RESEARCH & DEVELOPMENT

The Piedmont Service: Hydrogen Fuel Cell Locomotive Feasibility

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FEASIBILITY REPORT

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16. Abstract

The North Carolina Department of Transportation, Rail Division (NCDOT) is responsible for the Piedmont passenger train that connects Raleigh and Charlotte. The benchmark locomotive-hauled trains comprise a diesel-electric locomotive, intermediate passenger cars, and a cab control unit. Diesel combustion results in exhaust containing air pollutants and greenhouse gas emissions. The Rail Division desires to reduce emissions. Battery and hydrogen fuel cell technologies applied to railways offer the opportunity to eliminate harmful exhaust emissions with potential for a low- or zero-emission energy supply chain. Technical feasibility of diesel, hydrogen and hybrid options with batteries for the Piedmont service were assessed. Modeling of various train and powertrain configurations was conducted, and energy and emission impacts estimated on a well-to-wheel basis. Single train simulation was utilized for feasibility assessment of powertrains while GREET was employed to estimate well-to-wheel emissions and energy. 25 train configurations and powertrain options were modelled, and nine hydrogen supply options were evaluated in addition to the diesel and electricity supply. Results show that diesel and hydrogen hybrid options as well as a hydrogen only option would be feasible for the Piedmont and that a low- or zero-carbon hydrogen supply chain could likely be possible. Energy reduction from operations ranged from 14% for a two locomotive diesel and battery option to 48% for a single locomotive fuel cell hybrid plugin powertrain. Hydrogen production from electrolysis where electricity is provided from renewables offers the highest well-to-wheel (WTW) energy savings without emissions in the supply chain if produced at the refueling site. Hydrogen delivery from a central location with the same method results in a small amount of emissions. Electrolysis with electricity from the SERC grid would result in energy and emission increases for some criteria pollutants and greenhouse gas emissions on a WTW basis compared to the diesel-electric. Production from natural gas or biomass would reduce emissions and energy consumption. Based on the results of this study, energy and emission reductions could be achieved with a diesel hybrid configuration. Significant further WTW reductions could be realized with a hydrogen rail (hydrail) option. Most significantly, the results indicate that hydrail technology is feasible for the Piedmont service.

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EXECUTIVE SUMMARY

The North Carolina Department of Transportation Rail Division (NCDOT) has responsibility for the Piedmont passenger rail service between Raleigh and Charlotte, NC. Standard train configuration is two locomotives in a pull-pull configuration with three to four railcars depending on daily ridership demands. NCDOT plans to switch to a locomotive plus cab control unit (CCU) push-pull configuration by mid-2021. Counties along the route were previously in EPA air quality non-attainment status. Combustion of diesel results in EPA regulated pollutants as defined in 40CFR1033. NCDOT has the desire to reduce their environmental impact from rail operations, specifically emissions impacting air quality. Previous projects included the extensive testing of biodiesel and trial installation of aftertreatment systems to the existing locomotives to reduce exhaust emission pollutants.

Hