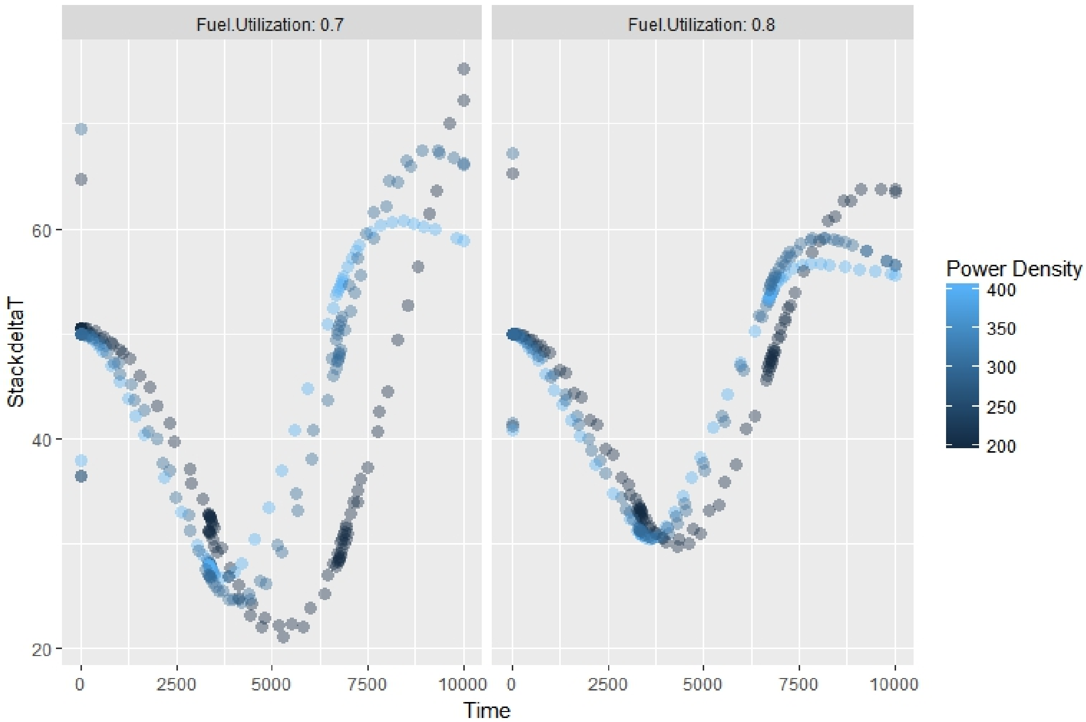

Figure 30. Stack temperature difference with variation of power density and fuel utilization

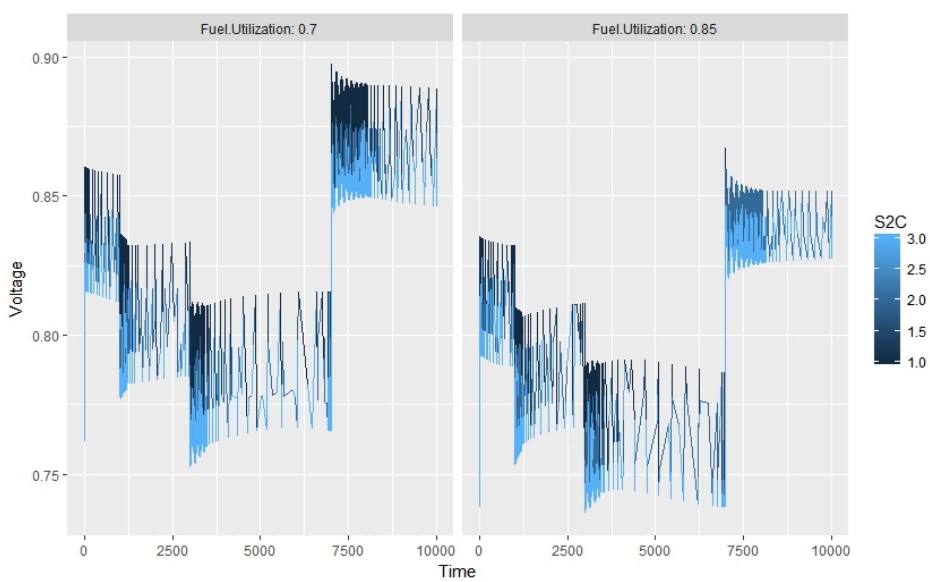

Figure 31. Voltage variation at different fuel utilizations and steam to carbon ratio

Figure 31 shows more stable operation of fuel cell stack at higher fuel utilization. At 0.85 hydrogen utilization, the system shows less transient variation. In addition, lower steam to carbon ration leads to higher voltage on the fuel cell.

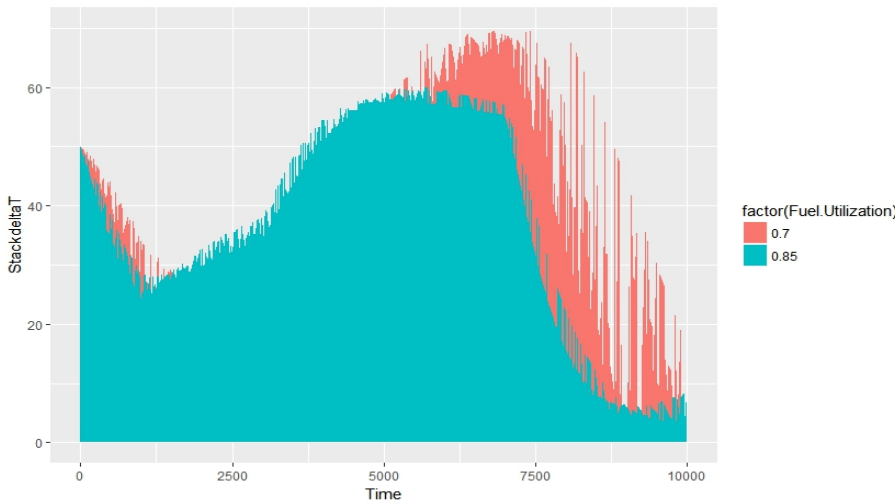

Figure 32. Dynamic stack temperature difference at different fuel utilizations

Figure 32 and Figure 33 show the dynamic stack temperature difference at different fuel utilizations. In addition to the higher value of stack temperature difference, which could be detrimental to stack operation, lower fuel utilization shows more transient behavior of the fuel cell.

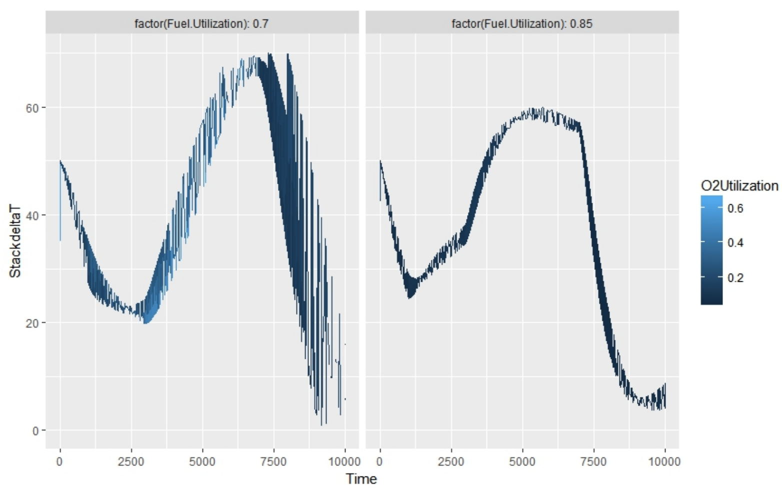

Figure 33. Stack temperature difference at different oxygen and fuel utilizations

3.3.5 System Modeling

The prototype system developed by the NFCRC consists of SOFC, gas turbine system, fuel preheater, and fuel cell bypass and heat exchanger bypass valves.

The compressor module consists of compressor map that calculates flow rate and efficiency of the compressor and gets the airflow rate, outlet pressure of the compressor and the rotational speed of the compressor as an input. The model solves the energy balance of the compressor. The system consists of fuel cell bypass.

Fuel Cell Mathematical Modeling

The development of mathematical modeling of the fuel cell stack is in several studies (McLarty, D, et.al., Martinez, A, et. al.). The system consisted of a three-dimensional model that resolves heat transfer and fluid dynamics equations through in electrode and electrolyte layers. Equation 7 to Equation 9 governs the temperature state of the solid portion of heat exchanger, and includes the heat transfer from both fluids and the conductive heat transfer between adjacent segments.

$$Q_{heat\ transfer} = h_c A_{surf}(\frac{T_{in}+T_{out}}{2} - T_{solid})$$

Equation 7

Where, Q is heat transfer, h_c is the enthalpy of combustion, A is area

$$\frac{dT_{out}}{dt} = \frac{(h.\dot{n})_{in-out} - h_c A_{sur}(\frac{T_{in}+T_{out}}{2} - T_{solid})}{C_p V_{node} C}$$

Equation 8

Where C_p is the constant pressure specific heat

$$\frac{dT_{solid}}{dt} = \frac{\left[\begin{matrix} h_c A_{sur,cold}(\frac{T_{in,cold}+T_{out,cold}}{2} - T_{solid}) \\ h_c A_{sur,hot}(\frac{T_{in,hot}+T_{out,hot}}{2} - T_{solid}) \end{matrix}\right] k_{cond} A_{sur}(T_{n+1}+T_{n-1}-2.T_{solid})/L_{node}}{C_v V_{solid} \rho}$$

Equation 9

Where k is specific heat ratio, C_v is constant volume specific heat, L is length

The spatial discretization is generalized into n control volumes. The fuel cell modeling includes two-dimensional spatial discretization of the heat exchanger.

Gas Turbine Dynamic Model

A dynamic compressor and turbine model utilizes dynamic conversion equations and industry standard performance maps. The approach solves a dynamic torque balance equation for the shaft and includes mass storage for stall/surge analysis. The compressor model inputs include inlet temperature, pressure, and species concentrations, shaft speed, and an exhaust pressure. The flow rate supplied by the compressor and compression efficiency are determined from the empirical correlations using turbine speed, pressure ratio, and inlet temperature.

$$N_{RPM} = RPM\sqrt{{T_0}/{T_{des}}.RPM_{des}}$$

$$N_{Flow} = \frac{Flow}{Flow_{des}}.\frac{\sqrt{T_0/T_{des}}}{P_{in}/P_{des}}$$

$$PR = \frac{P_{out}.P_{des}}{P_{in}.PR_{des}}$$

Where, N_{RPM} is the normalized shaft speed, RPM is revolutions per minute, PR is the pressure ratio, N_{Flow} is the normalized inlet mass flow.

The simulated turbine inputs are inlet temperature, inlet species concentration, inlet flow rate, and exhaust pressure.

$$\frac{dP}{dt} = \frac{(\dot{n}_{in} - \dot{n}_{out}).R_u.T_{inlet}}{V_{turb}}$$

$$\dot{n}_{out}\eta_{turb} = f(N_{RPM}, PR, T_{inlet})$$

$$\dot{W}_T = (h\dot{n})_{in} - \dot{n}_{out}[(h_{in} - h_{ises})\eta_T]$$

$$\frac{dT_f}{dt} = \frac{\dot{W}_T + (h\dot{n})_{in-out} + h_c A(T_s - T_f)}{cP_{out}V_{turb}/R_u T_{out}}$$

$$\frac{dT_s}{dt} = \frac{h_c A\left(T_f - T_s\right) + \epsilon\sigma A(T_a^4 - T_s^4 c)}{c_p m}$$

$$\frac{d\omega}{dt} = \frac{(\dot{W}_T - \dot{W}_C - \dot{W}_{Gen})}{\omega I_0}$$

$$I_0 = \frac{\rho L \pi r^4}{2}$$

The recuperated gas turbine models were calibrated for efficiency and mass flow rate versus power generation for C65 gas turbine. The off-design performance is calibrated to test data at UCI. The model has been compared to data from NETL facility to validate the open loop control response to fuel valve step change.

Route Simulation

The simulated route for the prototype design is from Bakersfield to Mojave shows the prototype system design for the 1 MW prototype system. An R code has been written to extract the elevation profile of the map obtained from the Google API Console. The route includes the famous Tehachapi Loop.

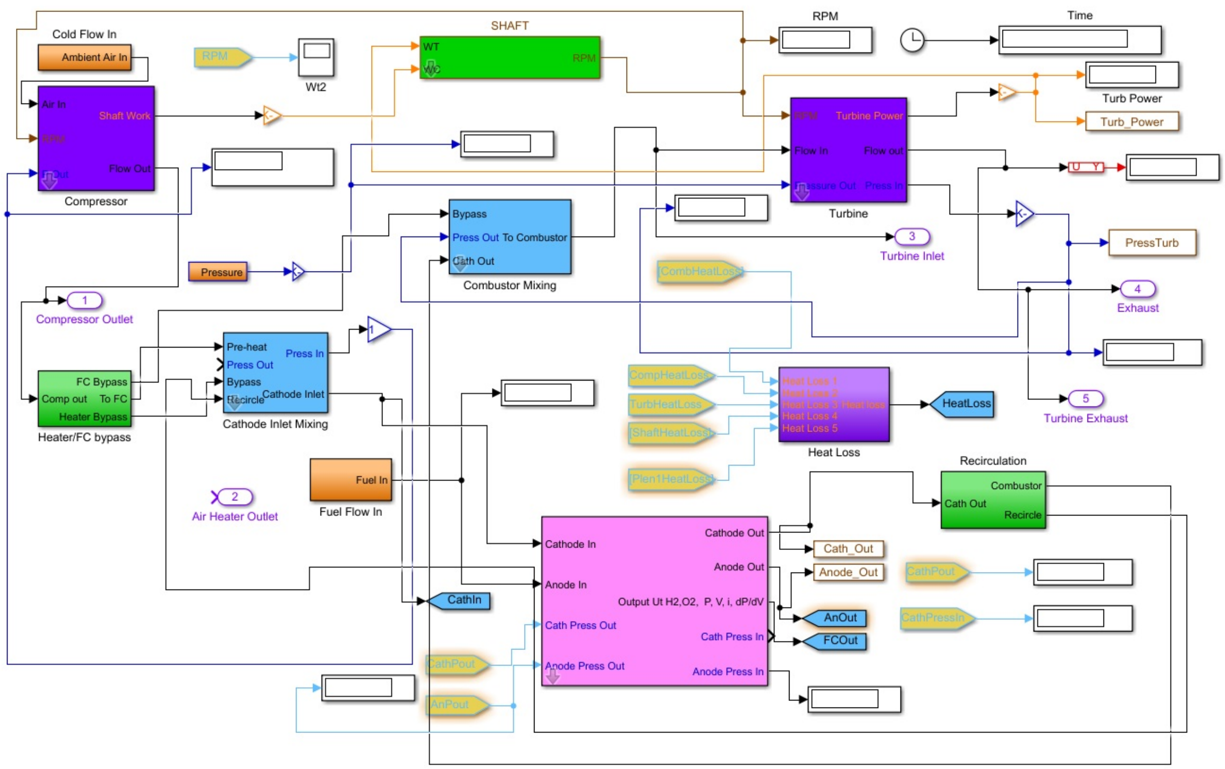

Figure 34. Prototype design of a 1 MW switcher locomotive

Figure 35 shows the test railroad of the Bakersfield to Mojave route that includes the Tehachapi Loop. The simulation of 1 MW switcher system is conducted on the aforementioned long-haul route.

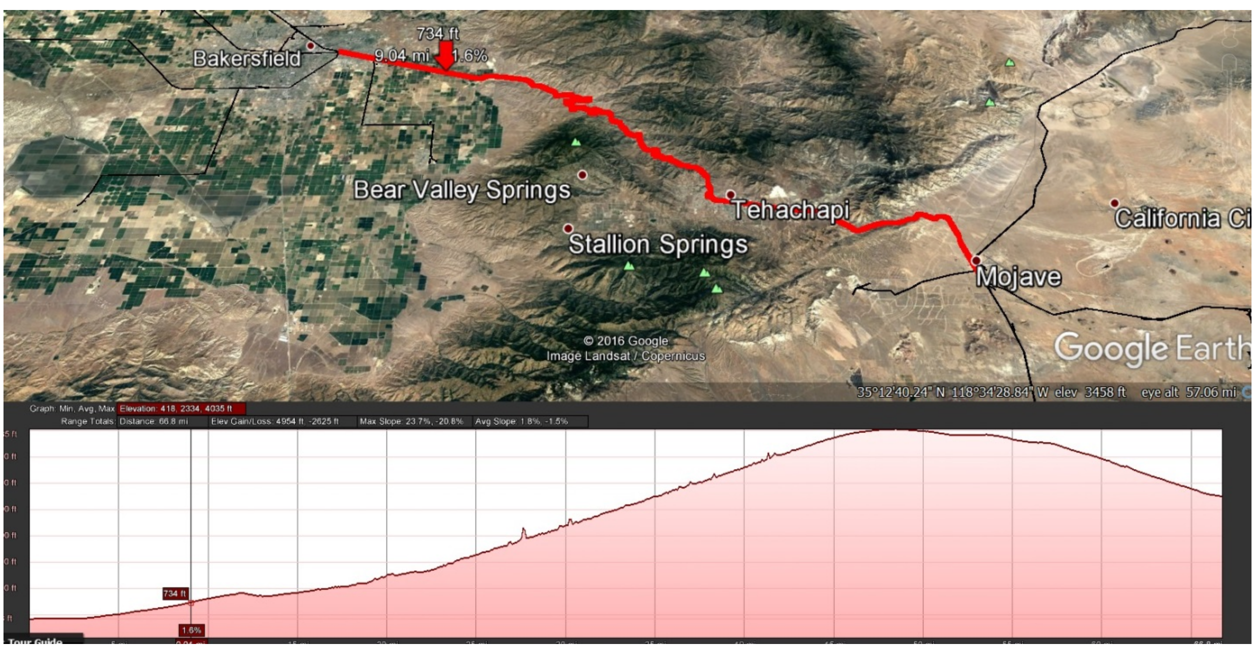

Figure 35. Schematic of the Bakersfield to Mojave route and elevation

[Figure 36](#) shows the dynamic simulation tool developed for the vehicle and the notching system.

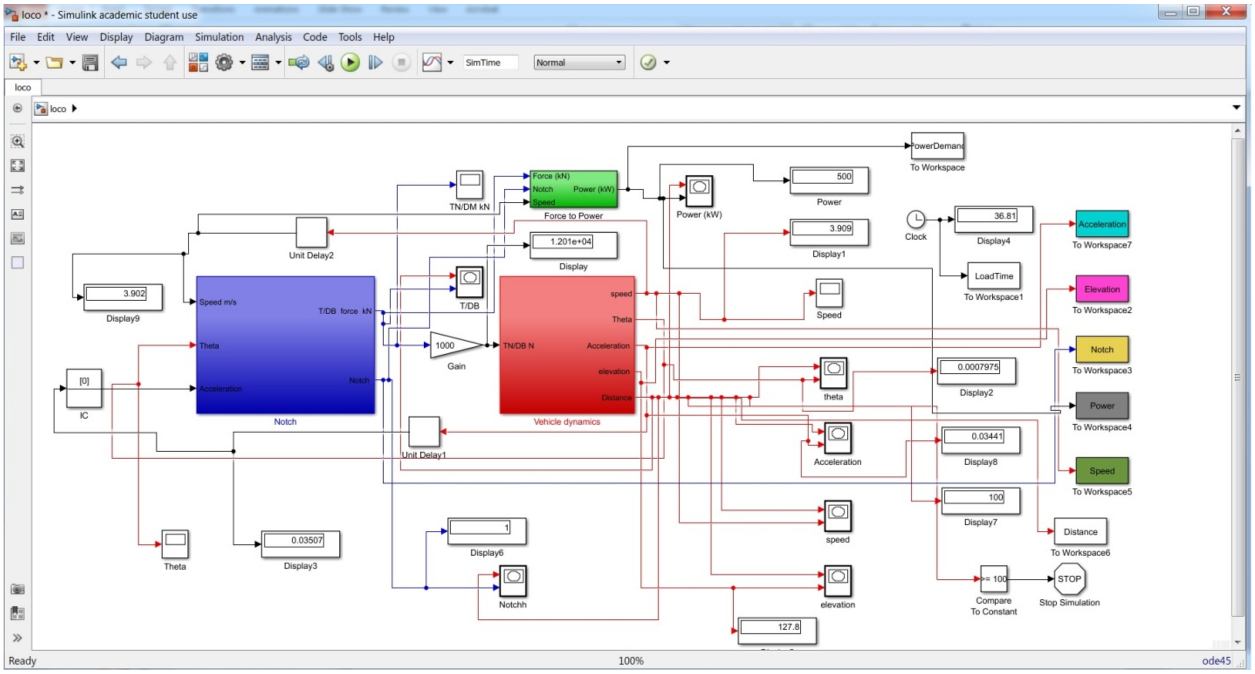

Figure 36. Vehicle and notching dynamic modeling

Notching Algorithm:

- The maximum desired train velocity was 60 mph (26.82 meters per second).
- The power notching had to progress by one notch at a time, whether increasing or decreasing notch. This decision could be made at every time step of the overall simulation.
- The same restriction was placed on the notching for braking.
- A power notch of both zero and one indicated 25 percent system power.
- A notch of zero on both power and braking indicated a coasting situation.
- The sign of the grade (whether uphill or downhill) could influence the decision-making process.
- Acceleration influences the decision-making process.

Figure 37 shows the Matlab/Simulink implementation of the notching algorithm. This algorithm has been applied in the MATLAB/Simulink platform. The algorithm consists of two sections of notching algorithm and vehicle dynamic simulation (Figure 38).

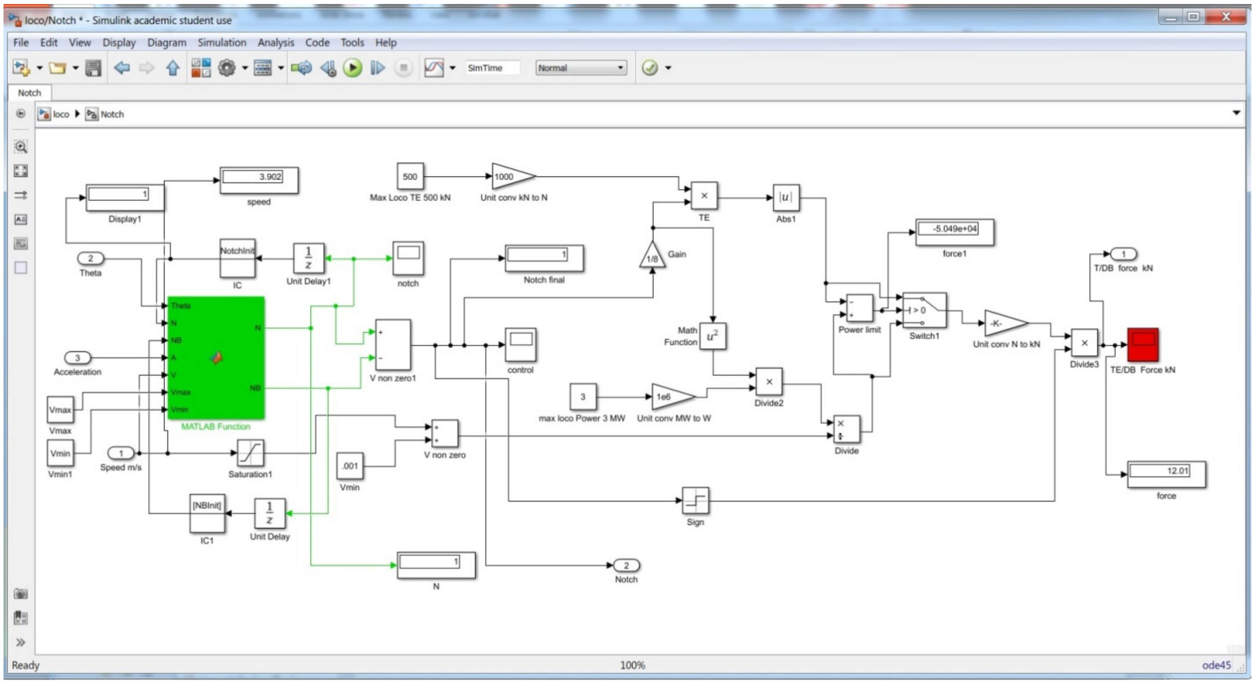

Figure 37. Notching algorithm implementation

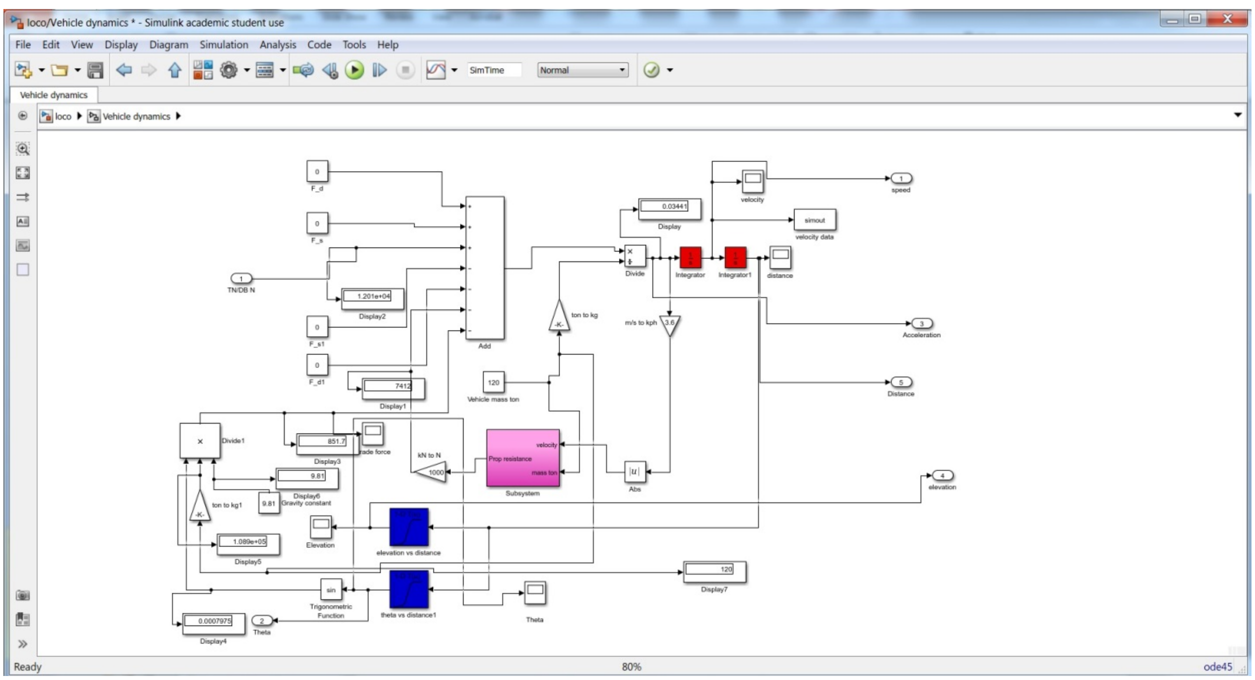

Figure 38. Vehicle dynamics algorithm implementation

Figure 39 shows the dynamic notching profile on the Bakersfield to Mojave route. The positive notch corresponds to engine propulsion, while the negative notch corresponds to braking. Notch zero corresponds to coasting. The Figure 40 through Figure 47 show the results of the simulation of the 1 MW switch engine locomotive.

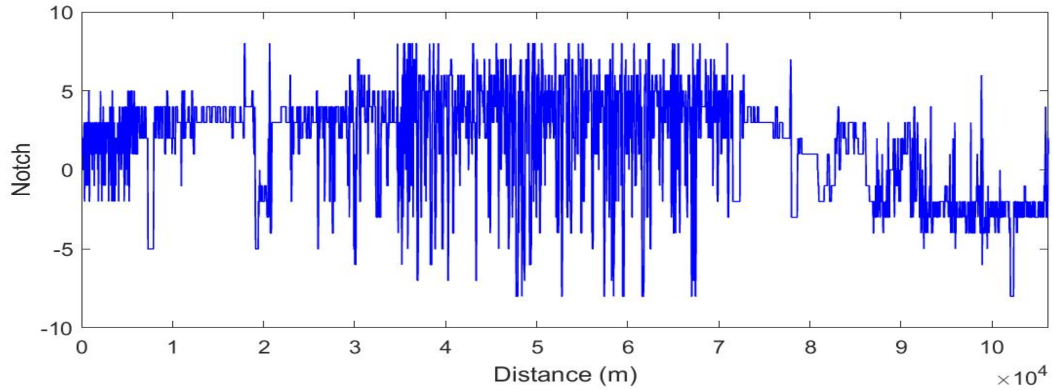

Figure 39. Notching dynamics over the Bakersfield to Mojave route

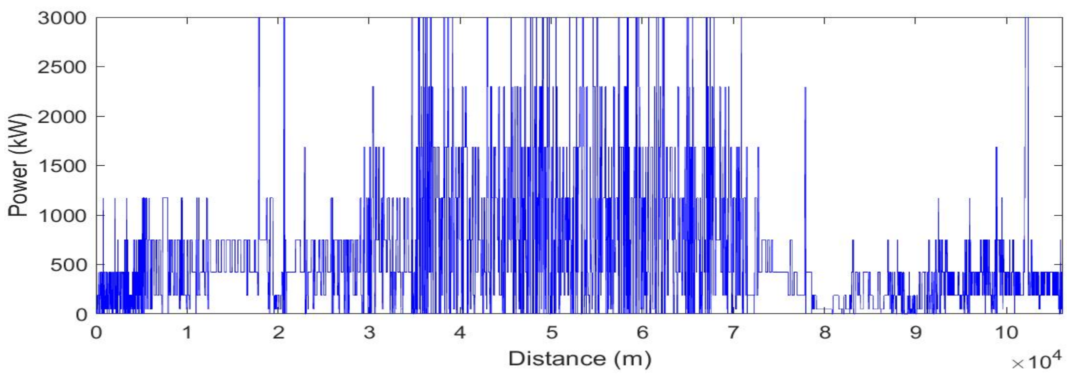

Figure 40. Power demand profile of a 1 MW switcher locomotive over the Bakersfield to Mojave route

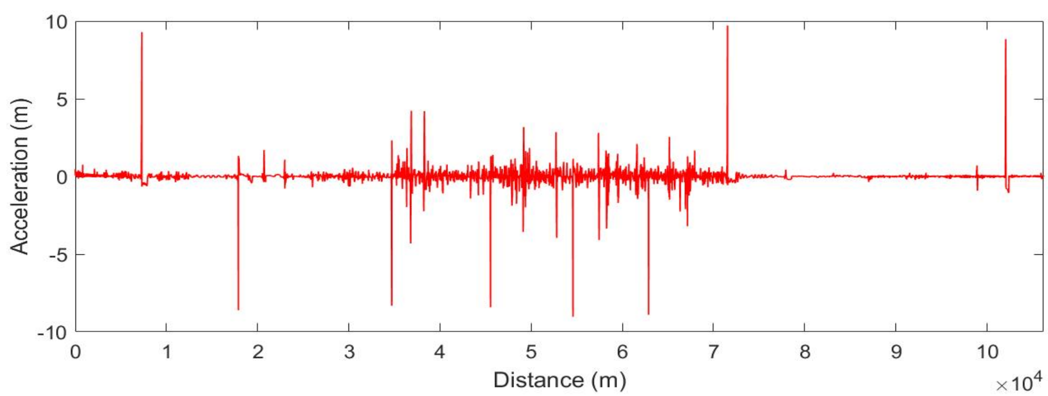

Figure 41. Acceleration profile over the Bakersfield to Mojave route

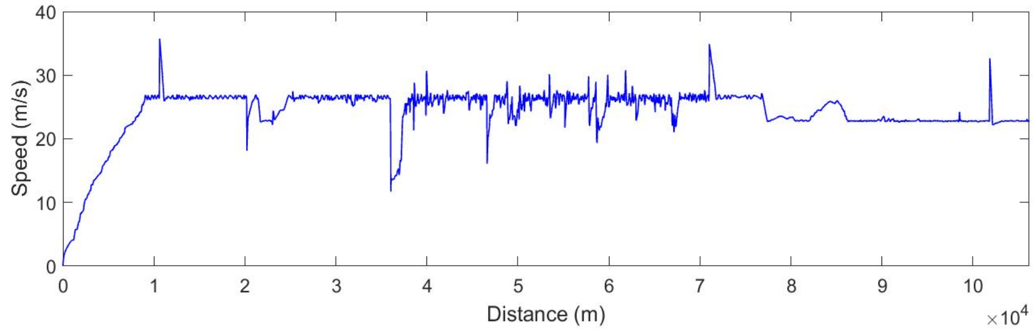

Figure 42. Speed profile of a 1 MW switcher locomotive

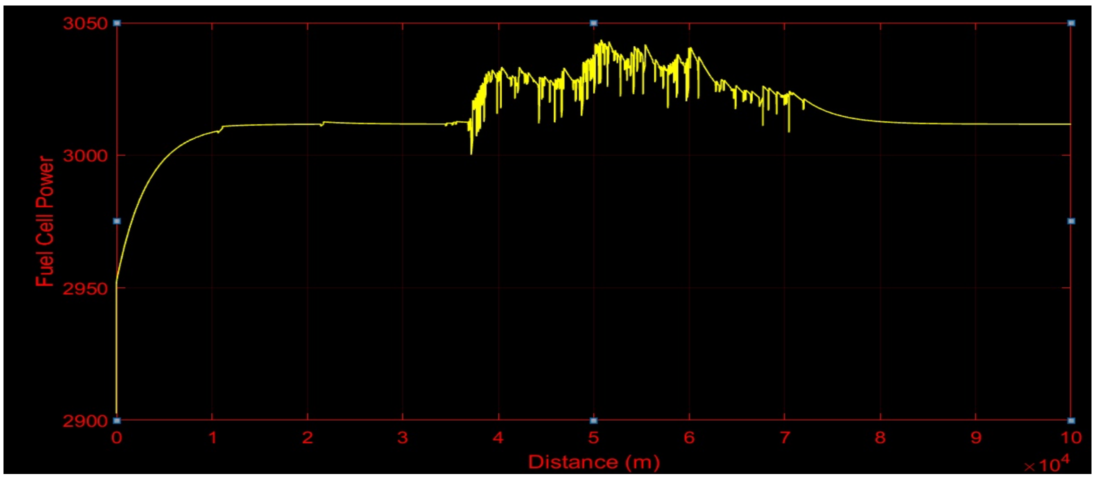

Figure 43. Stand-alone fuel cell power profile over the Bakersfield to Mojave route

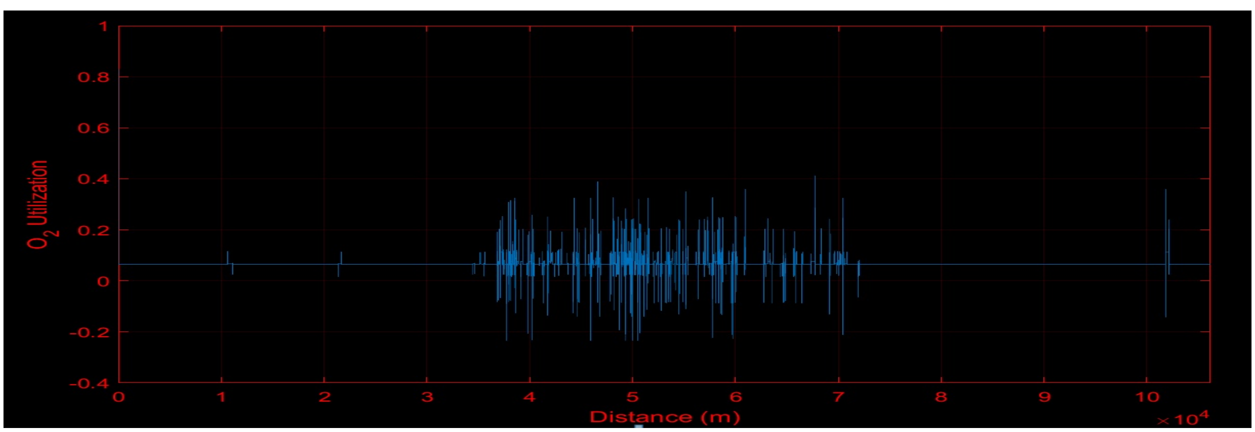

Figure 44. Stand alone oxygen utilization profile over the Bakersfield to Mojave route

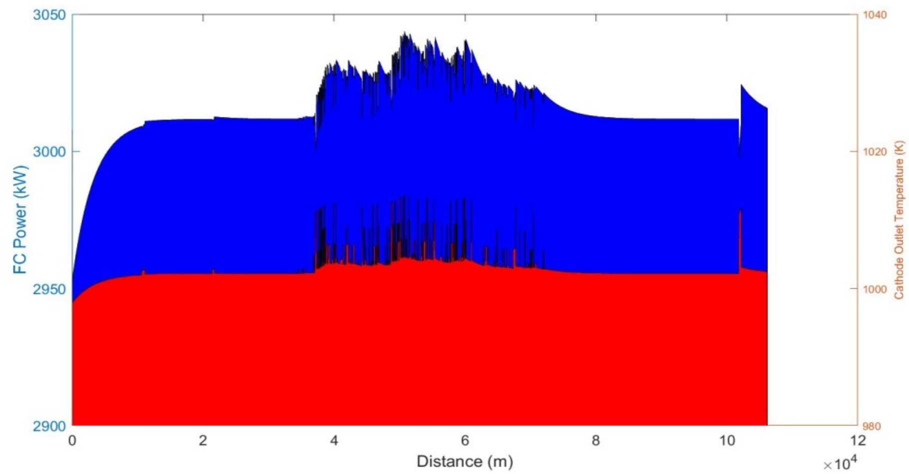

Figure 45. Cathode outlet temperature over the Bakersfield to Mojave route

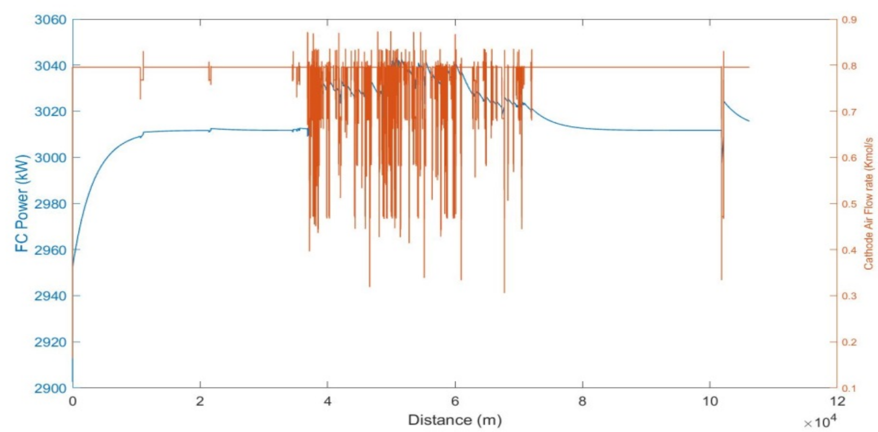

Figure 46. Cathode airflow rate over the Bakersfield to Mojave route

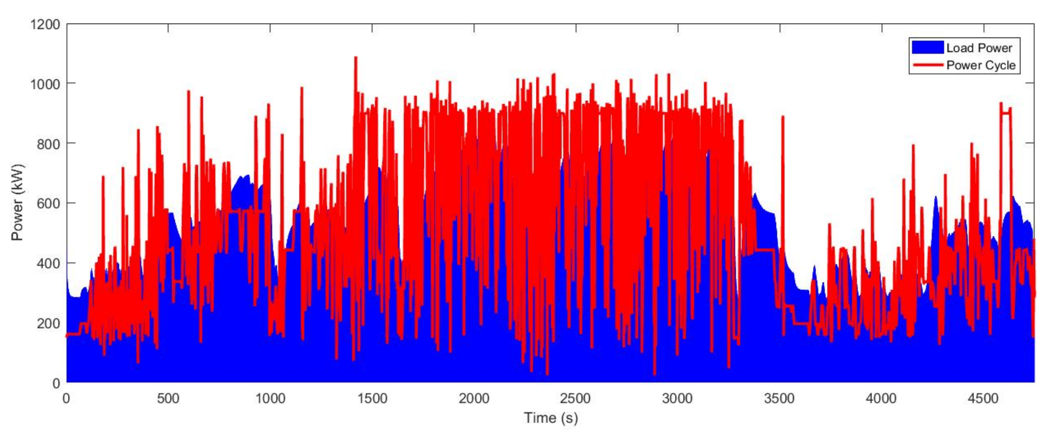

Figure 47. Power demand of a 1 MW switcher locomotive

Parametric Studies

Parametric study for fuel cell power density:

Figure 48 shows the dynamic plot of the fuel cell power density simulation over the Bakersfield to Mojave route. To make the data interpretable, Figure 49 shows the time independent data.

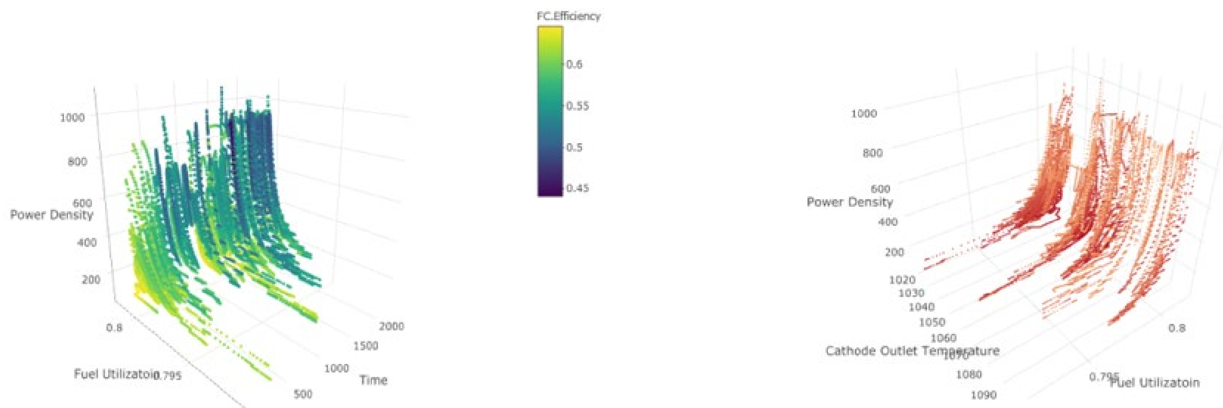

Figure 48. Fuel cell power density data over the Bakersfield to Mojave route

Figure 49 shows the data of fuel cell power density based on airflow and fuel utilization for the Bakersfield to Mojave route. The data is accumulated over the time range of simulation. In general, the data demonstrates strong independency of fuel cell operation from the airflow. However, there is strong correlation between the power density and the fuel utilization. At higher load power, where locomotive requires maximum traction force, higher fuel utilization is needed. The graph shows that the locomotive performance needs a high fuel utilization from 0.75 to 0.8. Economic algorithms can be developed to reduce the amount of fuel that is used in the locomotive.

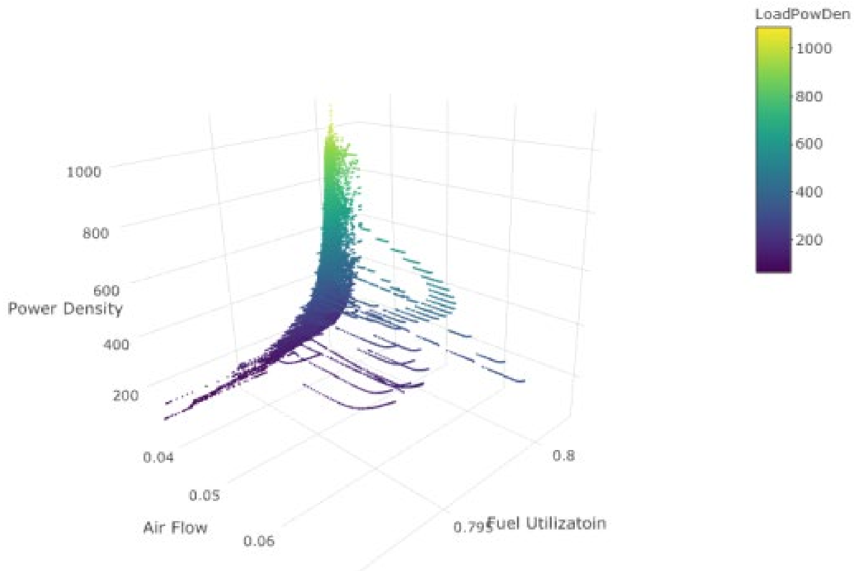

Figure 49. Fuel cell power density data over the Bakersfield to Mojave route

Figure 50 shows the parametric analysis for fuel cell power density over fuel and oxygen utilization over the Bakersfield to Mojave route. The power profile is highly dependent on the fuel and oxygen utilizations. The performance data is accumulated over the time range of the simulation.

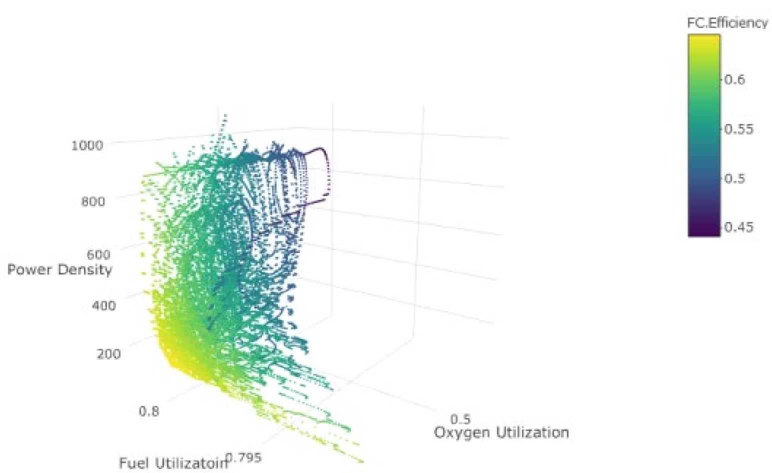

Figure 50. Interactive plot of fuel cell power density data, and fuel cell efficiency over the Bakersfield to Mojave route

The annual temperature of Tehachapi Loop varies between 0 ºC (32 °F) and 30 ºC (89.6 °F), as shown in the figure below. As the ambient temperature has a significant impact on the hybrid system performance, parametric studies have been accomplished for the hybrid system based on the ambient temperature in the range of 0 ºC (32 °F) and 30 ºC (89.6 °F).

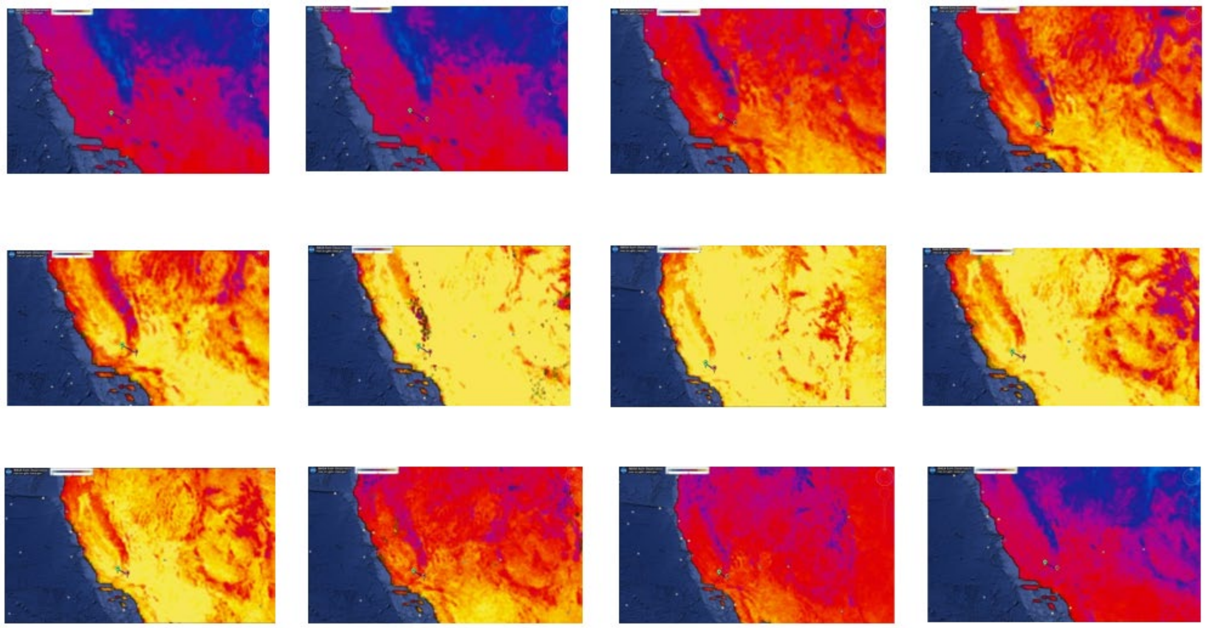

Figure 51. Temperature variation across Tehachapi Loop

Results of the parametric analysis for ambient temperature are a subject of current study.

4. Prototype Design and Evaluation

Table 8 shows the list and features of switcher locomotive engines investigated for developing the prototype design of a hybrid SOFC-GT system for locomotive applications. Recall that the step-by-step development process for the locomotive is as follows:

Prototype → Switcher → Medium Haul → Long-Haul

Table 8 also shows the total number of switcher locomotives of each type that was built and the power output of these locomotives. The table shows the total units of the switcher produced and the power output in both horsepower (hp) and kilowatts (kW).

Table 7. Features of Switcher Locomotives Currently in Use

Model Designation	Build Year	Total Produced	Power Output
EMC pre – SC	1935	2	600 hp (447 kW)
NW1	1937–1939	27	900 hp (671 kW)
NW2	1939–1949	1,145	1,000 hp (750 kW)
NW3	1939–1942	7	1,000 hp (750 kW)
TR	1940	3	2,000 hp (1,490 kW)
TR1	1941	2	2,700 hp (2,013 kW)
SW7	1949–1951	489	1,200 hp (895 kW)
SW8	1950–1954	815	800 hp (600 kW)
SW9	1950–1953	815	1,200 hp (890 kW)
SW600	1954–1962	15	600 hp (447 kW)
SW900	1954–1969	371	900 hp (670 kW)
SW1500	1966–1974	808	1,500 hp (1,100 kW)
SW1200	1954–1969	1,056	1,200 hp (890 kW)

The modeling process is divided into two sections of modeling the switcher and modeling the long-haul locomotive. The switcher modeling is used to develop a small order of magnitude 1 MW prototype system design, while the 3–4 MW class design is for the ultimate goal of designing a long-haul hybrid SOFC-GT locomotive.

4.1 Dynamic Simulation Capabilities Enhanced

A significant improvement to the dynamic simulation capabilities of the MATLAB Simulink SOFC-GT hybrid system model took place to simulate a locomotive on the route from Bakersfield to Mojave, but this system is not dynamic enough to match the power demand on this route completely. To mitigate this issue, an integration of the battery into the existing model occurred in order to provide instantaneous power when required, and absorb excess power from the SOFC-GT hybrid when available. Results show that the route can be successfully completed with a 1.5 MW SOFC-GT system combined with a 1 MW, 36 kWh battery.

Previous reports, introduced the MATLAB/Simulink SOFC-GT hybrid system model, and the use of dynamic CFD modeling was to demonstrate the feasibility of a Capstone gas turbine for a locomotive application. However, the successful modeling of the load cycle for the system along a representative route has not occurred yet. The current goal of this research project is to demonstrate that the dynamic operation of the SOFC-GT hybrid system is possible for such a route to gain confidence in a successful prototype test run. To achieve this, there was a major dedicated effort towards simulating the power demand curve for a 120-ton locomotive traveling from Bakersfield to Mojave via the Tehachapi Loop (Section 3.3). Using the results of this simulation, the next part of the effort was to implement the resulting load curve into Simulink and obtain the best possible power output curve from the model. In this way, the greatest challenge facing the SOFC-GT hybrid, namely meeting a highly dynamic load profile, can be addressed.

4.2 Hybrid System Modeling

Previously, the use of the Simulink model was to demonstrate steady-state functioning of the SOFC-GT hybrid system, and some experiments were made to introduce dynamic load changes. However, to accommodate a highly dynamic load profile on the scale of the locomotive route, two significant alterations had to be made. First, the model still crashed when attempting to follow the raw power demand curve so this had to be smoothed out. To accomplish this while keeping the curve similar to its original shape, MATLAB's curve fitting tool with the option "smoothing spline" was used. Figure 52, Figure 53, and Figure 54 show how the smoothing parameter affects the shape of the curve. It was found that the best results were achieved with a smoothing parameter of 0.05.

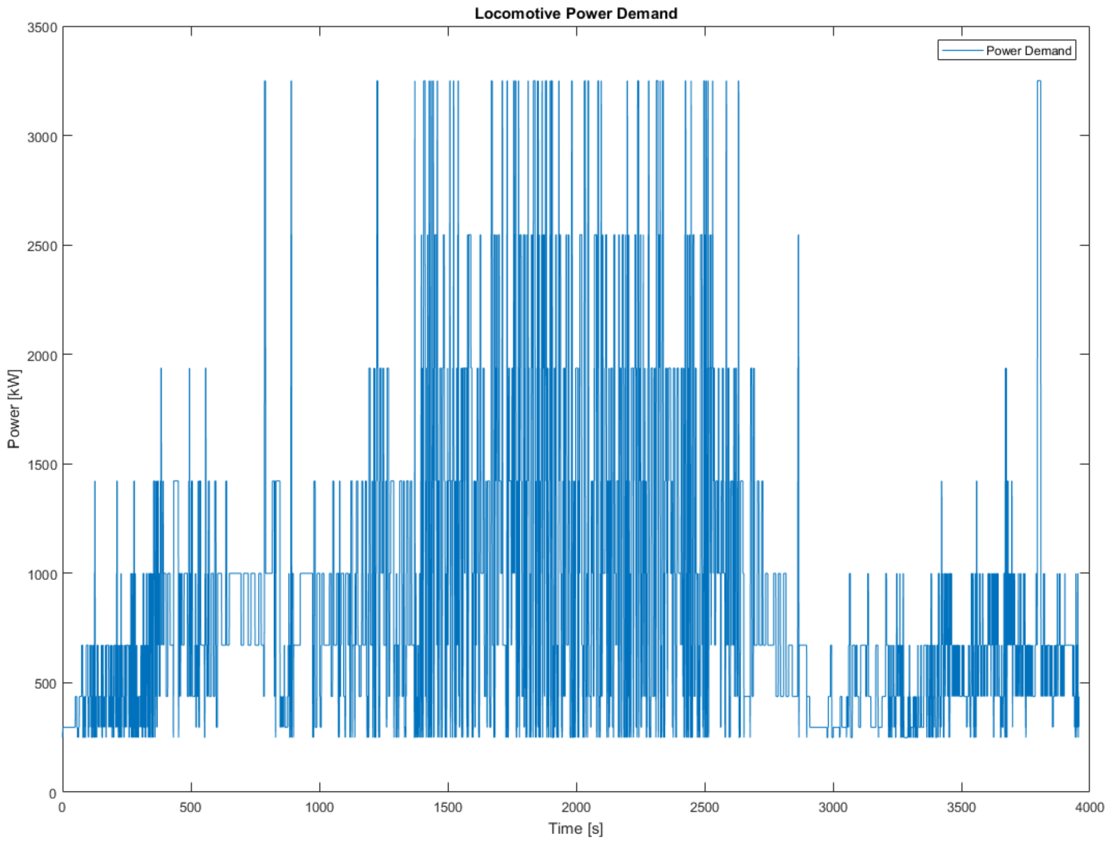

Figure 52. Raw power demand curve

The graph above shows the raw power demand from the Google Earth method with no time delays, i.e., instantaneous steps in power demand. This is not feasible with the SOFC-GT model and causes it to fail. Note that all power demand curves, including this one, were adjusted upwards by 250 kW to account for the fact that there is a minimum operating power below which the system cannot function. This is an improvement based on earlier runs where up to 900 kW had to be added for the system to run. Note, that the length of the x-axis (3,957 seconds) corresponds to the time that is calculated for the locomotive to travel the Bakersfield to Mojave route.

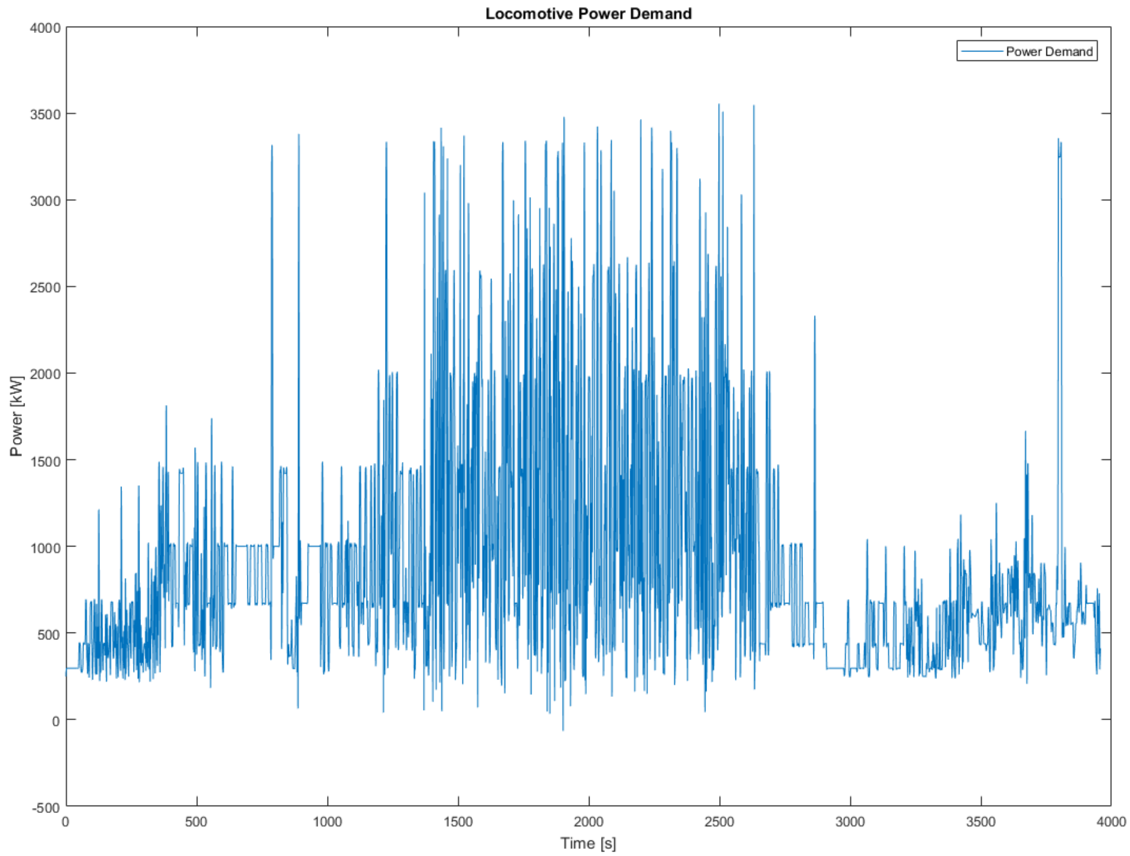

Figure 53. Smoothed power demand curve, smoothing parameter 0.5

For comparison, Figure 53 is a smoothed version of the curve in Figure 52. It is less dynamic, but still causes an error in the SOFC-GT system.

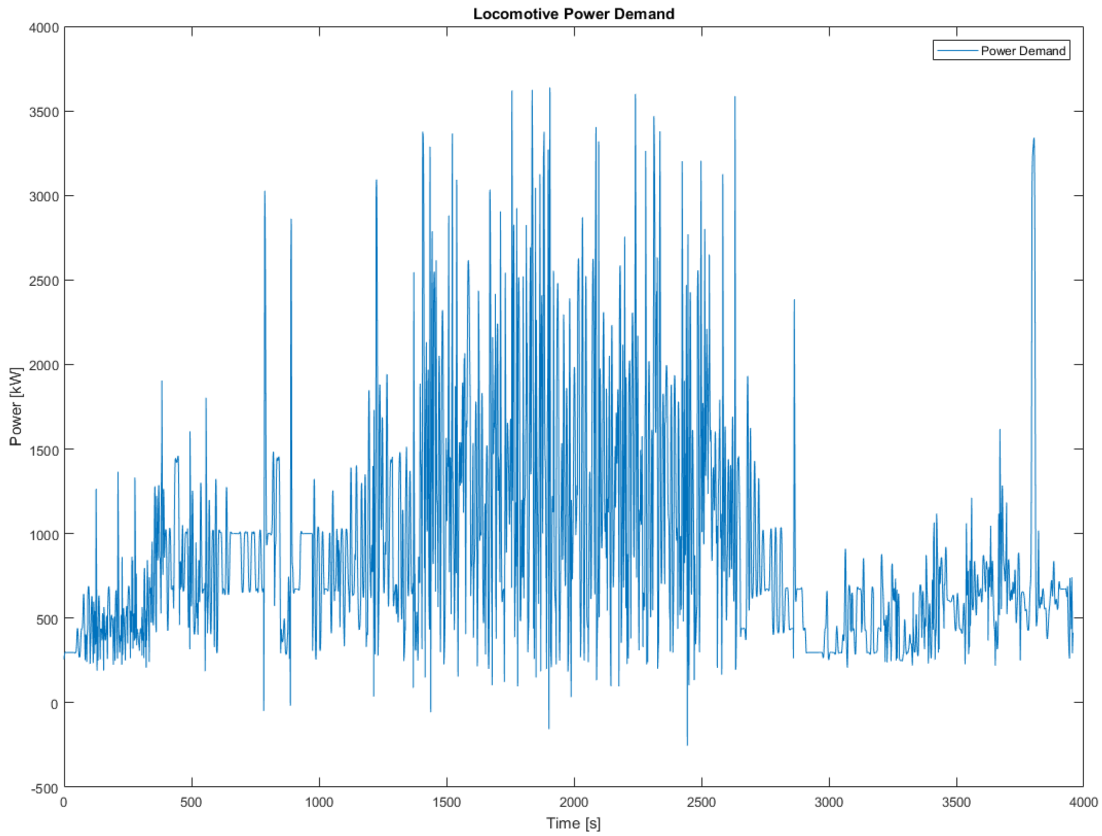

Figure 54. Smoothed power demand curve, smoothing parameter 0.05

The above graph, Figure 54 shows the optimal amount of smoothing for this purpose. Although it looks similar to the one above, it is just smooth enough for the system to be able to handle it.

Secondly, the sensitivity of the current controller was decreased in order to accelerate the dynamic response of the fuel cell stack. The model only previously showed an insignificant response to fast changes in the power demand on the order of seconds. There are still delays, but the system can now be classified as highly dynamic, considering that even the best current controller requires a finite amount of time until it can cause a significant difference in fuel flow, which ultimately determines the power output. Figure 55 and Figure 56 visualizes the progress in following the power demand achieved through the change in the controller. Further improvements are part of ongoing and future work.

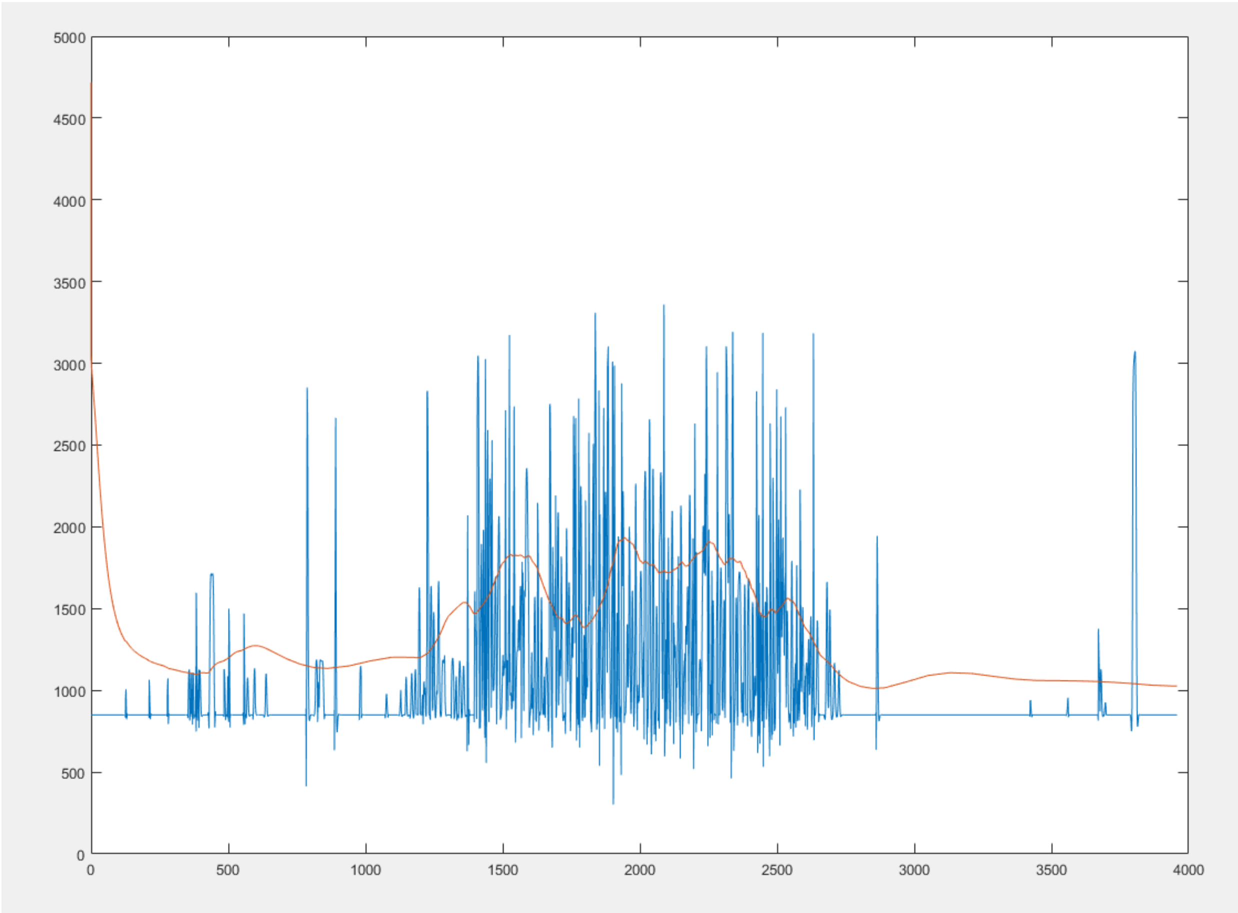

Figure 55. Smoothed power demand (blue) and power output (red) with old controller setting

It is obvious from this graph that the old controller setting was not designed for a highly dynamic system because the output barely correlated with the demand. Also, the lowest power output was more than half of the maximum and so not only the dynamic response, but also the range of possible power output had to be improved.

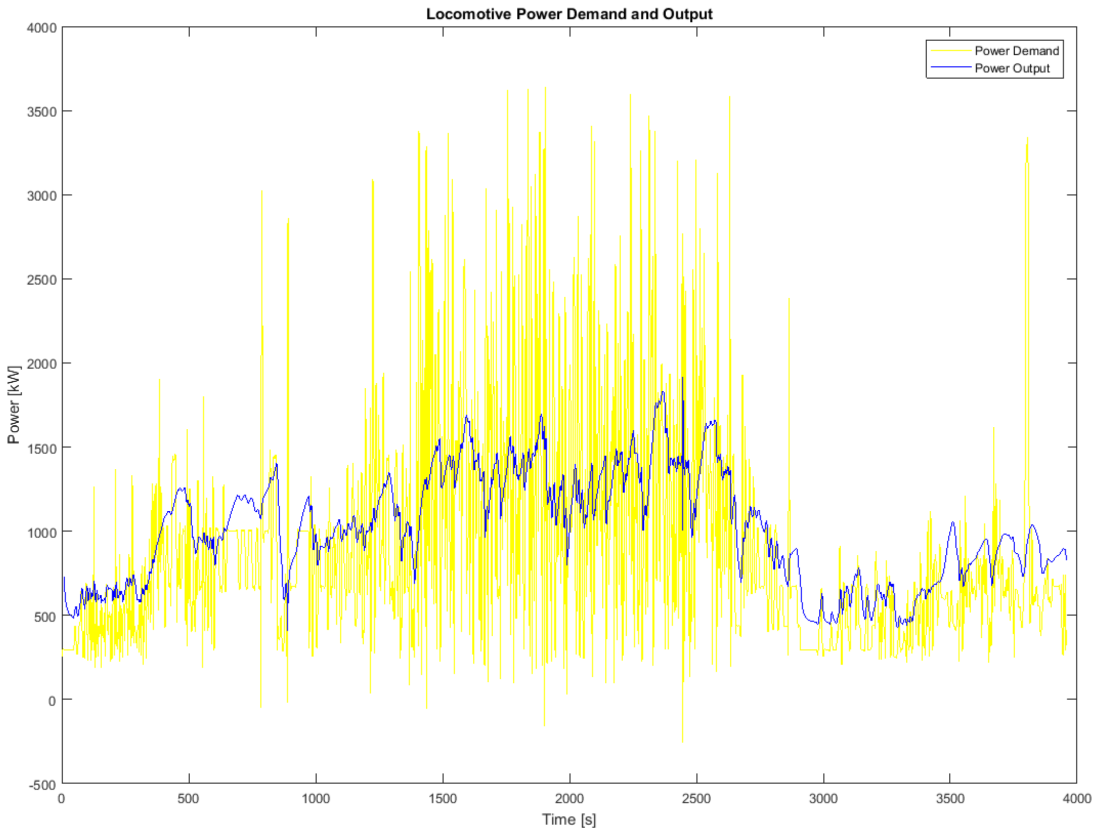

Figure 56. Smoothed power demand and power output with new controller setting

After changing the controller setting, both issues above were alleviated. The range of power outputs now goes as low as 20 percent of the maximum and the power curve is significantly more dynamic. Clearly, it still does not nearly follow the power demand, but it is promising and it will be interesting to see how the performance and dynamic response of the prototype system on a real testbed will compare. Also, the smoothing in MATLAB does not allow taking the average of the power demand over larger time periods, thus reducing the maximum power demand. If this could be done in another way, the power output could possibly follow the demand more closely.

It is important to note that the peak output power is about 1.8 MW, but the maximum power demand is above 3 MW. However, the average of the output matches the average demand very closely and a solution to reconcile the two proposed below.

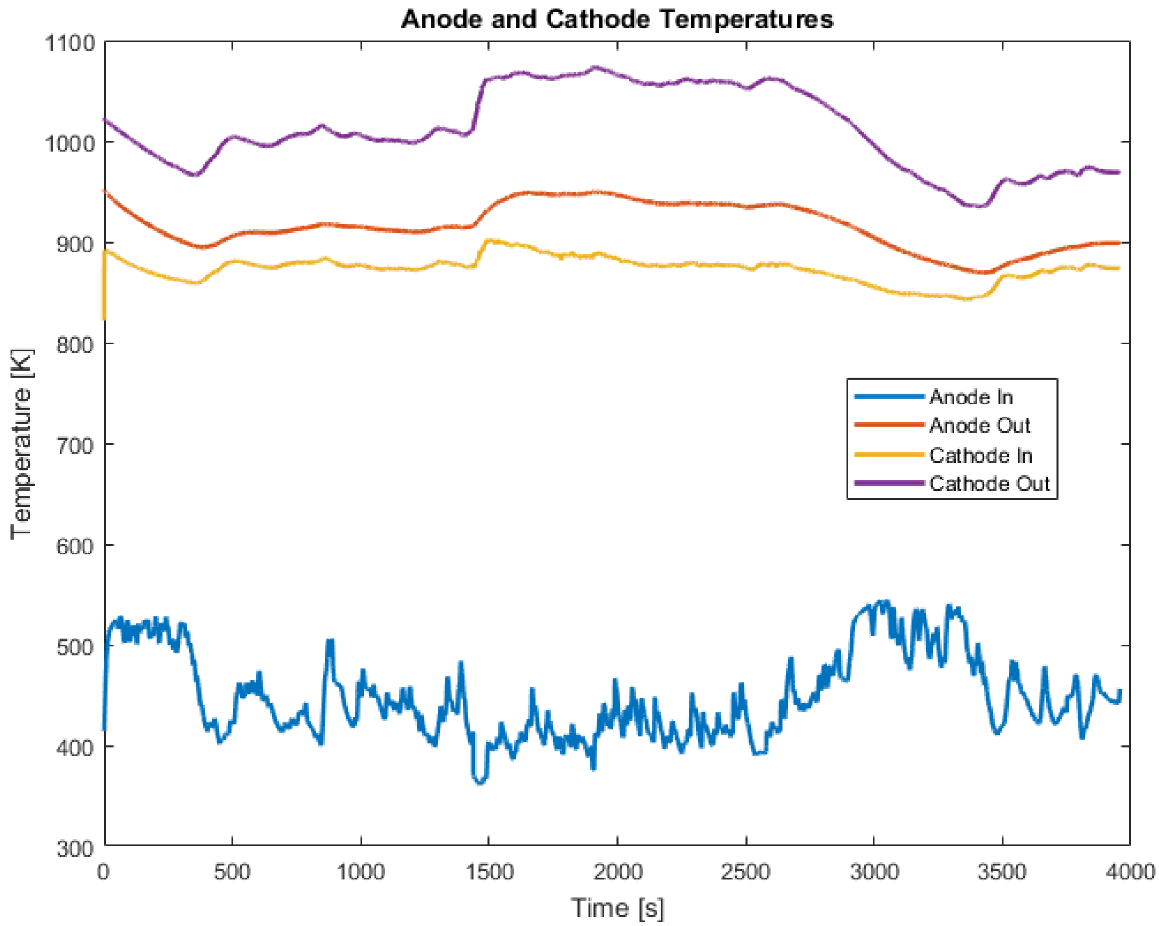

Figure 57. Nernst voltage (blue), cell voltage (red), ohmic overpotential (purple), and activation overpotential (yellow)

Figure 57 shows the influences on the cell voltage in red. The Nernst voltage is consistently between 0.92 and 0.94 V and varies only slightly because of temperature variations in the fuel cell stack. The activation overpotential also varies with temperature but is generally low due to the good kinetics of novel fuel cell materials. It can be seen that the largest and most significant contributor to variations in the cell voltage is the ohmic overpotential. This is because the parameter varying the most with time is the current—when the power demand is increases, the current increases and the ohmic resistance is high, whereas lowering the power demand causes less current and therefore lower ohmic resistance. Therefore, the cell voltage varies almost exactly with the negative of power output and ohmic resistance.

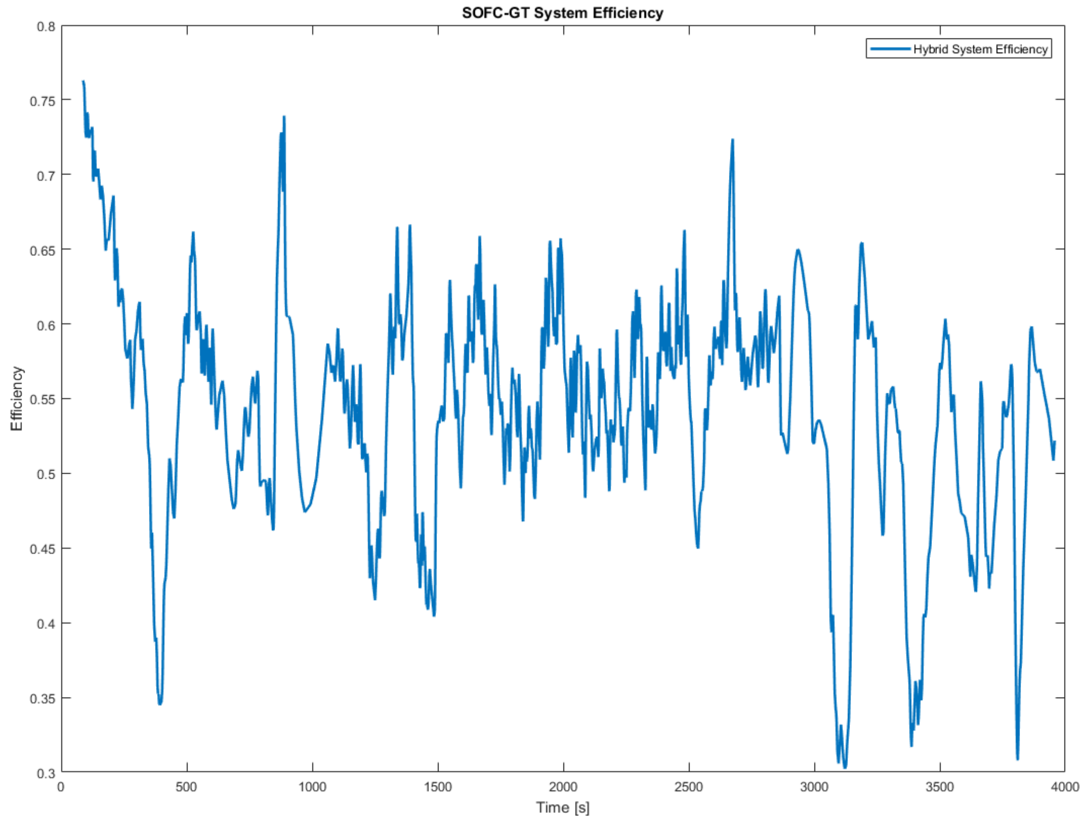

Figure 58. System efficiency versus time

As observed from Figure 58, the system efficiency curve follows the cell voltage curve exactly, because the fuel cell stack efficiency is calculated as the ratio of actual cell voltage divided by the Nernst voltage at standard condition. For the calculation of the overall system efficiency, the fuel utilization in the fuel cell stack and the efficiency of the gas turbine also need to be taken into account. However, since the utilization is kept constant at 80 percent and the gas turbine efficiency is always close to 30 percent, the variation of the system efficiency effectively only depends on the cell voltage.

The anode and cathode inlet and outlet temperatures are shown below as a function of time. All of these somewhat oscillate, but the anode inlet temperature varies the most which makes it seem like it oscillates the most. This is because of dynamic operation—the fuel flow rate through the fuel pre-heater varies and the heating rate cannot be adjusted with exact precision. However, it can be seen in Figure 59 that this has little effect on the temperature towards the exit of the stack.

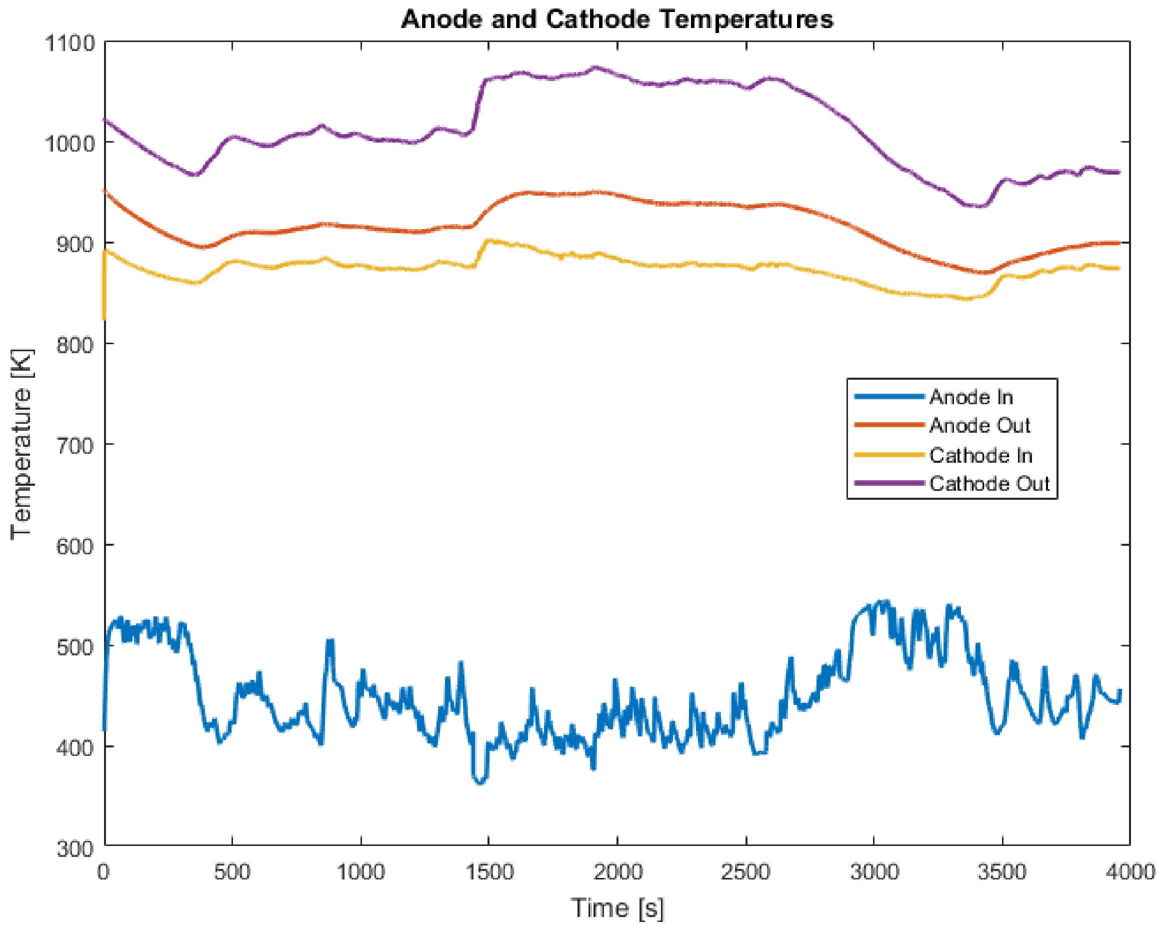

Figure 59. Anode and cathode inlet and outlet temperatures versus time

4.3 Inclusion of a Battery into the System Design and Operation

One idea for mitigating the issue that the SOFC-GT output power curve does not meet the power demand of the locomotive is to add a battery as a new component to the system. It provides relatively short bursts of power when the power demand is high/above average and be charged by the fuel cell when the power demand is low/below average. This would not only vastly improve the dynamic operation of the system, but also reduce the maximum power required of the SOFC-GT hybrid since it will be complemented by a battery. To accomplish this, a circuit consisting of a lithium ion battery, a controlled current source for the load, and a power source to represent the SOFC-GT hybrid, was created in Matlab Simulink using SimPowerSystems. The next step will consist of simulating the new SOFC-GT-Battery hybrid on the Bakersfield to Mojave power demand curve and analyzing how accurately it can follow this load. If an improved performance is demonstrated, the physical system design of the locomotive powertrain can be updated to match the changes in the simulated system design.

The team built a circuit in Matlab Simulink R2014b that has a battery and two controlled current sources, one for the load and one for the fuel cell output. The FC-GT operating data can be imported from Matlab R2017a by copying and pasting the workspace variables. This enables adjustment of the power demand and output for the battery, but that is not proportional to the current since the cell voltage decreases with the increasing current. Instead, the total system current needs to be found. For the output, this can be done by dividing the power output by the cell voltage (LoadCurrent=LoadPower/Voltage); for the load, this task is not obvious—the power demand is known but the voltage needs to be estimated as a function of power to calculate the current. Plotting voltage versus power yields a nontrivial relationship, which means that the greatest hurdle to this task is to find an appropriate relationship for V(P). Since the fuel cell is operating in the region of ohmic polarization of the V-I curve, it is assumed that V(P) is best approximated as a straight line that is decreasing. Using Excel's least squares computation, the equation of the best fit is V=0.9255-0.1646*P, where P is in MW.

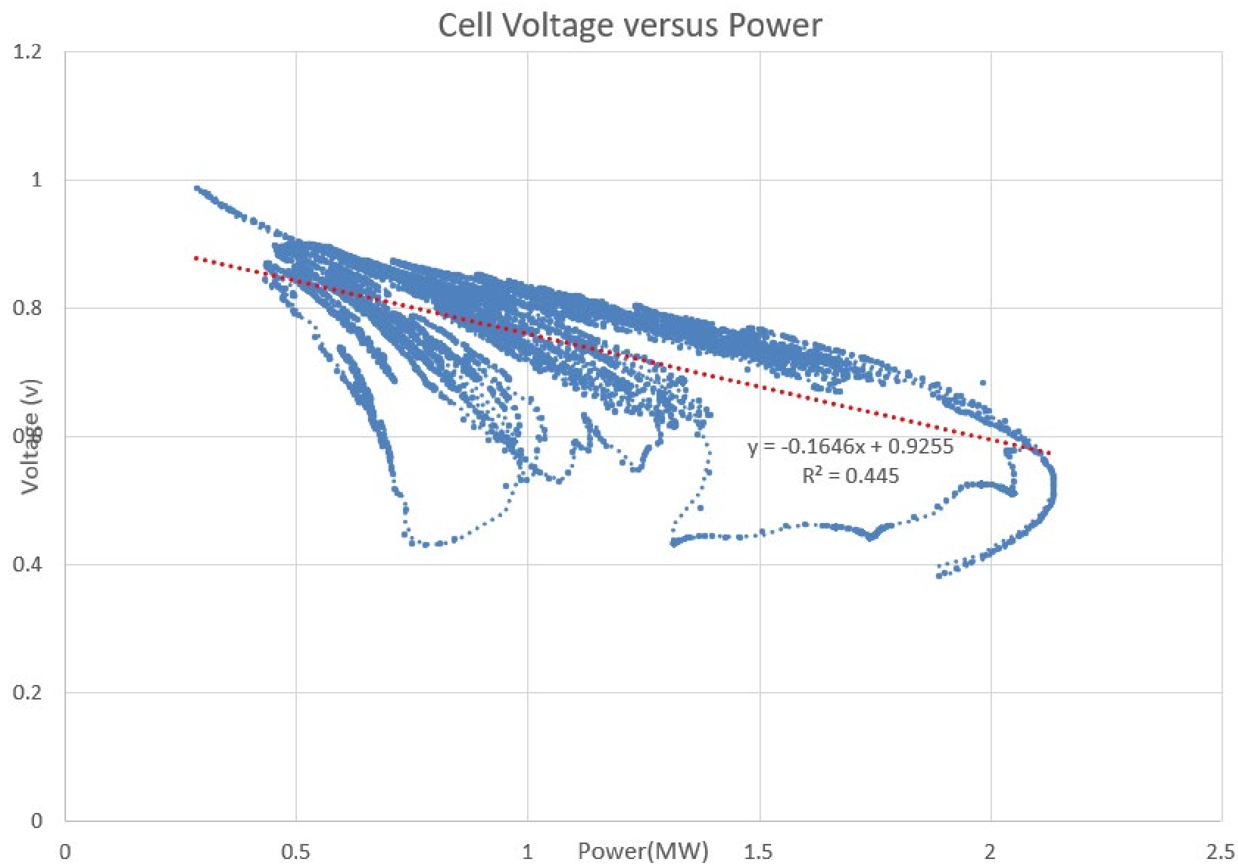

Figure 60. Scatterplot of the cell voltage values for different power values

Figure 60 shows that it is very difficult to accurately approximate the cell voltage as a function of power. This is, once again, due to the high dynamicity of the system; voltage generally decreases with increasing power/current but it does not instantly change to its expected value when the current is changed. For example, when quickly reducing the power, the voltage will be lower than expected while it is still increasing and vice versa.

The following results in Figure 61 came from using a lithium ion battery with a nominal voltage of 200 V and a rated capacity of 180 Ah.

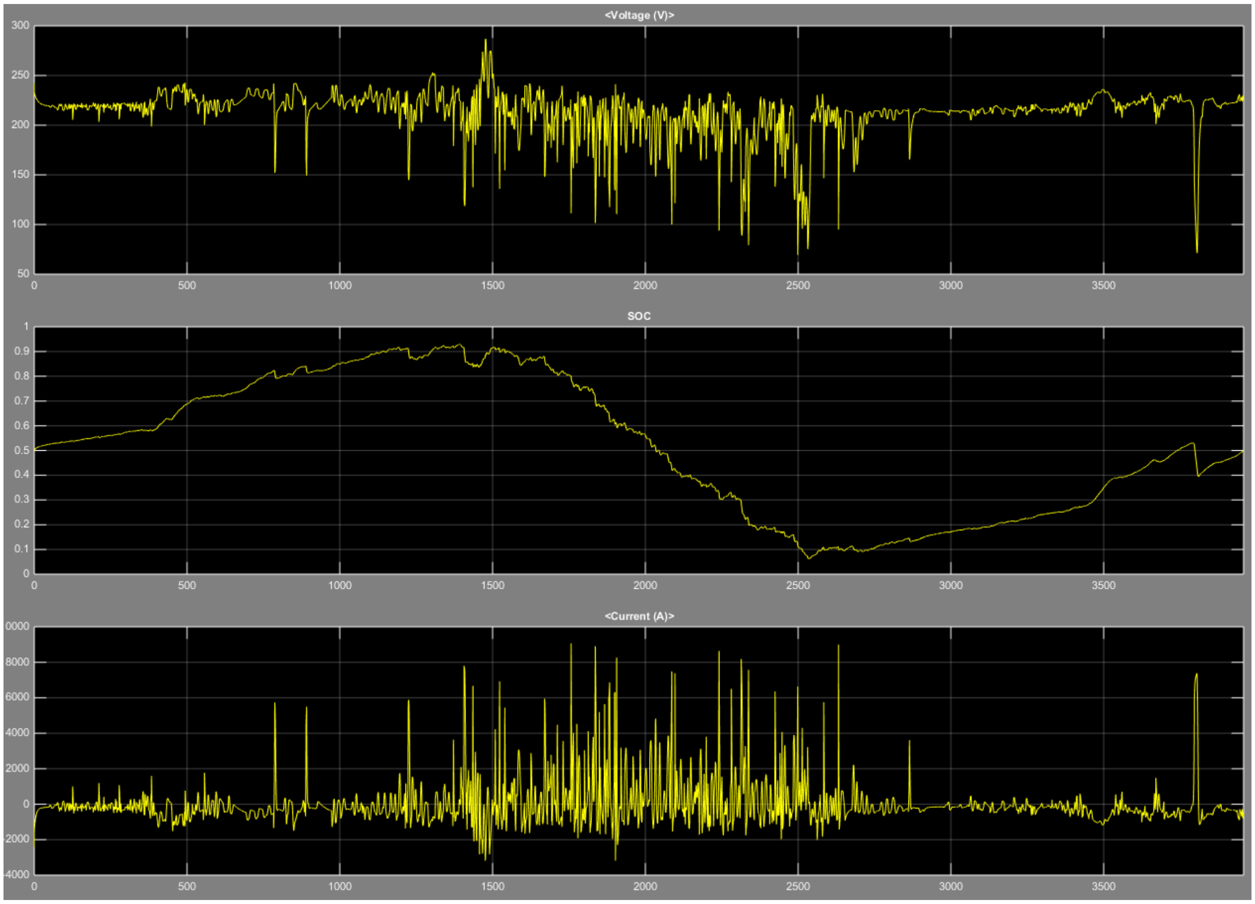

Figure 61. Battery voltage, SOC, and current versus time

The SOC, middle plot starts off at 50 percent and increases gradually to above 90 percent during the first section of the route, which is relatively flat. Then, during the middle section, where the incline is mostly steep and uphill, most of the battery is discharged because the SOFC-GT system does not provide enough power. Towards the end, there is once again a surplus in power and so the battery is charged back to its initial SOC.

As for the power and capacity requirements of the battery, it should be noted that its rated capacity is quite low at 36 kWh—a positive indicator that the SOFC-GT system is relatively close to meeting its dynamic power demand. However, the maximum power required from the battery is high because of the sudden large spikes in the power demand that the SOFC-GT system is not able to cope with. The maximum power of the battery at any point is 1.0 MW, which means that the power-to-capacity ratio would be unusually high for a battery. This means that the option of using a supercapacitor for this system may be worth investigating, and comparing the power-to-capacity ratio to real batteries and capacitors in order to select the appropriate device to complement the SOFC-GT hybrid.

Implementing smoothing and better controls improved the SOFC-GT hybrid system model significantly for a freight locomotive application. While better dynamic operation has been demonstrated, it cannot match the power demand for the representative route from Bakersfield to Mojave. Following this, a battery was implemented into the model to complement the power output for the locomotive. Preliminary results show that the route can be completed using the

SOFC-GT hybrid with a maximum power of 1.8 MW and a battery with a maximum power of 1.0 MW and a capacity of 36 kWh.

5. Economic Analyses

This section of the report describes a study of the comparative economics of locomotives used for line-haul freight operations in the United States. The study is based on statistics for operations by Class I railroads, which are those with a threshold annual revenue of approximately $450 million in 2017.

The purpose of examining the economics of different locomotive technologies is to enable a comparison of several alternative locomotive technologies with the incumbent diesel-electric locomotive technology. The use of Locomotive Cost Model (LCM) is to calculate the levelized cost of energy (LCOE) delivered to the locomotive traction motors for each locomotive technology. The LCM is also used to calculate more-standard railroad metrics such as cost per revenue ton-mile.

The alternative locomotive technologies included in the comparative economic analysis include: (i) Diesel-electric with a battery tender; (ii) diesel-electric with a liquefied natural gas (LNG) tender; (iii) SOFC-GT hybrid with an LNG tender; (iv) SOFC-GT hybrid with a liquefied hydrogen (LH_2) tender; and, electric-only with electricity provided through an overhead electric catenary system. A sensitivity case is also examined for a combination of a short-haul electric-only locomotive and a long-haul diesel-electric locomotive that covers the same line-haul distance as all of the other locomotive technologies.

5.1 LCM Data Input Requirements

Table 9 and Table 10 shows the data inputs required for each locomotive technology and provide the base case values in the LCM Input Matrix. Data input values include locomotive cost and operating parameters, financial parameters, fuel- and emissions-related parameters, and parameters related to how Class I freight trains are operated in the United States. In the tables, IOU refers to investor-owned utility, POU refers to publicly-owned utility and BEITC refers to business energy investment tax credit. By necessity, base case input values are based on averages, but the LCM Input Matrix structure allows the base case input values to be changed at will by the user for sensitivity analyses. However, caution must be exercised to ensure that all input values are in the correct units required by the LCM cost calculations.

Table 8. LCM Input Matrix: Data Input Requirements and Base Case Values

		1	2	3
		Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive
1	Gross Capacity (MW; 1 hp = 0.746 kW)	3.2824	3.2824	3.2824
2	Annual Capacity Factor	0.269	0.269	0.269
3	Instant Cost (MM$)	3	3	2.7
4	Battery Replacement Cost Maintenance Fee per BES Tender ($/kW-yr)	0	304.66	0
5	VOM ($/MWh @ Traction Motor)	19.39	19.39	23.27
6	HR (MMBtu/MWh @ Traction Motor)	12.319	10.5376	13.726
7	HR Degradation	0.01	0.01	0.01
8	SMR Conversion Efficiency for Nonrenewable H2 Production	0	0	0
9	Debt Term (Yrs)	12	12	12
10	Economic Life (Yrs) (Cannot exceed 40 years for tax calcs)	30	30	30
11	Federal Tax Life (Yrs)	14	14	14
12	State Tax Life (Yrs)	15	15	15
13	Ad Valorem Tax Rate	0.01098	0.01098	0.01098
14	Ownership Type (1=Merchant;2=IOU;3=POU)	1	1	1
15	Fuel Delivery Losses (Related to Tenders and Catenary Use)	0	0.19	0.0125
16	Fuel Type (0=RE;1=LNG;2=LH2;3=Diesel;4=Diesel:LNG;5=Diesel:BES;6=Elect)	3	5	4
17	Fuel Density (MMBtu/gallon for liquid fuels; MMBtu/MWh for electricity)	0.1374	0.1374	0.1111
18	Fraction of MWh Provided from Tenders	0	0.2	0.5
19	SMR Cost for Nonrenewable H2 Production ($/kg H2)	0	0	0
20	H2 Liquefaction Cost Multiplier vs. NG Liquefaction Cost	0	0	0
21	CO 2009 Emissions Factor (g/bhp-hr)	5	4.0112	6.25
22	CO Annual Emissions Reduction Factor	0	0	0
23	HC 2009 Emissions Factor (g/bhp-hr)	0.418	0.3438	0.5225
24	HC Annual Emissions Reduction Factor	0.0671	0.05368	0.03355
25	NOx 2009 Emissions Factor (g/bhp-hr)	7.933	6.3534	5.15645
26	NOx Annual Emissions Reduction Factor	0.0555	0.0446	0.02775
27	PM 2009 Emissions Factor (g/bhp-hr)	0.236	0.1912	0.246
28	PM Annual Emissions Reduction Factor	0.0764	0.06112	0.0382
29	SOx 2009 Emissions Factor (g/bhp-hr)	0.05	0.0412	0.025
30	SOx Annual Emissions Reduction Factor	0.01	0.008	0.005
31	CO2 Emissions Factor (tons CO2/MMBtu fuel) (/MWh electricity)	0.11	0.106	0.097
32	Renewable Resource Fraction for Fuel Type	0	0	0
33	Renewable Resource Fraction Annual Increase	0	0	0
34	Average Cars per Train	72	72	72
35	Locomotives Required per Train	3	3	3
36	Net Freight Train Load (Freight Tons+Some Allocated Wt of Cars)	3529	3529	3529
37	Fraction of Cars Loaded (Prior to Lowering Based on Tenders Required)	0.574	0.574	0.574
38	Revenue Tons per Car Loaded	60	60	60
39	Hours Required for Loading and Unloading	18	18	18
40	Length of Haul (Miles)	1000	1000	1000
41	Network Velocity (mph)	19.6	19.6	19.6
42	Annual Availability	0.64	0.64	0.64
43	Locomotive Rebuild Interval (Years)	10	10	10
44	Locomotive Rebuild Cost (% of Instant Cost)	0.25	0.25	0.25
45	Instant Cost per Tender (MM$)	0	6	1
46	Useful Tender Capacity (Gallons for Liquid Fuels, MWh for BES)	0	5	20000
47	Useful Energy Per Tender (MWh)	0	5	160.32
48	Miles of Catenary Infrastructure Installed	0	0	0
49	Catenary Infrastructure Cost (Million $)	0	0	0
50	Catenary Infrastructure Usage (Trains per Day)	0	0	0
51	Manufacturing Percent per Year	1,0,0,0,0,0	1,0,0,0,0,0	1,0,0,0,0,0
52	Manufacturing Months per Year	12,0,0,0,0,0	12,0,0,0,0,0	12,0,0,0,0,0

Table 9. LCM Input Matrix: Data Input Requirements and Base Case Values

		4	5	6
		SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (H2 Fuel)	Electric-Only Locomotive (Catenary)
1	Gross Capacity (MW; 1 hp = 0.746 kW)	3.2824	3.2824	3.2824
2	Annual Capacity Factor	0.269	0.269	0.269
3	Instant Cost (MM$)	5	5	5
4	Battery Replacement Cost Maintenance Fee per BES Tender ($/kW-yr)	0	0	0
5	VOM ($/MWh @ Traction Motor)	33.93	33.93	13.57
6	HR (MMBtu/MWh @ Traction Motor)	10.579	9.617	1.312
7	HR Degradation	0.02	0.02	0.005
8	SMR Conversion Efficiency for Nonrenewable H2 Production	0	0.9	0
9	Debt Term (Yrs)	12	12	12
10	Economic Life (Yrs) (Cannot exceed 40 years for tax calcs)	20	20	30
11	Federal Tax Life (Yrs)	14	14	14
12	State Tax Life (Yrs)	15	15	15
13	Ad Valorem Tax Rate	0.01098	0.01098	0.01098
14	Ownership Type (1=Merchant;2=IOU;3=POU)	1	1	1
15	Fuel Delivery Losses (Related to Tenders and Catenary Use)	0.025	0.025	0.1
16	Fuel Type (0 =RE;1=LNG;2=LH2;3=Diesel;4=Diesel:LNG;5=Diesel:BES;6=Elect)	1	2	6
17	Fuel Density (MMBtu/gallon for liquid fuels; MMBtu/MWh for electricity)	0.0848	0.036	3.412
18	Fraction of MWh Provided from Tenders	1	1	0
19	SMR Cost for Nonrenewable H2 Production ($/kg H2)	0	1.5	0
20	H2 Liquefaction Cost Multiplier vs. NG Liquefaction Cost	0	2.16	0
21	CO 2009 Emissions Factor (g/bhp-hr)	0.115	0.037	0.056
22	CO Annual Emissions Reduction Factor	0	0	0
23	HC 2009 Emissions Factor (g/bhp-hr)	0.009614	0.031	0.047
24	HC Annual Emissions Reduction Factor	0	0	0
25	NOx 2009 Emissions Factor (g/bhp-hr)	0.182459	0	0.035
26	NOx Annual Emissions Reduction Factor	0	0.0007	0.0010
27	PM 2009 Emissions Factor (g/bhp-hr)	0.000007	0.008	0.012
28	PM Annual Emissions Reduction Factor	0	0	0
29	SOx 2009 Emissions Factor (g/bhp-hr)	0	0.004	0.006
30	SOx Annual Emissions Reduction Factor	0	0	0
31	CO2 Emissions Factor (tons CO2/MMBtu fuel) (/MWh electricity)	0.05082	0.07933	0.306
32	Renewable Resource Fraction for Fuel Type	0	0.3333	0.273
33	Renewable Resource Fraction Annual Increase	0	0.0151	0.0151
34	Average Cars per Train	72	72	72
35	Locomotives Required per Train	3	3	3
36	Net Freight Train Load (Freight Tons+Some Allocated Wt of Cars)	3529	3529	3529
37	Fraction of Cars Loaded (Prior to Lowering Based on Tenders Required)	0.574	0.574	0.574
38	Revenue Tons per Car Loaded	60	60	60
39	Hours Required for Loading and Unloading	18	18	18
40	Length of Haul (Miles)	1000	1000	1000
41	Network Velocity (mph)	19.6	19.6	19.6
42	Annual Availability	0.64	0.64	0.64
43	Locomotive Rebuild Interval (Years)	5	5	10
44	Locomotive Rebuild Cost (% of Instant Cost)	0.33	0.33	0.25
45	Instant Cost per Tender (MM$)	1	1.1	0
46	Useful Tender Capacity (Gallons for Liquid Fuels, MWh for BES)	20000	20000	0
47	Useful Energy Per Tender (MWh)	160.32	74.87	0
48	Miles of Catenary Infrastructure Installed	0	0	1000
49	Catenary Infrastructure Cost (Million $)	0	0	20
50	Catenary Infrastructure Usage (Trains per Day)	0	0	70
51	Manufacturing Percent per Year	1,0,0,0,0,0	1,0,0,0,0,0	1,0,0,0,0,0
52	Manufacturing Months per Year	12,0,0,0,0,0	12,0,0,0,0,0	12,0,0,0,0,0
53	BEITC	0,0,0,0	0,0,0,0	0,0,0,0

5.2 Locomotive Cost and Operating Parameters

In the first instance, the LCM calculates the LCOE for energy delivered to the traction motors of the locomotive. Locomotive cost and operating parameters are expressed in standard electricity units wherever possible.

- Each locomotive's gross capacity is expressed in megawatts (MW) by converting locomotive capacity in hp to locomotive capacity in MW by multiplying by the standard conversion factor of 1 hp = 0.746 kW.
    - Locomotive capacity is assumed to be 4,400 hp for all locomotive technologies, which is the equivalent of 3.2824 MW.
    - Since the capacity is the same for all locomotive technologies, all locomotives are assumed to be capable of handling the same loads.
- Each locomotive's annual capacity factor is the fraction of the year that the locomotive operates at full power, assuming 100 percent availability. Since line-haul freight locomotives spend 50 percent of their duty cycle either idling or braking, the full-power annual capacity factor is quite low at 26.9 percent.
    - The basis of the derivation of the 26.9 percent full-power annual capacity factor is locomotive duty cycle data in the Title 40 Code of Federal Regulations (CFR) Part 1033, Subpart F, Section 530–Duty cycles and calculations. Table 11 provides excerpts from § 1033.530 and illustrates the derivation of the 26.9 percent full-power annual capacity factor for line-haul locomotives.
    - The adjustment of the annual capacity factor is subsequently within the LCM cost calculations by the locomotive's annual availability, which is estimated to be 64 percent.[4] The annual availability reflects the percentage of time during the year that the locomotive is operating.

The capital cost of each locomotive is expressed in millions of dollars, whereas the variable operating and maintenance (VOM) cost is expressed in dollars per megawatt-hour (MWh).[5]

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[4] The 64 percent annual availability was derived indirectly based on the annual availability required to achieve approximate equivalence with several annual operating statistics such as annual revenue ton-miles per locomotive and revenue ton-miles per gallon of diesel fuel that are reported in the *Railroad Ten-Year Trends* report published annually by the Association of American Railroads (AAR).

[5] Locomotive capital costs are from Railtec, 2016, Table S.2, page xv. VOM costs are based on Railtec, 2016, p. 6, which estimates $150,000/year in VOM costs for a diesel-electric locomotive. Initial VOM costs in $/MWh are calculated based on the assumed annual average capacity factor of 26.9 percent, and subsequently adjusted to reflect actual locomotive availability within the LCM cost calculations.

Table 10. Derivation of Line-Haul Locomotive Full-Power Annual Capacity Factor

CFR Title 40, Part 1033, Section 1033.530			Implied
Power Setting	Percent of Rated Power	Time in Mode	Capacity Factor
Low and Normal Idle	0.0%	38.0%	0.0%
Dynamic Brake	0.0%	12.5%	0.0%
Notch 1	4.5%	6.5%	0.3%
Notch 2	11.5%	6.5%	0.7%
Notch 3	23.5%	5.2%	1.2%
Notch 4	35.0%	4.4%	1.5%
Notch 5	48.5%	3.8%	1.8%
Notch 6	64.0%	3.9%	2.5%
Notch 7	85.0%	3.0%	2.6%
Notch 8	100.0%	16.2%	16.2%
TOTAL			26.9%

- The locomotive annual heat rate is the energy input required by the locomotive at full power and is expressed in million British thermal units (MMBtu) per MWh delivered to the traction motors.[6]
    - The heat rate for the electric-only locomotive is expressed as MWh-in per MWh-out, where the MWh-in is the electricity delivered to the locomotive from the overhead electric catenary system and the MWh-out is the MWh delivered to the traction motors.

The initial locomotive annual heat rate is assumed to increase each year based on the heat rate degradation value. The locomotive annual heat rate is reset to its initial value periodically based on the locomotive rebuild interval. The locomotive is assumed to be rebuilt at each locomotive rebuild interval at a cost equal to a specified fraction of the original capital cost.

5.2.1 Financial Parameters

The financial parameters specify the locomotive's economic life, including the number of years between each rebuild. The financial parameters also specify the applicable Federal and State tax lives and tax rates for the locomotive. Class I railroads are assumed to operate competitively under merchant (i.e., private) ownership, though it is recognized that components of their operations are subject to regulation by the Surface Transportation Board (STB).

Since all locomotives are assumed to have the same gross capacity of 4,400 hp, the financial parameters are similar for all locomotive technologies.

- Most locomotive technologies are assumed to have a 30-year economic life, though the SOFC-GT hybrid locomotive technology is assumed to have a 20-year economic life.

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[6] Locomotive annual heat rates are taken from Hoffrichter, *et al.*, 2012, p. 30, and are expressed in Higher Heating Value (HHV) units. HHV units are used throughout this analysis.

- The Federal and State tax life for all locomotive technologies is set to 15 years.[7]
- The Federal tax rate is 35 percent, the California State tax rate is 8.84 percent, the California sales tax rate is 7.94 percent, and the California ad valorem rate on new capital is 1.098 percent.

Twenty percent of all locomotive capital is assumed to be financed over a 12-year period, with the remaining 80 percent of capital provided by equity holders. The cost of financed debt is 4.0 percent and the required return on equity is 11.5 percent, based on 5-year averages found in the *Railroad Ten-Year Trends* report published annually by the AAR.[8]

5.2.2 Fuel-Related Parameters

The cost of locomotive fuel is specified in the LCM calculations in $/MMBtu (HHV), except for the cost of electricity, which is specified in $/MWh. The specification of the input parameters of the fuel type for each locomotive technology is the fuel density in MMBtu per standard unit of fuel (e.g., gallons, kilograms). The fuel density value for the incumbent diesel-electric locomotive technology is used for LCM calibration to calculate the ton-miles per gallon of diesel fuel, another statistic reported by the AAR, which is in turn used for LCM calibration.

The U.S. Energy Information Administration (EIA) produces long-term energy price forecasts each year in its Annual Energy Outlook (AEO). Table A3 of each year's AOE contains energy prices by sector and source, in both nominal and real (inflation-adjusted) dollars. The basis of all fuel forecasts in the LCM are nominal transportation sector energy price forecasts from the AEO 2017 to ensure a consistent suite of fuel price forecasts.

The AEO 2017 transportation sector diesel price forecast is for on-road use and includes Federal and State taxes. To the extent that railroads are exempt from such taxes, the diesel price forecast may overstate the cost of diesel. However, the transportation sector natural gas price forecast also includes estimated taxes, so there should be no resultant fuel-related bias. The natural gas price forecast is specifically for natural gas used in motor vehicles, trains, and ships, and includes dispensing costs. The electricity price forecast for the transportation sector is used "as is" in the LCM cost calculations.

The AEO 2017 energy price forecast does not include hydrogen, making it necessary to derive a hydrogen price forecast. To maintain consistency with the other price forecasts used in the LCM cost calculations, the gaseous hydrogen price forecast for non-renewable hydrogen is derived in part from AEO 2017 transportation sector natural gas price forecasts. The gaseous hydrogen price forecast for renewable hydrogen is derived based on the cost of the associated electrolyzer equipment.

- For non-renewable hydrogen derived from natural gas in a steam methane reformer (SMR), the cost of the natural gas price input to the SMR is based on the AEO 2017

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[7] Locomotives used in commercial operations technically have a 14-year Federal tax life (Thomson Reuters), but using the half-year convention for accelerated depreciation results in depreciation being spread over 15 years. Accelerated depreciation rates for a 14-year Federal tax life using the half-year convention are taken from Table A-14 of U.S. Internal Revenue Service Publication 946 (2016).

[8] Association of American Railroads, 2016, *Railroad Ten-Year Trends*.

industrial sector natural gas price forecast, with a 10 percent MMBtu loss for SMR conversion, and a $1.50/kilogram of hydrogen SMR equipment cost adder.[9]

- An estimated electrolysis equipment cost factor of $4.35/kilogram of hydrogen is used as a proxy price forecast for renewable hydrogen, which is assumed to be derived at no additional cost from otherwise-curtailed renewable energy through electrolysis.[10]
- A weighted average gaseous hydrogen price forecast is calculated based on the user-specified percentages of SMR-derived non-renewable hydrogen and electrolysis-derived renewable hydrogen.
    - The California Energy Commission (CEC) mandates that one-third of all hydrogen dispensed from hydrogen-fueling stations receiving CEC funding must be derived from renewable sources.[11]

The fueling infrastructure for non-diesel fuel used to power the alternative locomotive technologies is incorporated into the LCOE calculations in several different ways, as follows:

- The cost of the diesel fueling infrastructure is assumed to be included in the cost of diesel fuel.
- The cost of the natural gas fueling infrastructure is assumed to be included in the cost of natural gas in the AEO 2017.
    - The AEO 2017 "natural gas dispensing cost" component is estimated by subtracting the AEO 2017 industrial sector natural gas price forecast from the AEO 2017 transportation sector natural gas price forecast. The "natural gas dispensing cost" estimated in this manner averages about $13.50/MMBtu from 2016–2040, a cost that is high enough to include both liquefaction and dispensing costs.
    - Over half of the $13.50/MMBtu cost is assumed to be for natural gas liquefaction with the remaining 46 percent assumed to be for LNG dispensing infrastructure.[12] Based on this split, separate LNG liquefaction and dispensing cost components are obtained.
    - The use of LNG as a locomotive fuel requires the use of LNG tenders to carry and store sufficient LNG to provide the required amount of LNG fuel input required

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[9] The $1.50/kilogram hydrogen SMR equipment cost adder is in line with total H_2 cost (no sequestration) values derived in National Academy of Sciences, 2004, pp. 201–204, for medium-scale hydrogen production levels.

[10] This cost estimate is for an alkaline electrolyzer and is based on previous Power-to-Gas research. A somewhat higher estimate of $4.77/MMBtu can be derived using values in Alliance Technical Services, Inc., 2006, Slide 19, though the Alliance estimate includes some items such as site preparation that are not included in the $4.35/MMBtu estimate used in this analysis.

[11] California Energy Emission, 2016–2017 Investment Plan Update for the Alternative and Renewable Fuel and Vehicle Technology Program, 2016.

[12] This split is based on hydrogen liquefaction costs being 2.16 times greater than LNG liquefaction costs per MMBtu. The 2.16 cost factor is derived from the Reversible Power Requirements for the liquefaction of hydrogen and methane provided at Block, et al., 1988, p. 18. Technical solutions for large-scale hydrogen liquefaction that would achieve significant cost reductions for clean energy applications are discussed in Cardella, et al., 2017.

by the applicable locomotive technology. Diesel-electric locomotives with LNG tenders are assumed to generate 50 percent of their motive energy from LNG, a value that can be changed by the user in the LCM Input Matrix. LNG is the only external fuel required by the SOFC-GT hybrid locomotive; the beneficial impact of using exhaust heat recovery from the SOFC to fuel the gas turbine is reflected in the lower SOFC-GT hybrid heat rate.

  - The number of LNG tenders required for each locomotive is calculated within the LCM cost calculations, based on 20,000 gallons of useable LNG storage per tender.[13] Based on the base case values for LNG tenders shown in Figures 1-A and 1-B, each diesel-electric locomotive requires 0.19 LNG tenders and each SOFC-GT hybrid locomotive requires 0.38 LNG tenders.[14]
  - Each freight train is assumed to have three locomotives, another value in the LCM Input Matrix that can be changed by the user. The required number of LNG tenders per locomotive is therefore multiplied by three and rounded up to determine the actual number of LNG tenders to include in the LCM base case cost calculations.
  - Each LNG tender costs $1 million (Railtec, 2016, p. xv.). These LNG tender costs are included in the LCM base case cost calculations and are considered part of the natural gas fueling infrastructure costs.

- The cost of the hydrogen liquefaction and dispensing fueling infrastructure must be added to the weighted average gaseous hydrogen price forecast derived above. Hydrogen liquefaction costs are about $2.00/kilogram of hydrogen and are highly sensitive to the cost of electricity.[15] Once liquefied, LH_2 dispensing costs are assumed to be the same as LNG dispensing costs.
  - As is the case for LNG, the use of LH_2 as a locomotive fuel requires the use of LH_2 tenders. Approximately twice as many LH_2 tenders as LNG tenders are required for each locomotive based on the relative fuel density of the two fuels. The LH_2 tender costs are included in the LCOE calculations and are considered part of the hydrogen fueling infrastructure costs.
  - Since LH_2 requires a lower temperature (-252 °C/-423 °F) than LNG (-162 °C/-260 °F) to be liquefied and to remain liquid (National Petroleum Council, 2012, p.

[13] Chart Industries' LNG tank car SR-603 has a capacity up to ~30,680 gallons. A useful capacity of 20,000 gallons of LNG provides a significant margin of error, consistent with reliability-oriented freight railroad operating practices.

[14] Railtec, 2016, p. xv, states that 0.64 LNG tenders are required for both these locomotive technologies. That both these locomotive technologies would require the same number of LNG tenders appears to be inconsistent with the fact that each locomotive technology produces a different fraction of motive power using LNG. It is for this reason that the required number of LNG tenders for each locomotive technology is calculated endogenously in the LCM cost calculations.

[15] Fuel Cells and Hydrogen Joint Undertaking, 2013, p. 23, estimates hydrogen liquefaction costs at €1.38/kilogram LH_2 for a €50/MWh electricity cost and €1.72/kilogram LH_2 for a €100/MWh electricity cost. The averaging of these costs is €1.55/kilogram LH_2, converted to $2.02/kilogram LH_2 using a then-current (2013) currency conversion of $1.30/€1.00.

2), LH_2 tenders are assumed to incur a 10 percent cost premium compared to LNG tenders.[16]

- The cost of the electricity provided to a diesel-electric locomotive by a battery electric storage (BES) tender includes all of the costs associated with the BES tender, including the initial capital cost of the BES tender, a fast charger for each tender, periodic battery replacement costs, and the cost of the electricity to charge the batteries.
    - Each BES tender provides useful energy storage of 5 MWh (Railtec, 2016, p. 16).
    - Each BES tender discharges electricity to the diesel-electric locomotive over a certain number of operating hours, after which the BES tender must be recharged at a fast-charging station. Regenerative braking can contribute to recharging the BES tender but cannot fully recharge the BES tender.
    - The number of BES tenders required by each locomotive is calculated endogenously in the LCM cost calculations, based on the fraction of MWh assumed to be provided by the BES tenders. The base case values show in Figure 1-A result in 2.44 battery tenders required for each locomotive.[17]
    - The initial capital cost of a BES tender is $5 million, with additional capital of $3 million required every three years to replace the batteries (California Air Resources Board, 2016, p. X-3).
    - The periodic battery replacement costs are allocated over the life of the battery tender as an ongoing maintenance cost. These costs are expressed in units of $ per kilowatt-year (kW-yr) per locomotive in the LCM cost calculations.
    - The capacity of the locomotive technology in kW is multiplied by the $/kW-yr battery replacement cost to determine the annual battery replacement cost to be included in the LCM cost calculations.
- An electric locomotive is defined by the STB as a locomotive whose electricity is provided solely through an overhead electric catenary system. For clarity of exposition, electric locomotives are referred to throughout this report as “electric-only” locomotives.
    - The estimated installation costs of an overhead electric catenary system differ by orders of magnitude, from a low of $5 million per mile to a high of $50 million per mile (Railtec, 2016, p. 20). The LCOE of an electric-only locomotive varies directly with the assumed overhead electric catenary system installation cost per mile, the assumed number of electrified miles, and the assumed number of electric-only locomotives using the overhead electric catenary system.
    - For comparison purposes with the other locomotive technologies, the base case for this analysis assumes that the full 1,000 miles typical of a Class I freight train haul is electrified. Much of a 1,000-mile route is likely to be through rural areas, so the base case assumes that the installation of the overhead electric catenary system is at a cost of $20 million per mile. This is two-thirds of the current

[16] No citation available; estimate based on assumed additional insulation required for LH_2 vs. LNG tenders.

[17] Railtec, 2016, p. xv, estimates that each locomotive would require 2.83 BES tenders.

estimated $30 million per mile cost for the 51 miles of CalTrain—California commuter rail—electrification going up the peninsula from San Francisco to San Jose, CA (California Air Resources Board, 2016, p. VIII-10), reflecting the assumption that some of the 1,000-mile route would be rural in nature.

- Results are also presented for a sensitivity case that assumes that only the 130 miles between Long Beach and Barstow, CA, are electrified at a cost of $25 million per mile. This per-mile cost is greater than that assumed for the 1,000-mile route but less than the estimated $30 million per mile CalTrain cost estimate, given that the Long Beach to Barstow rail corridor is a less densely populated route than the San Francisco to San Jose rail corridor but a more densely populated route than the assumed 1,000-mile route.[18]
- The cost of the electricity provided to an electric-only locomotive through an overhead electric catenary system includes both the cost of the electricity and the allocated costs of the overhead electric catenary system that delivers the electricity to the locomotive.

Plant losses associated with each fuel type and any required fuel tenders increase the amount of fuel required for the related locomotive technology. The impact of the plant losses can either be reflected as an increase in the absolute amount of fuel required or as an increase in the per MMBtu fuel cost before accounting for the plant losses. In the LCM cost calculations, plant losses values are used to gross up the per MMBtu fuel cost for each applicable locomotive technology and fuel type.

The required number of fuel tenders displaces other rail cars one-for-one. The displaced rail cars are assumed to contain revenue-generating freight. Thus, the required number of fuel tenders reduces the amount of revenue-generating freight carried by the freight train and increases all costs express in revenue ton-miles.

5.2.3 Emissions-Related Parameters

The U.S. Environmental Protection Agency (EPA) has issued increasingly strict emissions standards for line-haul locomotives for several pollutants periodically since 1999, which standards are published in CFR Part 1033, Subpart B, § 1033.101. EPA's standards fall into one of five tiers, with each tier defined base on the locomotive's year of original manufacture. Tier 4 standards apply to line-haul locomotives manufactured since 2015, Tier 3 standards apply to those manufactured from 2012–2014, Tier 2 from 2005–2011, Tier 1 from 1993–2004, and Tier 0 from 1973–1992.

Estimated emissions costs, emissions rates, and an annual emissions rate reduction factors are included in the LCM cost calculations for each locomotive technology for the following pollutants:

- Carbon dioxide (CO_2)

[18] Another North American data point for comparison is the estimated cost of planned passenger light-rail electrification in Toronto, which ranges from $40 million to $60 million per mile for the 262-kilometer (157-mile) route (International Railway Journal, January 20 and February 11, 2016).

- Nitrogen oxides (NO_x)
- Sulfur oxides (SO_x)
- Carbon monoxide (CO)
- Total hydrocarbons (HC)
- Particulate matter (PM)

Estimated emissions rates for the incumbent diesel-electric locomotive technology vary widely, and little to no information is available for the alternative locomotive technologies. Estimated emissions rates and reduction factors are based on numerous assumptions described below. The LCM Input Matrix readily allows the user to change both emissions rates and reduction factors to perform emissions-related sensitivity analysis. The total physical tons of each type of emissions are also calculated and compared to the incumbent diesel-electric locomotive emissions over the lifetime of each locomotive technology.

The cost of emissions is based on historical prices of Emissions Reduction Credits (ERCs) in California's SCAQMD for criteria pollutant emissions. The cost of ERCs in the SCAQMD is a one-time, up-front payment based on an entity's lifetime expected annual tons of emissions. For purposes of the LCM's cost calculations, that one-time ERC cost is allocated over the lifetime of each locomotive technology. This is done in part to avoid front-loading emissions costs into locomotive first-year costs because locomotive first-year costs are subsequently used to calculate common line-haul freight train statistics, as described in the next section.

Since 2014, the California cap-and-trade program for greenhouse gases (GHG) linked with the cap-and-trade program of the province of Quebec. The fuels sector has been part of California's cap-and-trade program since 2015, with historical carbon emissions costs in the range of \$12–\$15/metric ton (California Air Resources Board, 2017). However, since the application of carbon emissions costs are not explicit in most jurisdictions around the globe, the decision was made to include no carbon emissions costs in the base case results presented in Section III. This allows for a straightforward comparison of the comparative economics of each locomotive technology, without having to make any assumptions about future carbon emissions costs. For completeness, however, the performance of sensitivity analyses on costs for CO_2 emissions were for an assumed flat CO_2 emissions cost of \$25/ton and \$50/ton. Section IV presents the comparative economic results of these sensitivity analyses for each locomotive technology.

Emissions rates and reduction factors for the incumbent diesel-electric locomotive technology are based on EPA 2009, Tables 5, 6, and 7, for NO_x, PM, and HC emissions, respectively. The basis of diesel-electric locomotive CO emissions are based on EPA, 1997, Table 9. Based on a review of CO emissions standards over time, no reduction factor is applied to CO emissions for any input fuel. Diesel-electric locomotive CO_2 emissions are based on the carbon intensity of diesel fuel in California Air Resources Board, 2009, Table 7.

LNG criteria pollutant emissions rates for the diesel-electric locomotive technology with LNG tenders are based on ratios of diesel-related emissions versus LNG-related emissions from diesel-electric locomotive combustion.[19] CO and HC emissions rates are estimated to be 50 percent higher and NO_x emissions rates 70 percent lower for LNG than for diesel when combusted in a

[19] The ratios are mostly derived from BNSF, et al., pp. 46–48, and European Commission, 2016, p. 1.

diesel-electric locomotive. The estimation of the PM emissions rates are to be 0.02 grams/brake horsepower-hour higher for LNG fuel than for diesel fuel in a diesel-electric locomotive, based on differences calculated from values in BNSF, et al., pp. 46–48. SO_x emissions rates are reduced by the fraction of MWh generated using LNG, since LNG is assumed to contain no sulfur. The basis of CO_2 emissions are the combustion-related carbon intensity of diesel fuel and North American natural gas delivered by pipeline and liquefied at 90 percent efficiency, as reported in California Air Resources Board, 2009, Table 7, in proportion to the fraction of each fuel assumed to be utilized by the locomotive.

The basis of emissions rates for the SOFC-GT locomotive technology using LNG fuel are directly or indirectly on Martinez, et al., 2015, p. 432, which estimates that NO_x emissions rates for the SOFC-GT locomotive technology are reduced by 97.7 percent compared to the incumbent diesel-electric locomotive technology. Lacking any other data source, reduction of CO and HC emissions for the SOFC-GT technology assumedly are the same percentage. The PM emissions rate is taken from FuelCell Energy's specification sheet for its 3.7 MW SureSource 4000 fuel cell. SO_x emissions rates for the SOFC-GT locomotive technology are assumed to be zero due to the purity requirements of both LNG and the fuel input requirements of the SOFC-GT locomotive. SOFC-GT locomotive technology CO_2 emissions are based on the 53.8 percent reduction versus a diesel-electric locomotive reported by Martinez, et al., 2015, p. 432. No emissions rate reduction factors were included for the SOFC-GT locomotive fueled with LNG, though future reductions would result to the extent that renewable natural gas (e.g., bio-methane) becomes part of the natural gas mix that is ultimately liquefied into LNG. Such "greening" of the natural gas supply would improve the emissions profile of the SOFC-GT locomotive technology using LNG fuel as compared to the incumbent diesel-electric locomotive technology.

The LCM includes a parameter to specify the percent of renewable energy included in each locomotive technology's fuel input, grid electricity included. Renewable energy input is assumed to have no associated emissions, thereby reducing the quantity (and associated cost) of emissions in proportion to the assumed amount of renewable energy input. The percent of renewable energy for each fuel input is assumed to increase each year at a user-specified rate.[20]

The electric-only locomotive technology produces no onsite emissions; its emissions rates depend on the average emissions rates of the California electric grid from which the overhead electric catenary system draws its electricity. Future CO_2 emissions are assumed to decline as a function of the increasing level of renewable generation on the California electric grid. Renewable generation on the California electric grid is (likely conservatively) estimated to grow at a rate of 1.51 percent a year to reach the 50 percent mandated level by 2030.

Emissions rates for the SOFC-GT hybrid locomotive technology using LH_2 fuel are all associated with the fraction of non-renewable hydrogen utilized as fuel input (assumed to be generated from natural gas in an SMR). The emissions from the 1.08 kWh of electricity input required per MMBtu of gaseous H_2 output by the SMR are based on the same average (and declining) emissions rates for the California electric grid described in the previous paragraph; the 0.079 tons of CO_2 emissions from the natural gas input required by the SMR are based on current

[20] The estimated 2015 emissions rates for the California electric grid already include reflect the impact of the 27.3 percent of Total System Power provided by renewables (including large hydro) (California Energy Commission, 2017). Emissions rates for the California electric grid are assumed to decline in proportion to the annual rate of increase in renewable generation.

SMR technology.[21] The fraction of renewable hydrogen utilized as fuel is assumed to be generated by electrolyzers whose electricity input is assumed to be otherwise-curtailed renewable energy with no generation-associated emissions.

The emissions rates and reduction factors for those locomotive technologies that are fueled with a combination of fuels (e.g., diesel-LNG, diesel-BES) are based on a weighted average of the proportion of each fuel utilized for locomotive propulsion, a proportion that can readily be changed within the LCM Input Matrix. Base case fuel proportions are 50 percent LNG for the diesel-LNG locomotive technology, and 20 percent BES for the diesel-BES locomotive technology.

5.2.4 Class I Freight Train Operating Parameters

The LCOE at the locomotive's traction motors provides one metric that may be used to compare the economics of different locomotive technologies, but it is not a metric commonly used in the railroad industry. To remedy this, various Class I line-haul freight train statistics are combined with the first-year, all-in costs for each different locomotive technology to derive metrics more familiar in the railroad industry, such as cost per revenue ton-mile. Class I line-haul freight train statistics are predominantly taken from 5-year average values found in AAR's *Railroad Ten-Year Trends* report.

- One ton-mile represents the transportation of a ton of freight for 1 mile.
- One revenue ton-mile represents the transportation of a ton of revenue-generating freight for 1 mile.
- The average Class I line-haul freight train consists of 72 cars (AAR, 2016, p. 125) powered by three locomotives (AAR, 2016, p. 27 [see footnote 8]) with an average haul of 1,000 miles (AAR, 2016, p. 123 [see footnote 8]).[22]
- On average, only 57.4 percent of a freight train's cars are loaded (AAR, 2016, p. 120 [see footnote 8]) and those cars that are loaded on average contain 60 tons of revenue freight (AAR, 2016, p. 128 [see footnote 8]). Using these average values, each loaded car that is transported over 1 mile would equate to 60 revenue ton-miles.
- The average network velocity of a Class I line-haul freight train is 19.6 mph, taking into account all delays during a haul (AAR, 2016, p. 130 [see footnote 8]). It is assumed that a total of 18 hours are required for loading and unloading each freight train, a value that can changed by the user in the LCM Input Matrix.

Each of the above Class I line-haul freight train statistics is included in the derivation of cost per revenue ton-mile for each locomotive technology. Care should be taken in making changes to the values in the LCM Input Matrix to ensure that those values are realistic with respect to actual

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[21] The values used to derive the SMR-related emissions factors are derived from values reported in Sections 2.7 and 2.8 of IEA Greenhouse Gas (IEAGHG), 2017.

[22] As noted previously, base case results are presented using the average 1,000-mile haul for each individual locomotive technology. Sensitivity results are subsequently presented for a scenario that examines the economics of using electric-only locomotives for the 130 miles from Long Beach to Barstow, combined with using diesel-electric locomotives for the remaining 870 miles of the total 1,000-mile haul.

freight train operations. The LCM cost calculations will provide results for almost any input values, but the results are only meaningful if the input values bear some semblance to reality.

Calculated results from the LCM for the incumbent diesel-electric locomotive technology are calibrated against the 5-year averages reported by AAR for several metrics. The LCM calculates 67.14 million annual revenue ton-miles per locomotive compared to the 67.04 million annual ton-miles per locomotive reported at AAR, 2016, p. 135, a difference of less than 1 percent. The LCM calculates 454 revenue ton-miles per gallon of diesel compared to the 474 revenue ton-miles per gallon of diesel reported at AAR, 2016, p. 134, a difference of less than 5 percent. The latter metric could have been calibrated closer to the AAR 5-year average through a slight improvement in the heat rate of the diesel-electric locomotive technology. This re-calibration was not done in favor of maintaining a single source for all the locomotive technology heat rates (Hoffrichter, et al., 2012, p. 30).

5.3 Base Case Economic Results

The two main metrics calculated by the LCM are: (i) The LCOE for each locomotive technology, expressed in $/MWh delivered to the locomotive's traction motors, and (ii) the cost of operating the freight train with three locomotives, expressed in cents per revenue ton-mile. The LCOE metric takes into account the MWh delivered to the traction motors by the locomotive for the lifetime miles traveled by the locomotive, but it does not take into account the associated tons of revenue freight transported. The cost per revenue ton-mile is a widely used metric in the railroad industry and the levelized cost per revenue ton-mile metric considers the lifetime tons of revenue freight transported by the locomotive. The rankings based on the more-dynamic levelized cost per revenue ton-mile should therefore take precedence over the more-static LCOE metric to the extent that these two rankings differ for any given locomotive technology. Both these metrics are impacted by the number of tenders required (if any) per train, since tenders are assumed to displace carloads of revenue freight on a one-for-one basis. Table 12 provides the number of tenders required for each train and the resultant percentage of cars loaded with revenue freight.

Table 11. Tenders Required and Impact on Cars of Revenue Freight, by Locomotive Technology

	Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
Tenders/Train	0	8	1	2	3	0
% Cars Loaded	57.4%	46.3%	56.0%	54.6%	53.2%	57.4%

Table 13 presents the values for the LCOE and cents per revenue ton-mile metrics for each locomotive technology, based on the base case values in the LCM Input Matrix presented in Tables 1-A and 1-B. The cents per revenue ton-mile values are presented in two ways, first for Year 1 freight train operations (representing current year, non-discounted costs) and then on a levelized basis, (representing discounted and levelized costs over the economic life of each locomotive technology). There are no CO_2 emissions costs included in any of the base case results.

Table 12. Base Case LCOE and Cents per Revenue Ton-Mile Results (No CO_2 Emissions Cost)

(No CO_2 Emissions Cost)	Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
LCOE ($/MWh)	$538.20	$1,740.21	$522.78	$535.22	$676.03	$582.38
Rank Order:	3	6	1	2	5	4
Year 1: ¢/Rev Ton-Mile	2.11¢	11.35¢	2.36¢	2.79¢	3.90¢	2.92¢
Rank Order:	1	6	2	3	5	4
Levelized (x 10^{-6}): ¢/Rev Ton-Mile	7.31¢	29.31¢	7.28¢	7.64¢	9.90¢	7.91¢
Rank Order:	2	6	1	3	5	4

The importance of considering how each locomotive technology operates in serving freight trains is immediately evident from the differences in the rank order of the results when comparing the LCOE results with the Year 1 and levelized cents per revenue ton-mile results in Table 14.

- The LCOE of the incumbent diesel-electric locomotive technology is higher than the LCOE of the two locomotive technologies using LNG tenders but lower than the LCOE of the electric-only locomotive technology, the diesel-electric locomotive technology with BES tenders, and the SOFC-GT hybrid locomotive technology with LH_2 tenders.
    - The higher LCOE for the electric-only locomotive technology results from the costs of the overhead electric catenary system, which was priced in the base case at $20 million per mile.
    - The higher LCOE for the latter two locomotive technologies is a direct result of the higher cost of the batteries for the BES tenders and of costs of liquefying hydrogen for the LH_2 tenders.

- The incumbent diesel-electric locomotive technology has the lowest Year 1 cents per revenue ton-mile results, followed closely by the diesel-electric locomotive technology with LNG tenders, the SOFC-GT hybrid technology with LNG tenders, and the electric-only locomotive technology.
    - The cents per revenue ton-mile values for the two locomotive technologies with LNG tenders are impacted by the lower number of revenue ton-miles that result from the displacement of cars of revenue freight because of the required number of LNG tenders.
    - The cents per revenue ton-mile value for the electric-only locomotive technology is impacted by the costs of the overhead electric catenary system and by the relatively high Year 1 cost of electricity at $29.38/MMBtu compared to the $16.80/MMBtu cost of diesel.
    - The higher cents per revenue ton-mile values for the diesel-electric locomotive technology with BES tenders and the SOFC-GT hybrid locomotive technology with LH_2 tenders are impacted by the same factors that resulted in the higher LCOE values above, exacerbated by the lower number of revenue ton-miles due to the displacement of revenue freight by the required number of tenders.
- The diesel-electric locomotive technology with LNG tenders has the lowest levelized cents per revenue ton-mile results, followed closely by the incumbent diesel-electric locomotive technology; the SOFC-GT hybrid locomotive technology with LNG tenders and the electric-only locomotive technology are less than 5 percent and 10 percent higher, respectively.
    - The two locomotive technologies with LNG tenders benefit over their economic lives from the fact that EIA's 2017 AEO transportation sector natural gas prices are forecast to increase more slowly than its transportation sector diesel and electricity prices.
    - The incumbent diesel-electric locomotive technology's levelized cents per revenue ton-mile value suffers from the fact that EIA's 2017 AOE transportation sector diesel prices are forecast to escalate faster than both its transportation sector natural gas price and electricity price forecasts.

The electric-only locomotive technology benefits greatly from not having any revenue freight displaced by tenders, a benefit that accrues throughout its economic life. The electric-only locomotive technology also benefits from the fact that EIA's 2017 AEO transportation sector electricity prices are forecast to increase more slowly than diesel prices.

5.4 Comparative Economics Sensitivity Results

In order to gain a better understanding about how different factors impact the cost of the locomotive, several cost sensitivity analyses were performed. They include the cost of capital, the various locomotive technologies under consideration, CO_2 and lifetime emissions, hydrogen, and energy. This leads to conclusions about the conditions under which different locomotive technologies provide economic advantages and disadvantages.

5.4.1 Capital Cost Sensitivity

The capital costs for each locomotive technology were based on Railtec, 2016, a study that was commissioned by the California Air Resources Board (CARB). The estimated capital cost for the SOFC-GT hybrid locomotive was estimated at $5 million in Railtec, 2016, p. xv. The follow-up report by the CARB estimates that the SOFC-GT hybrid locomotive power plant alone would cost $6.5 million, with an additional $1.5 million required for "the locomotive platform, mechanical and traction components, electrical and auxiliary systems," resulting in a total cost of $8 million per SOFC-GT hybrid locomotive (California Air Resources Board, 2016, p. X-3). Table 5 presents the comparative results for all the locomotive technologies in the same format as Table 4, but using an $8 million locomotive capital cost instead of the $5 million value for the SOFC-GT hybrid locomotive technology used for the base case results in Table 4.

Table 13. LCOE and Cents per Revenue Ton-Mile Results, SOFC-GT Hybrid Capex at $8 Million

(No CO_2 Emissions Cost)	Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
LCOE ($/MWh)	$538.20	$1,740.21	$522.78	$674.98	$833.33	$582.38
Rank Order:	2	6	1	4	5	3
Year 1: ¢/Rev Ton-Mile	2.11¢	11.35¢	2.36¢	3.47¢	4.62¢	2.92¢
Rank Order:	1	6	2	4	5	3
Levelized (x 10^{-6}): ¢/Rev Ton-Mile	7.31¢	29.31¢	7.28¢	9.63¢	12.20¢	7.91¢
Rank Order:	2	6	1	4	5	3

Increasing the SOFC-GT hybrid locomotive technology capital cost by 60 percent expectedly changes the rank order of all three metrics, with the SOFC-GT hybrid locomotive technology with LNG tenders and LH_2 tenders now ranking fourth and fifth, respectively, in all categories. Since the SOFC-GT hybrid locomotive technology is still in the concept phase, the actual capital cost of the technology remains unknown. However, if the Railtec, 2016, capital cost estimate of $5 million for the SOFC-GT hybrid locomotive technology is realistic, this alternative locomotive technology would be cost competitive with the incumbent diesel-electric locomotive technology on both an LCOE and cost per revenue ton-mile basis with only a 5 percent cost reduction, all other LCM Input Matrix parameter values being the same.

5.4.2 Overhead Electric Catenary System Cost and Usage Sensitivity

Another important sensitivity analysis was performed for the electric-only locomotive technology with the overhead electric catenary system. Although the results for 1,000 miles of electrification were quite favorable from an LCOE and cost per revenue ton-mile perspective at the assumed $20 million per mile capital cost, the reality of installing an overhead electric catenary system for that length of rail would likely be very challenging, given political realities, interstate issues, and anticipated not-in-my-backyard opposition. For that reason, the perhaps more realistic case of electrifying the 130 miles between Long Beach and Barstow, CA, was also examined. In this case, instead of the train being unloaded in Barstow, there would be an engine exchange, with diesel-electric locomotives taking the train the balance of the 1,000-mile haul. Table 15 presents the LCM results for the electric-only locomotive technology for several combinations of miles electrified and costs per miles, with the base case results from Table 14 for the electric-only locomotive technology repeated in the left-most column of results as a point of reference.

Table 14. Sensitivity Analysis, Electric-Only Locomotive Technology with Overhead Electric Catenary

(No CO_2 Emissions Cost)	Electric-Only Locomotive (Catenary)	Electric-Only Locomotive (Catenary)	Electric-Only Locomotive (Catenary)	Electric-Only Locomotive (Catenary)	Electric-Only Locomotive (Catenary)	Electric-Only Locomotive (Catenary)
Miles Electrified	1,000	1,000	1,000	130	130	130
Cost/Mile ($ MM)	$20	$20	$30	$25	$25	$30
Trains/Day	70	35	70	70	35	70
LCOE ($/MWh)	$582.38	$713.40	$647.89	$532.86	$614.34	$549.15
Year 1: ¢/Rev Ton-Mile	2.92¢	3.73¢	3.33¢	5.27¢	6.27¢	5.47¢
Levelized (x 10^{-6}): ¢/Rev Ton-Mile	7.91¢	9.69¢	8.80¢	14.54¢	16.77¢	14.99¢
Annual Revenue Ton-Miles	201.42 million	201.42 million	201.42 million	100.29 million	100.29 million	100.29 million

The results for the electric-only locomotive technology presented in Table 15 show that there are three main cost drivers associated with rail electrification via installation of an overhead electric catenary system, those being the miles electrified, the cost per mile, and the density of use (as represented by the assumed number of trains per day).

- Although the LCOE for the 130-mile electrification cases look good from an LCOE perspective, the cost per revenue ton-mile is much higher than for the 1,000-mile electrification cases with similar per-mile costs and density of use. The reason for this is two-fold.
    - First, a much greater proportion of the locomotive's availability is taken up with loading (or unloading) and switching engines for the shorter 130-mile assumed route than for the 1,000-mile route.

- Second, there are fewer revenue ton-miles per haul for the shorter route. Although there are more hauls per year for the shorter route, the hours lost due to more loading and unloading cycles overall results in fewer revenue ton-miles for the same overall locomotive operating parameters (i.e., capacity factor, annual availability).
- The combined impact of these two factors is seen in the last row of Table 15, which shows that there are 201.42 million revenue ton-miles per electric-only locomotive for the 1,000-mile route and 100.29 million revenue ton-miles per electric-only locomotive for the 130-mile route.

As was the case with the SOFC-GT hybrid locomotive technology, the comparative economics of the electric-only locomotive technology with an overhead electric catenary system depend on the robustness of the cost estimates entered into the LCM Input Matrix.

5.4.3 Combined Electric-Only Locomotive & Diesel-Electric Locomotive Sensitivity

A mixed locomotive technology scenario that emphasizes reduced CO_2 and criteria pollutant emissions in the South Coast Air Basin could combine electric-only locomotive technology with an overhead electric catenary system for the 130 miles from Long Beach to Barstow with standard diesel-electric locomotive technology for the remainder of the 1,000-mile haul. The sensitivity in economic outcomes for the electric-only locomotive technology of reducing the total miles of overhead electric catenary structure from 1,000 miles to 130 miles to an engine switching point was examined above. The results in this section will create a combined, weighted average scenario using the 130 miles of overhead electric catenary system for the electric-only locomotive technology and the incumbent diesel-electric technology for the remaining 870 miles.

The comparative results for such a combined, weighted-average scenario can be calculated automatically by the LCM by simply modifying several of the values related to length of haul and miles of overhead electric catenary system installed in the LCM Input Matrix that was presented in Figures 1-A and 1-B. Table 16 provides all values for the incumbent diesel-electric locomotive technology and the electric-only locomotive technology from the LCM Input Matrix, with the modified values highlighted. The two modifications required are as follows:

- The base case value of 18 hours for loading and unloading is modified to 11.4 hours since the haul for each type of locomotive includes 9 hours of either loading or unloading and 2.4 hours of engine exchange in Barstow.

The electric-only locomotive technology will travel only over the 130 miles of overhead electric catenary system assumed to be installed at \$20 million per mile between Long Beach and Barstow; incumbent diesel-electric locomotive will travel the remaining 870 miles of the total 1,000-mile haul.

Table 15. Combined, Weighted-Average Scenario LCM Input Matrix Values

		7	8
		Tier 4 Diesel-Electric + Electric-Only	Electric-Only (Catenary) + Diesel-Electric
1	Gross Capacity (MW; 1 hp = 0.746 kW)	3.2824	3.2824
2	Annual Capacity Factor	0.269	0.269
3	Instant Cost (MM$)	3	5
4	Battery Replacement Cost Maintenance Fee per BES Tender ($/kW-yr)	0	0
5	VOM ($/MWh @ Traction Motor)	19.39	13.573
6	HR (MMBtu/MWh @ Traction Motor)	12.319	1.312
7	HR Degradation	0.01	0.005
8	SMR Conversion Efficiency for Nonrenewable H2 Production	0	0
9	Debt Term (Yrs)	12	12
10	Economic Life (Yrs) (Cannot exceed 40 years for tax calcs)	30	30
11	Federal Tax Life (Yrs)	14	14
12	State Tax Life (Yrs)	15	15
13	Ad Valorem Tax Rate	0.01098	0.01098
14	Ownership Type (1=Merchant;2=IOU;3=POU)	1	1
15	Fuel Delivery Losses (Related to Tenders and Catenary Use)	0	0.1
16	Fuel Type (0=RE;1=LNG;2=LH2;3=Diesel;4=Diesel:LNG;5=Diesel:BES;6=Elect)	3	6
17	Fuel Density (MMBtu/gallon for liquid fuels; MMBtu/MWh for electricity)	0.1374	3.412
18	Fraction of MWh Provided from Tenders	0	0
19	SMR Cost for Nonrenewable H2 Production ($/kg H2)	0	0
20	H2 Liquefaction Cost Multiplier vs. NG Liquefaction Cost	0	0
21	CO 2009 Emissions Factor (g/bhp-hr)	5	0.056
22	CO Annual Emissions Reduction Factor	0	0
23	HC 2009 Emissions Factor (g/bhp-hr)	0.418	0.047
24	HC Annual Emissions Reduction Factor	0.0671	0
25	NOx 2009 Emissions Factor (g/bhp-hr)	7.933	0.035
26	NOx Annual Emissions Reduction Factor	0.0555	0.001
27	PM 2009 Emissions Factor (g/bhp-hr)	0.236	0.012
28	PM Annual Emissions Reduction Factor	0.0764	0
29	SOx 2009 Emissions Factor (g/bhp-hr)	0.05	0.006
30	SOx Annual Emissions Reduction Factor	0.01	0
31	CO2 Emissions Factor (tons CO2/MMBtu fuel) (/MWh electricity)	0.11	0.306
32	Renewable Resource Fraction for Fuel Type	0	0.273
33	Renewable Resource Fraction Annual Increase	0	0.0151
34	Average Cars per Train	72	72
35	Locomotives Required per Train	3	3
36	Net Freight Train Load (Freight Tons+Some Allocated Wt of Cars)	3529	3529
37	Fraction of Cars Loaded (Prior to Lowering Based on Tenders Required)	0.574	0.574
38	Revenue Tons per Car Loaded	60	60
39	Hours Required for Loading and Unloading	11.4	11.4
40	Length of Haul (Miles)	870	130
41	Network Velocity (mph)	19.6	19.6
42	Annual Availability	0.64	0.64
43	Locomotive Rebuild Interval (Years)	10	10
44	Locomotive Rebuild Cost (% of Instant Cost)	0.25	0.25
45	Instant Cost per Tender (MM$)	0	0
46	Useful Tender Capacity (Gallons for Liquid Fuels, MWh for BES)	0	0
47	Useful Energy Per Tender (MWh)	0	0
48	Miles of Catenary Infrastructure Installed	0	130
49	Catenary Infrastructure Cost (Million $)	0	20
50	Catenary Infrastructure Usage (Trains per Day)	0	70
51	Manufacturing Percent per Year	1,0,0,0,0,0	1,0,0,0,0,0
52	Manufacturing Months per Year	12,0,0,0,0,0	12,0,0,0,0,0
53	BEITC	0,0,0,0	0,0,0,0

The comparative results for the combined, weighted-average scenario are shown in Table 17, along with the results for the SOFC-GT hybrid locomotive technology with LNG tenders, which is lowest cost alternative locomotive technology that would reduce emissions in the Basin without the need for an engine exchange at Barstow.

Table 16. Combined, Weighted-Average Scenario and SOFC-GT Hybrid Comparative Results

	Electric-Only + Diesel-Electric Combination	Electric-Only + Diesel-Electric Combination	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LNG Fuel))
Capex: SOFC-GT Locomotive			$5 million	$5 million	$8 million	$8 million
CO_2 Emissions Cost ($/ton)	None	$50/ton	None	$50/ton	None	$50/ton
LCOE ($/MWh)	$535.38	$598.88	$535.22	$563.10	$674.98	$702.85
Rank Order:	2	4	1	3	5	6
Year 1: ¢/Rev Ton-Mile	2.36¢	2.73¢	2.79¢	2.96¢	3.47¢	3.64¢
Rank Order:	1	2	3	4	5	6
Levelized (x 10^{-6}): ¢/Rev Ton-Mile	7.74¢	8.58¢	7.64¢	8.04¢	9.63¢	10.03¢
Rank Order:	2	4	1	3	5	6

For the SOFC-GT hybrid locomotive technology with LNG tenders having a base case capital cost of $5 million per locomotive, this alternative locomotive technology has lower values for both the LCOE and the levelized cost per revenue ton-mile than does the combined, weighted-average electric-only + diesel-electric scenario. This is true whether the assumed CO_2 emissions cost is zero or $50/ton.

If instead the SOFC-GT hybrid locomotive technology with LNG tenders has the higher capital cost of $8 million per locomotive, then the combined, weighted-average electric-only + diesel-electric scenario has lower values for both the LCOE and the levelized cost per revenue ton-mile for an assumed CO_2 emissions cost up to $50/ton. It is not until the CO_2 emissions cost reaches nearly $220/ton that the levelized cost per revenue ton-mile of the SOFC-GT hybrid locomotive technology with LNG tenders is lower than that of the combined, weighted-average electric-only + diesel-electric scenario, at 11.38¢ per revenue ton-mile and 11.41¢ per revenue ton-mile, respectively.

The role of SOFC-GT hybrid locomotive technology with LNG tenders in line-haul freight operations where reduction in emissions is important is one possible area of future research. The fruitfulness of this area of research would depend on how quickly SOFC power plant costs are reduced.

5.4.4 BES Cost and Tenders Sensitivity

It is important to highlight the impact of the high cost of the batteries and the relatively large number of required BES tenders. The high cost of the BES tenders themselves, when combined with the significant amount of revenue freight displaced by the BES tenders, results in both the LCOE and the cents per revenue ton-mile values being significantly higher than for any other locomotive technology.

- Given the deadweight of the BES tenders, it appears that the diesel-electric locomotive technology with BES tenders will not be cost-competitive for line-haul freight train applications unless the cost of batteries is greatly reduced.
  - Even if the cost of the BES tenders is reduced by 90 percent, the resultant LCOE is $1,197.90/MWh with a levelized 20.17×10^{-6} cents revenue ton-mile, with both metrics remaining higher than those of any of the other locomotive technologies.

The role of diesel-electric locomotive technology with BES tenders in short-haul freight operations where reduction in emissions is important is one possible area of future research. Areas where the diesel-electric locomotive technology would operate on battery power could be circumscribed very carefully to reduce the number of BES tenders required. The fruitfulness of this area of research would depend on how quickly battery costs are reduced.

5.4.5 CO_2 Emissions Cost Sensitivity

The base case results presented in Section 5.3 did not include any cost for CO_2 emissions. Given the large differences in CO_2 emissions rates between the different locomotive technologies, applying different levels of CO_2 emissions costs to locomotive CO_2 emissions will likely have a significant and differential economic impact for each locomotive technology. Given the uncertainty in how CO_2 emissions costs may evolve over time, this sensitivity analysis compares the economic impacts of a flat CO_2 emissions cost of $25/ton and $50/ton. Table 18 presents the $25/ton results and Table 19 presents the $50/ton results.

Table 17. LCOE and Cents per Revenue Ton-Mile Results, \$25/ton CO_2 Emissions Cost

(\$25/ton CO_2 Emissions Cost)	Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
LCOE (\$/MWh)	\$573.38	\$1,769.19	\$557.35	\$549.16	\$684.66	\$591.16
Rank Order:	3	6	2	1	5	4
Year 1: ¢/Rev Ton-Mile	2.32¢	11.56¢	2.57¢	2.87¢	3.98¢	2.99¢
Rank Order:	1	6	2	3	5	4
Levelized (x 10^{-6}): ¢/Rev Ton-Mile	7.79¢	29.79¢	7.76¢	7.84¢	10.03¢	8.02¢
Rank Order:	2	6	1	3	5	4

Table 18. LCOE and Cents per Revenue Ton-Mile Results, \$50/ton CO_2 Emissions Cost

(\$50/ton CO_2 Emissions Cost)	Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
LCOE (\$/MWh)	\$608.55	\$1,798.17	\$591.91	\$563.10	\$693.29	\$599.94
Rank Order:	4	6	2	1	5	3
Year 1: ¢/Rev Ton-Mile	2.52¢	11.78¢	2.78¢	2.96¢	4.06¢	3.05¢
Rank Order:	1	6	2	3	5	4
Levelized ($x\ 10^{-6}$): ¢/Rev Ton-Mile	8.26¢	30.28¢	8.24¢	8.04¢	10.15¢	8.15¢
Rank Order:	4	6	3	1	5	2

The SOFC-GT hybrid locomotive technology with LNG tenders has the lowest LCOE under both CO_2 emissions cost scenarios, but it is only in the \$50/ton CO_2 emissions cost scenario that the SOFC-GT hybrid locomotive technology with LNG tenders also achieves the lowest levelized cost in cents per revenue ton-mile. The savings in CO_2 emissions and their associated cost at that CO_2 emissions cost overcomes the deadweight revenue losses associated with the required LNG tenders. Although the SOFC-GT hybrid locomotive technology with LH_2 tenders has even lower emissions than the same locomotive technology with LNG tenders, the high cost of hydrogen production and liquefaction keeps the SOFC-GT hybrid locomotive technology with LH_2 tenders metrics above those of all other locomotive technologies except the diesel-electric with battery tenders.

5.4.6 Hydrogen Production Cost Sensitivity

One way that H_2 production costs could be reduced is to produce all gaseous H_2 using electrolyzers fueled only with otherwise curtailed renewable energy. The otherwise curtailed renewable energy input would therefore have zero applicable fuel cost and the H_2 production cost would be limited to the \$4.35/kg of H_2 electrolyzer cost, as discussed above in Section 5.2. This sensitivity case can be run in the LCM by simply changing the Renewable Resource Fraction to 100 percent for the SOFC-GT hybrid locomotive technology with LH_2 tenders at column 4, row 32 of the LCM Input Matrix shown in Table 16. Table 20 shows the results for the two different SOFC-GT hybrid locomotive capital costs for both the no CO_2 emissions cost and \$50/ton CO_2 emissions cost. Since gaseous H_2 produced using electrolyzers fueled only with otherwise curtailed renewable energy has no associated CO_2 emissions, there is no impact on its costs regardless of the level of the applicable CO_2 emissions cost.

Table 19. Hydrogen Production Cost Sensitivity, with SOFC-GT Hybrid Capex & CO_2 Emissions Costs

	Tier 4 Diesel-Electric Locomotive	Tier 4 Diesel-Electric Locomotive	SOFC-GT Locomotive (LH_2 Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	SOFC-GT Locomotive (LH_2 Fuel)
Locomotive Capex	\$3 million	\$3 million	\$5 million	\$5 million	\$8 million	\$8 million
Renewable %	n/a	n/a	33% +	100%	33% +	100%
CO_2 Emissions Cost (\$/ton)	None	\$50/ton	None	No CO_2 Emissions	None	No CO_2 Emissions
LCOE (\$/MWh)	\$538.20	\$608.55	\$676.03	\$601.55	\$833.33	\$741.31
Rank Order:	1	3	4	2	6	5
Year 1: ¢/Rev Ton-Mile	2.11¢	2.52¢	3.90¢	3.45¢	4.62¢	4.15¢
Rank Order:	1	2	4	3	6	5
Levelized (x 10^{-6}): ¢/Rev Ton-Mile	7.31¢	8.26¢	9.90¢	8.81¢	12.20¢	10.86¢
Rank Order:	1	2	4	3	6	5

Gaseous hydrogen produced using electrolyzers fueled only with otherwise curtailed renewable energy still yields cost metrics for the SOFC-GT hybrid locomotive technology with LH_2 tenders that are above the metrics for the incumbent diesel-electric locomotive technology in all cases if there is no cost of CO_2 emissions. At a \$50/ton cost of CO_2 emissions, the LCOE of the SOFC-GT hybrid locomotive technology with LH_2 tenders, 100 percent renewable H_2, and a \$5 million capex is lower than that of the incumbent diesel-electric locomotive technology. Even in that case, however, the deadweight impact of the required LH_2 tenders results in both the Year 1 and levelized cost per revenue ton-mile being higher for the SOFC-GT hybrid locomotive technology with LH_2 tenders. For the SOFC-GT hybrid locomotive technology with LH_2 tenders to be cost competitive in the future, there clearly must be additional research done to reduce the cost of liquefaction and dispensing of the liquefied H_2.

5.4.7 Energy Price Forecast Sensitivity

The sensitivity of results to the assumed energy price forecasts emphasizes the importance of using a consistent suite of energy price forecasts. The EIA's 2017 AEO energy price forecasts were used for all the results presented here, but differences in relative escalation among the various energy price forecasts would result in different results in absolute terms, and possibly even in rank order terms depending on how much the relative energy price escalations were changed. There are an infinite number of combinations of energy price forecasts, any number of which the user could use for sensitivity analysis.

5.5 Lifetime Emissions Analysis

The LCM also calculates the total tons of emissions for each locomotive over its economic life for each locomotive technology, based on the emissions rates in the LCM Input Matrix. The LCM then calculates the difference in lifetime tons of emissions for each type of alternative locomotive technology compared to the lifetime tons of emissions of an incumbent diesel-electric locomotive. Table 21 presented the comparative results for the difference in lifetime emissions compared to the incumbent diesel-electric locomotive technology.

Table 20. Comparative REDUCED Lifetime Emissions vs. Diesel-Electric Locomotive Technology

	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
REDUCED Lifetime Emissions Per Locomotive: Difference vs. Diesel-Electric (In Tons)					
CO_2	37,098	3,677	155,143	183,153	163,872
REDUCED Lifetime Emissions Per Locomotive: Difference vs. Diesel-Electric (In Tons x 10^{-6})					
CO	217.0	-274.3	1,080.4	1,095.3	1,087.8
HC	56.3	29.2	182.5	182.3	176.0
NO_x	890.0	1,571.1	2,983.0	3,008.5	3,003.8
PM	40.0	41.4	117.9	117.5	115.8
SO_x	2.3	6.2	11.9	11.7	10.9

The base case reduced lifetime emissions results in Table 21 reflect very favorably on the SOFC-GT hybrid locomotive technology with LH_2 tenders, despite the relatively higher costs of this technology discussed previously. In the 100-percent renewable hydrogen production case (discussed above), all types of lifetime emissions are reduced even further, by up to 15.0 percent in the case of CO_2 emissions. This relatively small magnitude of reduced CO_2 reductions reflects the fact that the even the electricity feeding the SMRs for the fraction of nonrenewable hydrogen production has a relatively large and growing amount of carbon-free renewable generation from the California grid already included.

5.6 Market Analysis

A market analysis of the market potential for alternative non-diesel-electric locomotive technologies is presented in Appendix A.

5.7 Market Analysis Conclusions

The results of the comparative economic analysis of the incumbent diesel-electric locomotive technology and the competing alternative locomotive technologies suggest that regulatory policy drivers will likely play a larger role in bringing alternative locomotive technologies into the Class I railroad fleet than will straight economics. Possible regulatory policy drivers might include outright bans on local or regional emissions of criteria pollutants, for instance at ports or in economically disadvantaged communities.

The most informative economic metric is the cost per revenue ton-mile, which is calculated in two ways. The first way is a Year 1 cost for each locomotive technology and the second way is a cost per revenue ton-mile levelized over each locomotive technology's lifetime. The second levelized cost per revenue ton-mile is a more informative metric since it considers costs over each locomotive's entire lifetime. Base case levelized costs per revenue ton-mile are calculated with criteria pollutants having a cost based on historical California prices and with CO_2 emissions initially having no cost.

Table 22 shows the relative rankings of all locomotive technologies for the base case with CO_2 emissions having no cost, for the \$25/ton CO_2 emissions cost case, and for the \$50/ton CO_2 emissions cost case. It can be seen that the relative rankings of the different locomotive technologies do not change for the \$25/ton CO_2 emissions cost and thus there would also be no change in the base case rankings at the current California CO_2 emissions cost of \$15/ton. As the cost of CO_2 emissions increases to \$50/ton, the SOFC-GT locomotive technology with LNG tenders becomes the lowest cost technology, displacing the incumbent diesel-electric locomotive technology.

Although the SOFC-GT hybrid locomotive technology with LH_2 tenders does not move from its fifth-place relative ranking, it is worth noting that its levelized cost per revenue ton-mile is increasing at a slower pace than that of most of the other locomotive technologies. This is because the CO_2 emissions associated with the production of gaseous H_2 are declining as the California grid becomes greener and as the share of renewable H_2 increases. If gaseous H_2 is produced using 100 percent renewable energy using electrolyzers, the levelized cost per revenue ton-mile drops to 8.81 (x 10^{-6}) cents, only 6.6 percent higher than the cost of the incumbent diesel-electric locomotive technology with a \$50/ton CO_2 emissions cost, with no assumed improvement in the cost of the SOFC-GT hybrid power plant.

Table 21. Levelized Cost per Revenue Ton-Mile Results for Various CO_2 Emissions Costs

Levelized (x 10^{-6}): ¢/Rev Ton-Mile	Tier 4 Diesel-Electric Locomotive	Diesel-Electric Locomotive + Battery Tender	Tier 4 Diesel-LNG Locomotive	SOFC-GT Locomotive (LNG Fuel)	SOFC-GT Locomotive (LH_2 Fuel)	Electric-Only Locomotive (Catenary)
No CO_2 Emissions Cost	7.31¢	29.31¢	7.28¢	7.64¢	9.90¢	7.91¢
Rank Order:	2	6	1	3	5	4
$25/ton CO_2 Emissions Cost	7.79¢	29.79¢	7.76¢	7.84¢	10.03¢	8.02¢
Rank Order:	2	6	1	3	5	4
$50/ton CO_2 Emissions Cost	8.26¢	30.28¢	8.24¢	8.04¢	10.15¢	8.15¢
Rank Order:	4	6	3	1	5	2

The cost impact of the historically derived criteria pollutant prices is so small that it gets lost in the rounding and has no impact on the relative rankings of the competing locomotive technologies. Therefore, it is unlikely that the future costs of criteria pollutants alone will impact the comparative economics. More likely, it will be regulatory policies highly valued by society (e.g., limiting absolute emissions of criteria pollutants) that will lead to alternative locomotive technologies displacing the incumbent diesel-electric locomotive technology. Such limitations would likely apply to limited geographic areas such as ports or economically disadvantaged communities.

The comparative economics for the electric-only locomotive technology are highly dependent on the assumed cost of installing the overhead electric catenary system. An offsetting (beneficial) cost impact is the fact that the electric-only locomotive technology requires no tenders, as do all the other alternative locomotive technologies examined. Since tenders are assumed to displace cars carrying revenue freight on a one-for-one basis, the cost per revenue ton-miles is increased for locomotive technologies requiring tenders due to the lower tonnage of revenue freight.

For purposes of reducing CO_2 emissions in the South Coast Air Basin, the SOCF-GT hybrid locomotive technology with LNG tenders is lower cost at 7.64 (x 10-6) cents per revenue ton-mile than the combined electric-only + diesel-electric locomotive scenario at 7.74 (x 10-6) cents per revenue ton-mile if the capital cost of the SOFC-GT hybrid locomotive is the base case cost of $5 million per locomotive. This emphasizes the importance of future research to reduce the cost of the SOFC-GT hybrid locomotive technology. In contrast, the diesel-electric locomotive with BES tenders does not appear to be a competitive locomotive technology under any reasonable assumptions about foreseeable reductions in BES costs.

6. Conclusion

With support from the Federal Railway Administration (FRA), the National Fuel Cell Research Center (NFCRC) has completed a major program that investigated the use of hybrid solid oxide fuel cell–gas turbine (SOFC-GT) systems for future zero emissions powering of locomotives. The research efforts are summarized as follows with all the major findings and accomplishments, which were completed in December 2017:

- Industrial partners for the development of a prototype SOFC-GT locomotive engine have been selected. FuelCell Energy, Inc. (FCE) was selected as the SOFC manufacturer. FCE is the world-leading manufacturer of carbonate fuel cell systems and leading developer and the manufacturer of state-of-the-art solid oxide fuel cell technology for stationary power, military, aerospace, and other applications. The other major partner identified is Capstone Turbines (Capstone), the world-leading manufacturer of micro-turbine generator (MTG) technology that is in the size class of the system requirements needed for the prototype system. FCE and Capstone have worked together previously in the development and demonstration of hybrid fuel cell gas turbine technology including previous efforts that have included the NFCRC.
- A prototype design for the SOFC-GT locomotive was completed, based upon the specifications of technology that FCE and Capstone can produce and that could be integrated into the first locomotive prototype hybrid SOFC-GT system. This prototype design is in the 200 kW – 1 MW size class, which is consistent with the step-by-step development concept (prototype to switcher to short haul to long haul) developed previously.
- The prototype system should first be tested as a stationary power plant at NFCRC facilities followed by installation and testing of the prototype on an actual rail platform. One of the platforms that is to be considered for this is that which could be provided by Burlington Northern & Santa Fe Railway (BNSF), a railroad company that has expressed interest in working with the team (i.e., NFCRC, FCE, and Capstone) to develop and test the prototype system.
- A test protocol for the prototype system was outlined in the current effort that includes a steady-state and dynamic set of parametric variations. This test protocol was used in the simulations and is planned for application in both the laboratory platform and the rail platform experiments. This test protocol includes subjecting the system to the dynamic operation requirements of both switcher end-use and long-haul locomotive end-use.
- A dynamic model of the prototype design was developed in the MATLAB/Simulink framework. This model was used to analyze the hybrid SOFC-GT system as a switcher locomotive and on the long-haul route from Bakersfield to Mojave. The switcher modeling is used to develop the first commercial system, which will follow demonstration of the prototype system in the step-by-step development process developed previously.
- A 1 MW-class switcher similar to EMD RS 1325 model was analyzed with the model. A single vehicle kinematic model was developed in the MATLAB/Simulink platform. The total distance traveled on a typical rail yard was calculated based upon double integration

of traction force. The net force on the locomotive was calculated using rolling resistance, air and axle resistance and the switcher weight.

- Control system development for the SOFC-GT locomotive was based upon the two main components of vehicle dynamics and notch calculations. It was found that the developed control strategy was able to safely operate the SOFC-GT locomotive, and was able to do so through the test protocol duty cycles for both a switcher and a long haul (using the Bakersfield to Mojave route through the Tehachapi loop) locomotive duty cycle.
- The prototype design and control strategy showed that an SOFC-GT system could safely (that is, within acceptable bounds of operation) fulfill the requirements for dynamic operation in both switcher and long-haul locomotive operating conditions.
- Due to concerns expressed by the development partners regarding the highly dynamic operation that was required, a separate study that evaluated the potential for adding some battery energy storage to the prototype SOFC-GT system design was conducted. It was found that even a quite small battery system could significantly reduce the dynamic operating requirements of the SOFC-GT system while still successfully meeting traction requirements even in the demanding duty cycle of the Bakersfield to Mojave route.
- Working with Empowered Energy, the team conducted a set of economic analyses of potential SOFC-GT locomotive production and operation costs in comparison to other low pollutant emitting alternatives (e.g., diesel-electric, battery electric, catenary-electric). The economic analyses show that SOFC-GT systems are likely to cost a bit more and lead to higher costs for delivering goods per ton-mile than the diesel electric alternative which has higher emissions. SOFC-GT locomotives are likely to produce lower operating costs compared to the catenary-electric alternative, and significantly lower operating costs compared to the battery-electric alternative.

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Appendix A.
Market Potential for Non-Diesel-Electric Locomotives

Market Potential Introduction

The market potential for non-diesel-electric locomotives is estimated based on historical trends in Class I railroad freight tons and carloads, diesel-electric locomotive replacement rates, and estimated capital costs for new locomotives. Class I railroads are those railroads that have annual operating revenues exceeding a threshold indexed to a base of $250 million in 1991 dollars, with the annual threshold calculated by the Surface Transportation Board (STB). The STB is an independent agency created by the U.S. Congress as the successor to the Interstate Commerce Commission. The STB has jurisdiction over railroad rates and service issues.

The seven Class I railroads with operations in the U.S. include:

- BNSF Railway
- Canadian National Railway
- Canadian Pacific Railway
- CSX Transportation, Inc.
- Kansas City Southern Railway
- Norfolk Southern Corporation
- Union Pacific Railroad

Each Class I railroad must file a highly detailed Class I Railroad Annual Report (Form R-1) with the STB. Annual statistics from the Class I Railroad Annual Reports filed with the STB are compiled by the Association for American Railroads (AAR) and published in the AAR's *Railroad Ten-Year Trends* report. This market analysis relies heavily on AAR's report, which was found to be the most comprehensive source of Class I railroad statistics available.

This market analysis is based on the demand for locomotives used to move freight over relatively long distances. This market analysis does not include the demand for locomotives operating in limited regions or for locomotives used solely for railyard operations.

Historical Class I Railroad Freight Traffic: Aggregate Data

The demand for locomotives used to move freight depends primarily on the tons of freight required to be transported. Each commodity has its own combination of bulk and weight, and each commodity therefore requires a different number of carloads for any given ton transported. The number of carloads required to be transported can therefore be considered a "companion" statistic to the tons of freight transported and both statistics should exhibit similar patterns over time.

Figure A-1 presents a summary of aggregate Class I railroad freight traffic statistics from 2001–2016.

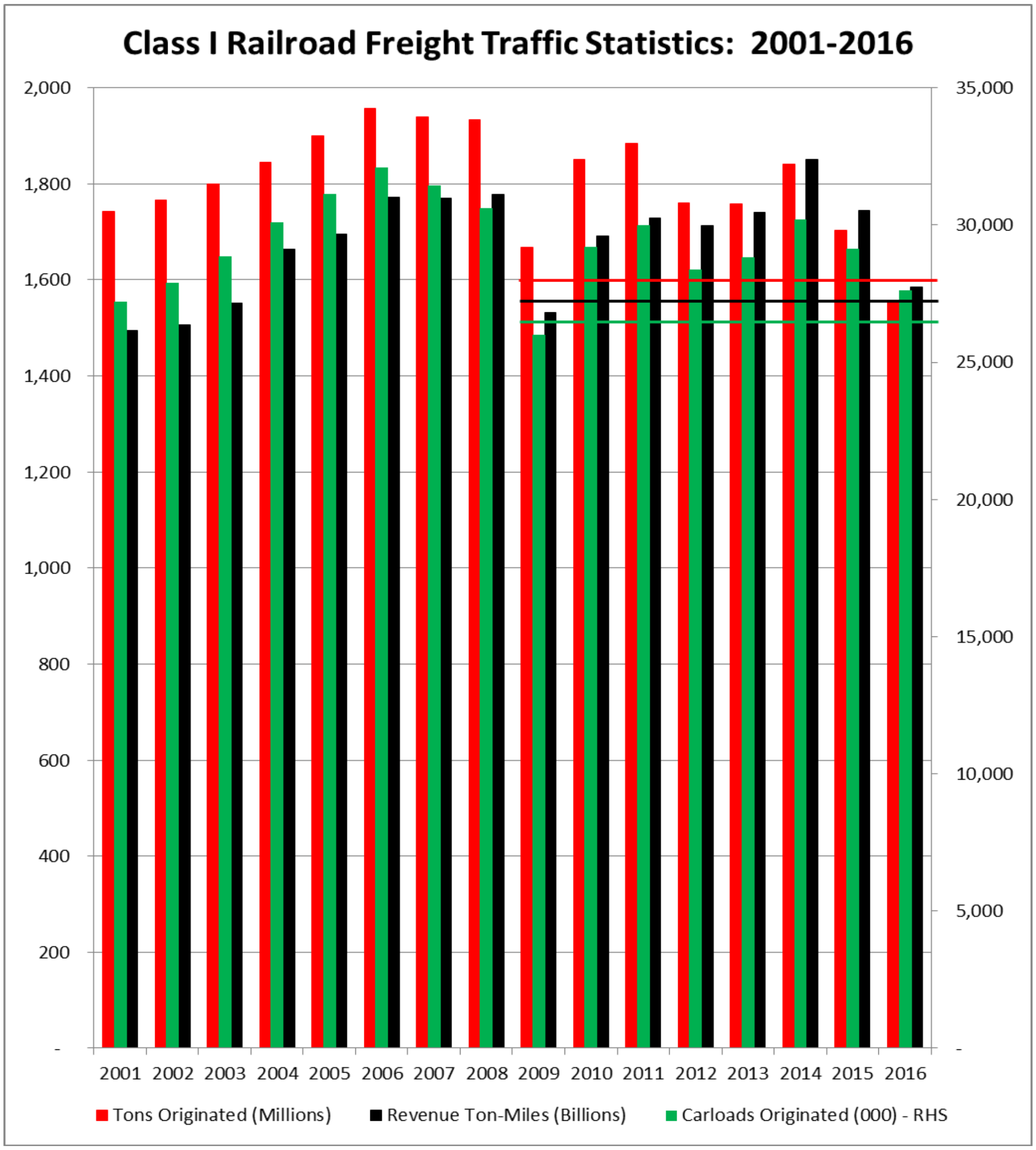


Figure A-1. Class I Railroad Freight Statistics: 2001–2016

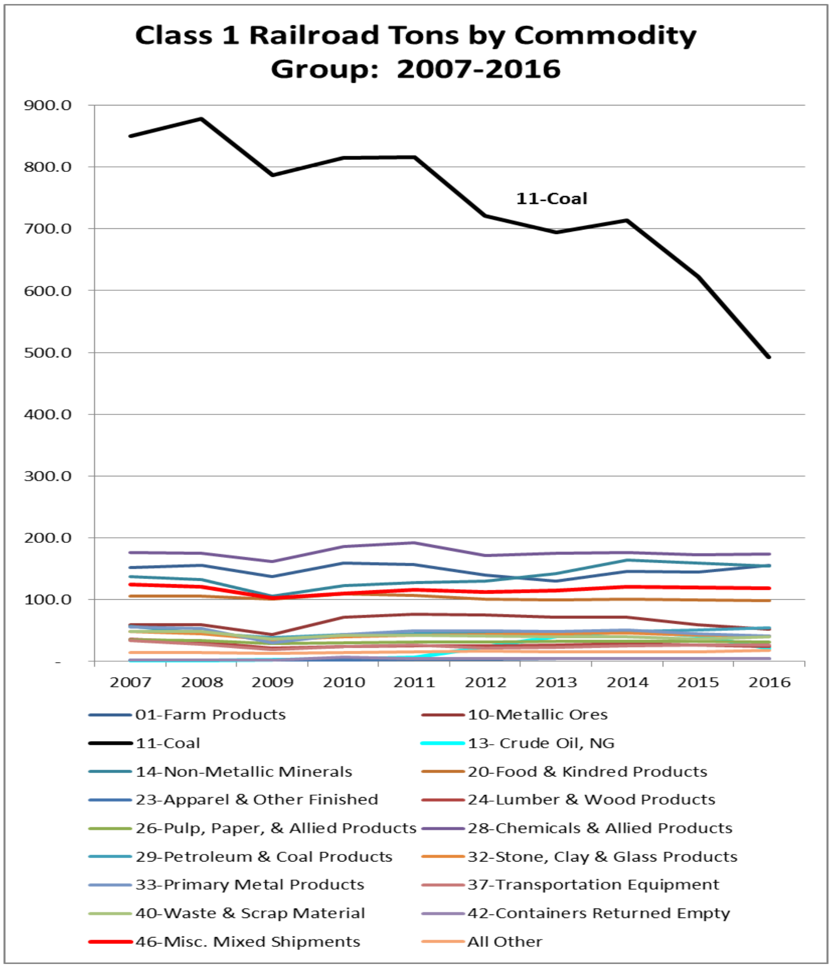
Figure A-1 includes annual tons of freight originated and annual carloads originated, as well as the annual revenue ton-miles. Revenue ton-miles is a standard railroad industry metric that multiplies the tons of freight times the miles those tons are transported, including only those tons of freight upon which revenue is earned.

The global recession of 2009 appears to separate the statistics in Figure A-1 into two distinct time periods. Prior to the global recession, all three of the statistics in Figure A-1 increased through 2006, and then declined starting in 2007, with a sharp drop during the recession. There was a rebound in all three statistics immediately after the global recession of 2009, followed by several years of ups and downs, with a general decline in all three statistics from 2014–2016. The three horizontal lines crossing the years comprising the second-time period approximate the average of the 2009 and 2016 end-points of that time period.

Historical Class I Railroad Freight Traffic: Commodity-Specific Data

To understand some of the key drivers of the aggregate freight traffic statistics presented in Figure A-1, it is useful to examine the annual tons and carloads in terms of the different commodity groups being transported.

The historical dominance of coal freight is clearly seen in Figure A-2, which shows the annual Class I railroad tons transported by commodity group for 2007–2016. Of particular note is the precipitous decline in tons of coal freight transported since 2008, the year that marks the beginning of the "shale revolution" in U.S. oil and natural gas production. Lower natural gas prices for electricity generation and increased climate change concerns have reduced coal's share of total electricity generation in the U.S. from over 50 percent in 2001 to 30 percent in 2016. During the same period, natural gas' share of total electricity generation in the U.S. has doubled, from 17 percent in 2001 to 34 percent in 2016 (U.S. Energy Information Administration, 2017).

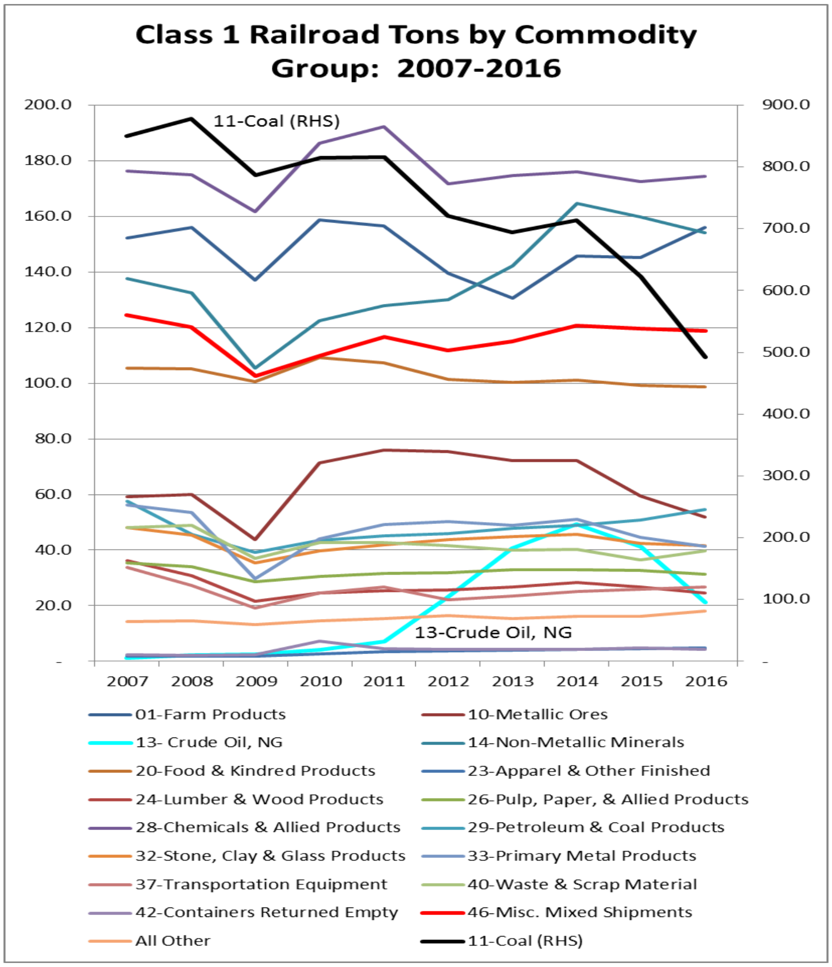


Data Source: American Association of Railroads, 2016, *Railroad Ten-Year Trends*, p. 41.

Figure A-2. Class I Railroad Tons by Commodity: 2007–2016

To enable a closer examination of the non-coal commodity groups, Figure A-3 presents the same information as in Figure A-2, but with the coal tons shown on the secondary (right-hand) vertical axis. With this change, the rise and fall of railroad transportation of crude oil and natural gas becomes very evident. The rise of railroad transportation of crude oil was dominated by oil development in the Bakken Formation in western North Dakota. However, as oil pipelines have been constructed to move that oil to market, the need for railroad transportation of crude oil has fallen.

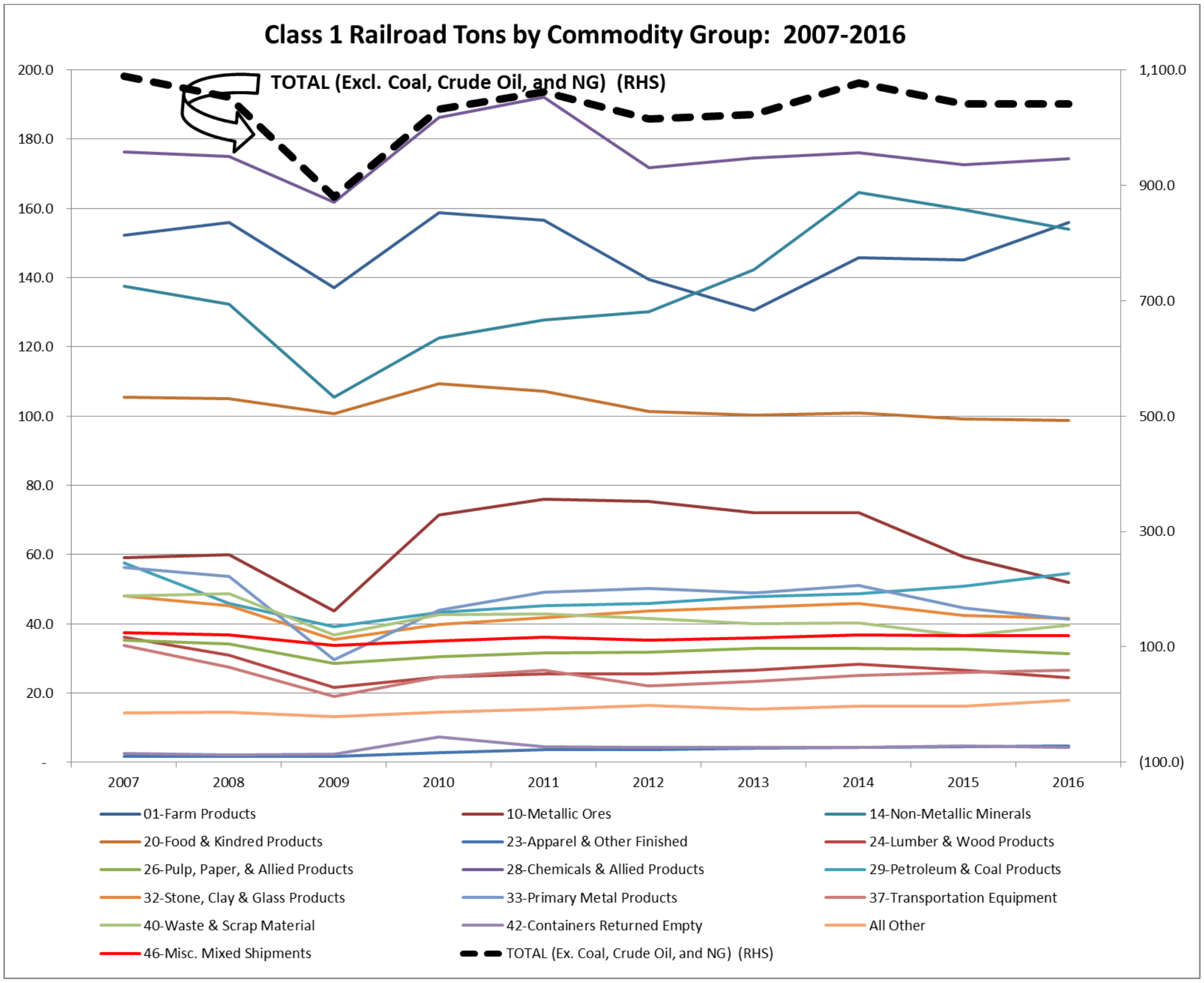
It is unlikely that the demand for railroad transportation for either coal or crude oil will recover to its earlier levels. This in turn has a significant (negative) impact on the future demand for locomotives.



Data Source: American Association of Railroads, 2016, *Railroad Ten-Year Trends*, p. 41.

Figure A-3. Class I Railroad Tons by Commodity: 2007-2016

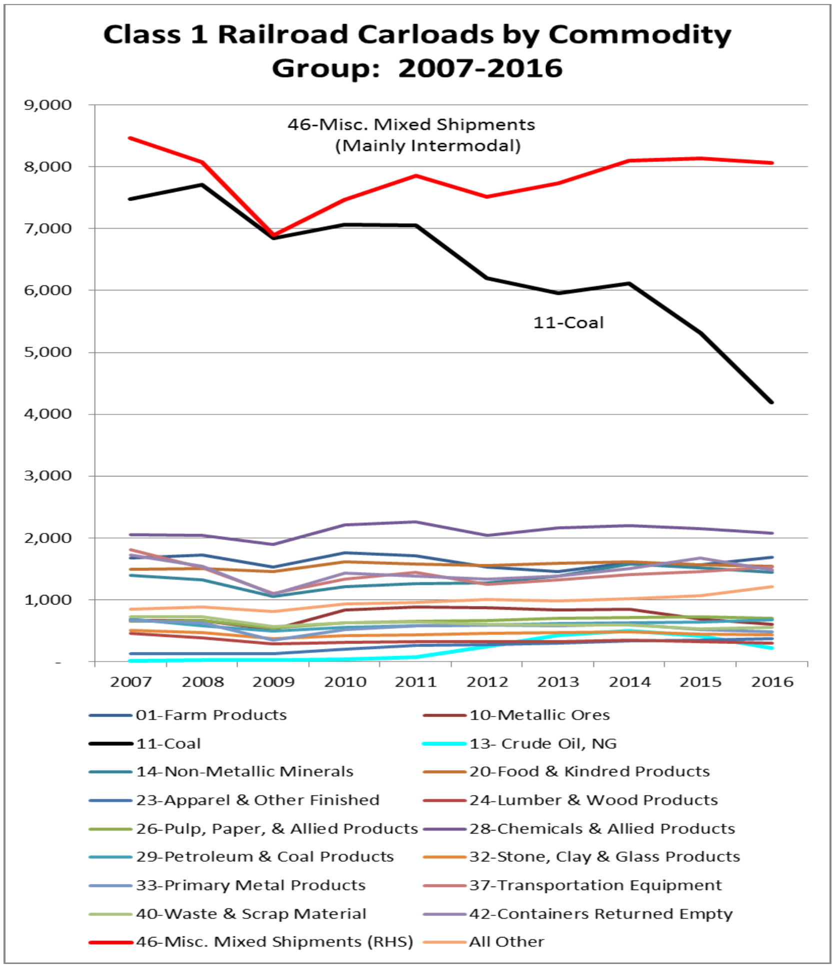
In Figure A-4, coal and crude oil tons have been removed from the total tons, which is represented by the heavy dashed line. The purpose of this illustration is to show that total tons transported, excluding coal and crude oil, were relatively flat over the past 10 years. With future declines in coal and crude oil tons transported by railroad more likely than future increases, it appears that the total tons of commodities transported by Class I railroads will remain relatively flat for the foreseeable future. Lack of strong growth in tons of commodity freight transported by Class I railroads will limit the potential market uptake of non-diesel-electric locomotives, as will be discussed below.



Data Source: American Association of Railroads, 2015 and 2016, *Railroad Ten-Year Trends*, p. 41.

Figure A-4. Class I Railroad Tons by Commodity Group, Excluding Coal, Crude Oil, and NG: 2007–2016

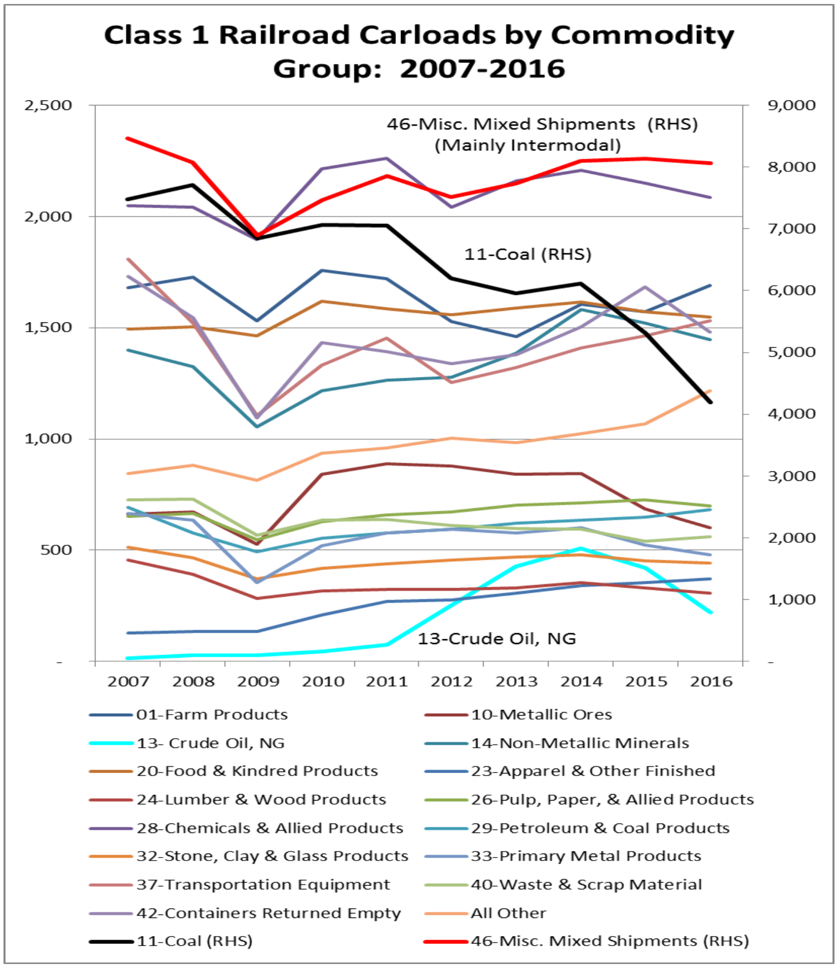
As expected, the “companion” statistics for Class I railroad ***carloads*** by commodity group have very similar trends to the statistics presented above for Class I railroad ***tons*** by commodity group, as seen in Figures A-5, A-6, and A-7. One major difference seen in Figure A-5 is the dominance of carloads of Category 46-Miscellaneous Mixed Shipments (Mainly Intermodal). As the category name suggests, these are mainly intermodal shipments made up of carloads of containers, large in number but not necessarily large in tons.



Data Source: American Association of Railroads, 2016, *Railroad Ten-Year Trends*, p. 42.

Figure A-5. Class I Railroad Carloads by Commodity: 2007–2016

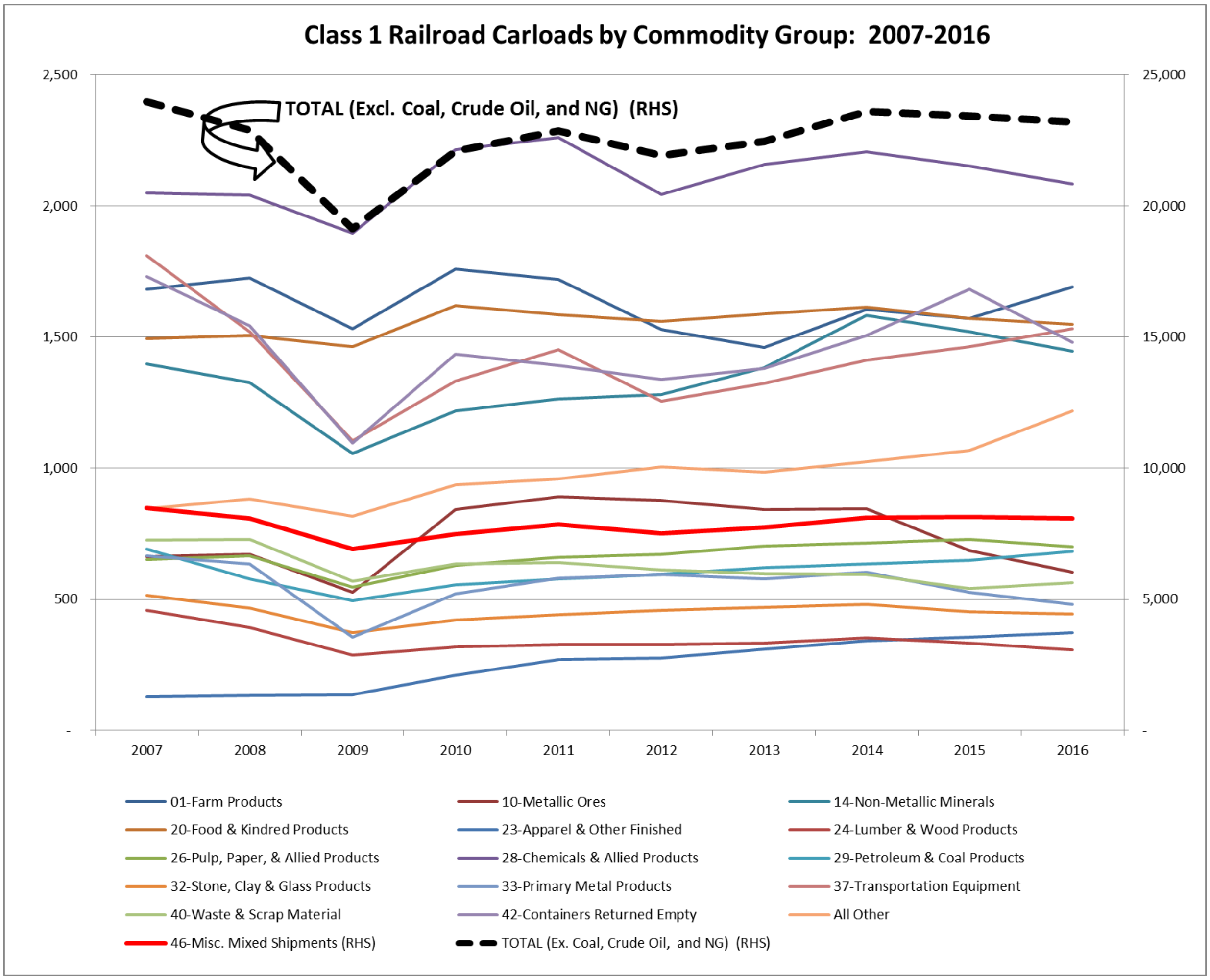
Figure A-6 presents the same information as in Figure A-5, but with the Category 11-Coal carloads and Category 46-Misc. Mixed Shipments carloads shown on the secondary (right-hand) vertical axis. As was the case for railroad tons, making this change highlights the rise and fall of carloads of Category 13-Crude Oil and Natural Gas transported by Class I railroad. As discussed above, it is not anticipated that increases in tons (or carloads) of freight will occur in either Category 11-Coal or Category 13-Crude Oil and Natural Gas in the foreseeable future.



Data Source: American Association of Railroads, 2016, *Railroad Ten-Year Trends*, p. 42.

Figure A-6. Class I Railroad Carloads by Commodity: 2007–2016

Figure A-7 shows the total annual carloads transported by Class I railroads from 2007–2016, with the carloads of Category 11-Coal and Category 13-Crude Oil and Natural Gas removed. As was the case for total annual tons transported, total annual carloads transported were relatively flat since the Class I railroads' full recovery from the global recession of 2009. This situation is not expected to change significantly in the foreseeable future and will negatively impact the demand for new locomotives going forward. This makes the potential uptake of non-diesel-electric locomotives slower than it might be in a stronger growth market.



Data Source: American Association of Railroads, 2016, *Railroad Ten-Year Trends*, p. 41.

Figure A-7. Class I Railroad Carloads by Commodity Group, Ex. Coal, Crude Oil, and NG: 2007–2016

Market Demand for Locomotives

As of the end of 2016 there were 26,716 locomotives in the Class I railroad fleet. This was a net increase of 398 locomotives from the end of 2015, as shown in the comparative end-of-year statistics for 2015 and 2016 in Table A-1. These locomotive counts include locomotives of all types (diesel-electric, steam, LNG, electric, other), but the locomotive count is heavily dominated by the incumbent diesel-electric locomotive technology. Although there are limited statistics that differentiate between different types of traction motors (i.e., direct current vs. alternating current), no statistics were found that differentiated between different types of locomotives.

Table A-1. Class I Railroad Locomotive Age Distribution

Date Built	Preliminary - 12/31/2016 Units in Age Bracket	Preliminary - 12/31/2016 % of Total	Preliminary - 12/31/2015 Units in Age Bracket	Preliminary - 12/31/2015 % of Total
1/1/2016-12/31/2016	576	2.2%	n/a	n/a
1/1/2015-12/31/2015	784	2.9%	777	2.9%
1/1/2010-12/31/2014	3,247	12.2%	3,248	12.2%
1/1/2005-12/31/2009	4,024	15.1%	4,030	15.2%
1/1/2000-12/31/2004	4,271	16.0%	4,272	16.1%
1/1/1995-12/31/1999	4,441	16.6%	4,439	16.7%
Before 1995	9,373	35.1%	9,808	36.9%
Total	26,716	100.0%	26,574	100.0%

Data Source: American Association of Railroads, 2015 and 2016, *Railroad Ten-Year Trends*, p. 106.

The count of locomotive units in Table A-1 is based on the initial year in which the locomotive was built. The data in Table A-1 do not reflect when a locomotive is rebuilt or refurbished, a process that is required periodically to maintain a locomotive's performance.[23] Since the "Date Built" age categories reflect the first year of a locomotive's life, the age categories can be used to estimate years of economic life for a diesel-electric locomotive.

In the literature, the estimated life of a diesel-electric locomotive ranges anywhere from 30 to 50 years. The data in Table A-1 can be used to derive an estimated average diesel-electric locomotive life of 40 years using the following steps:

- There were 435 locomotive units removed from service in the "Before 1995" age category between the end of 2015 and the end of 2016. This represents 4.4 percent of the 9,808 locomotives in the "Before 1995" age category at the end of 2015.
- If 4.4 percent of all "Before 1995" age category locomotives are removed from service each year, it would take nearly 23 years before this age category no longer has any locomotive units in service. (100 percent/4.4 percent = 22.7 years.)
- The locomotive age categories from January 1, 1995, to December 31, 2016, cover a 17-year span.
- Adding together the nearly 23 years it would take to empty the "Before 1995" age category to the 17-year span of locomotive build years since January 1, 1995, yields an estimated average locomotive live of 40 years.[24]

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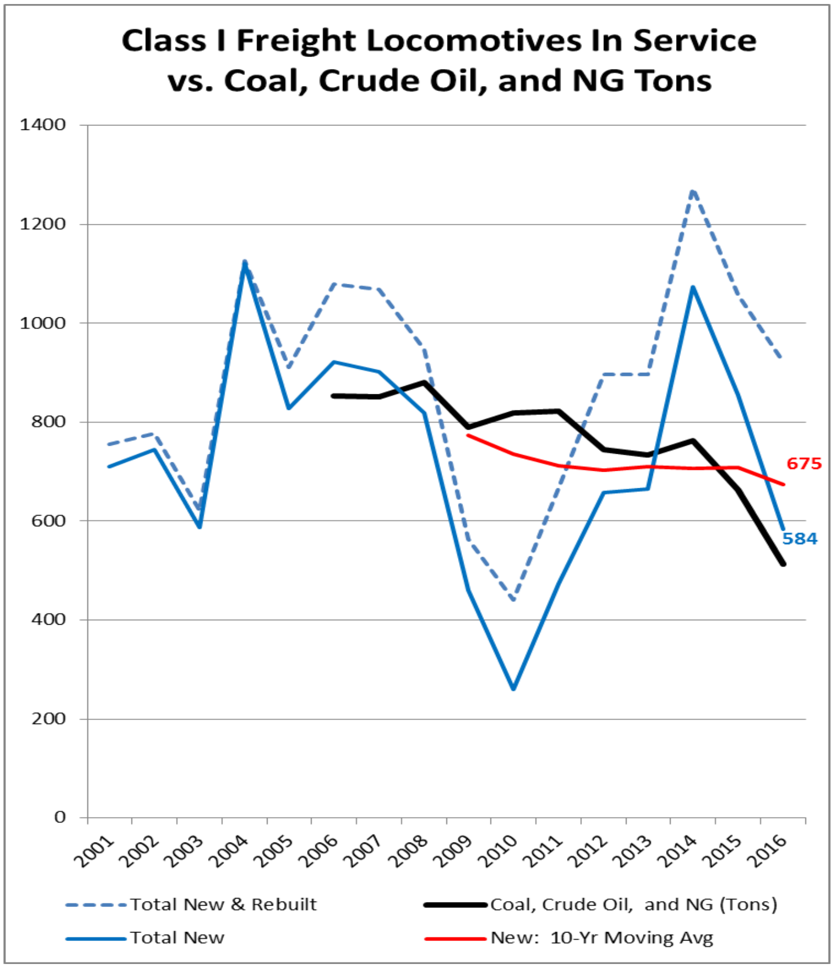
[23] The total count of locomotives in the "Date Built" age categories spanning the period from January 1, 1995–December 31, 2015, is 3,353 on both December 31, 2015, and December 31, 2016, though there appears to be some adjustments between specific age categories in 2016.

[24] The 434 locomotive units removed from service in the "Before 1995" age category between the end of 2015 and the end of 2016 represent only 1.6 percent of the total 26,574 locomotives in service at the end of 2015. This removal rate would imply an average locomotive life of over 60 years. (100 percent/1.6 percent = 62.5 years.)

The blue lines in Figure A-8 readily illustrate the volatility in the number of new and rebuilt locomotives put into service each year from 2001–2016. The red line in Figure A-8 is the 10-year moving average of new locomotives put into service during that same time period. The black line in Figure A-8 shows that the decline in annual tons of coal, crude oil, and natural gas transported by the Class I railroads that began during the global recession of 2009 dropped by nearly 40 percent since then, particularly since 2014. The number of new and rebuilt locomotives put into service each year has also dropped steadily since 2014.



Data Source: American Association of Railroads, 2016, *Railroad Ten-Year Trends*, pp. 41 and 105.

Figure A-8. Class I Railroad Freight Locomotives vs. Coal, Crude Oil, and NG Tons: 2007–2016

There appear to be four major factors that will negatively impact the future market potential for non-diesel-electric locomotive technologies:

- Market potential will be hampered by the slow turnover in the locomotive fleet, even assuming that a diesel-electric locomotive remains in service for an average of "only" 40 years.
- Based on the historical trends and future considerations impacting major commodity types such as coal and crude oil discussed in the previous section, the demand for any

type of locomotive technology based on tons of freight to be transported shows little sign of growth for the foreseeable future.

- Interoperability issues are a major consideration. To maximize the efficiency of railroad operations, it is important that all locomotive types be interchangeable with respect to their operations to the greatest extent possible. Fueling limitations for non-diesel-electric locomotive technologies must be minimized to the greatest extent possible to enhance interoperability.
- Low oil and natural gas prices. The price of both oil and natural gas have declined to historically low levels in real dollar terms and the relationship between the two prices has significantly changed over the past several years, as shown in Figure A-9. These changes have diluted the economic advantages of locomotives operating on natural gas versus those operating on diesel fuel.
- Non-competitive comparative economics for alternative locomotive technologies compared to the incumbent diesel-electric locomotive technology. Although the diesel-electric locomotive technology with LNG tenders becomes competitive with the diesel-electric locomotive technology at a CO_2 price of \$25/ton, it is not until CO_2 prices reach \$50/ton that truly alternative locomotive technologies such as the solid oxide fuel cell-gas turbine (SOFC-GT) locomotive technology using LNG fuel or the electric-only locomotive technology with an overhead electric catenary system become competitive with the incumbent diesel-electric locomotive technology.

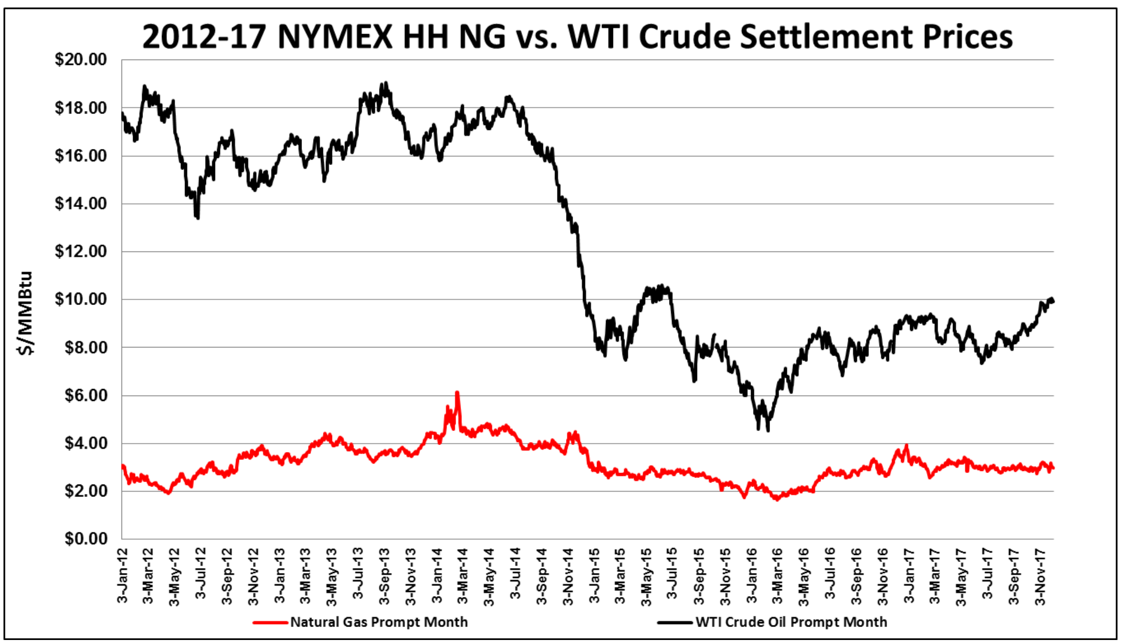


Figure A-9. Natural Gas and Crude Oil Prompt Month NYMEX Futures Prices: 2012–2017

Future Market Potential for Non-Diesel-Electric Locomotive Technologies

The future market potential for non-diesel-electric locomotives is quantified in Table A-2 and Table A-3 for three different locomotive fleet turnover periods (20, 30, and 40 years) and for new locomotive prices ranging from $3 million to $5 million per unit. The future market potential in Table A-2 is premised on 600 new locomotives being required each year, whereas the future market potential in Table A-3 is based on 800 new locomotives each year. A range of 600–800 new locomotives each year is estimated based on the analysis shown in Figure A-8.

Table A-2. Future Market Potential for Non-Diesel-Electric Locomotives (600 TOTAL New Per Year)

NEW LOCOMOTIVE TECHNOLOGY MARKET POTENTIAL				
	600	= TOTAL New Locomotives Built Per Year		
	$3.0	= New Locomotive Price (Low, MM$)		
	$5.0	= New Locomotive Price (High, MM$)		
Years for Locomotive Fleet Changeover (Yrs)	Locomotive Fleet Changeover Rate (Annual %)	Estimated Annual Market Potential (# of Locomotives)	Annual Market Potential LOW (MM$)	Annual Market Potential HIGH (MM$)
20	5.0%	30	$90.0	$150.0
30	3.3%	20	$60.0	$100.0
40	2.5%	15	$45.0	$75.0

Table A-3. Future Market Potential for Non-Diesel-Electric Locomotives (800 TOTAL New Per Year)

NEW LOCOMOTIVE TECHNOLOGY MARKET POTENTIAL				
	800	= TOTAL New Locomotives Built Per Year		
	$3.0	= New Locomotive Price (Low, MM$)		
	$5.0	= New Locomotive Price (High, MM$)		
Years for Locomotive Fleet Changeover (Yrs)	Locomotive Fleet Changeover Rate (Annual %)	Estimated Annual Market Potential (# of Locomotives)	Annual Market Potential LOW (MM$)	Annual Market Potential HIGH (MM$)
20	5.0%	40	$120.0	$200.0
30	3.3%	27	$80.0	$133.3
40	2.5%	20	$60.0	$100.0

Market Potential Conclusions

Low locomotive fleet turnover rates, little to no growth in Class I railroad tons to be transported, interoperability requirements, low oil and natural gas prices, and non-competitive comparative economics for alternative locomotive technologies will hamper the future market potential for non-diesel-electric locomotives for the foreseeable future. Positive market potential for non-diesel-electric locomotives will likely be dominated by niche market requirements such as improved local air quality and reduced noise as population centers continue to develop around existing railroad operations. Thus, the market potential for alternative locomotive technologies will likely be driven by regulatory policy acting as a stick rather than by competitive economics acting as a carrot.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ARB	Air Resources Board
AFC	Alkaline Fuel Cell
AEO	Annual Energy Outlook
AAR	Association for American Railroads
AA	Atomic Absorption
BES	Battery Electric Storage
BNSF	Burlington Northern Santa Fe Railway
BEITC	Business Energy Investment Tax Credit
CARB	California Air Resources Board
CEC	California Energy Commission
Capstone	Capstone Turbines
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CATI	Clean Air Technology Initiative
CFR	Code of Federal Regulations
CCHP	Combined, Cooling, Heating and Power
CHP	Combined Heat and Power
CSA	Compact SOFC Architecture
DOE	Department of Energy
DFC	Direct Fuel Cell
EIS	Electrochemical Impedance Spectroscopy
ERC	Emissions Reduction Credits
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FRA	Federal Railway Administration
FID	Flame Ionization Detector
FCE	FuelCell Energy, Inc.
FC-GT	Fuel Cell Gas Turbine
GC	Gas Chromatography
GT	Gas Turbine

ACRONYMS	EXPLANATION
GHG	Greenhouse Gases
HHV	Higher Heating Value
HP	Horsepower
HC	Hydrocarbons
H_2	Hydrogen
IEAGHG	IEA Greenhouse Gas
IR	Infrared
IOU	Investor-owned Utility
JP-8	Jet Propulsion Fuel
kW	Kilowatt
kW-yr	Kilowatt-year
LCOE	Levelized Cost of Energy
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LCM	Locomotive Cost Model
LHV	Lower Heating Value
MS	Mass Spectrometry
MW	Megawatt
MWh	Megawatt-hour
MTG	Micro-Turbine Generator
MMBtu	Million British Thermal Units
MCFC	Molten Carbonate Fuel Cell
NETL	National Energy Technology Laboratory
NFCRC	National Fuel Cell Research Center
NOx	Nitrogen Oxide
NDIR	Nondispersive Infrared
PM	Particulate Matter
PEN	Positive-Electrolyte Negative
C_3H_8	Propane
PEMFC	Proton Exchange Membrane Fuel Cell
POU	Publicly-owned Utility

ACRONYMS	EXPLANATION
Rail E3	Rail Energy, Environment and Engine
SJVAPCD	San Joaquin Valley Air Pollution Control District
SOFC	Solid Oxide Fuel Cell
SOFC-GT	Solid Oxide Fuel Cell-Gas Turbine
SECA	Solid State Energy Conversion Alliance
SoCAB	South Coast Air Basin
SCAQMD	South Coast Air Quality Management District
SOC	State Of Charge
SMR	Steam Methane Reformer
STB	Surface Transportation Board
TIT	Turbine Inlet Temperature
VOM	Variable Operating and Maintenance
UCI	University of California, Irvine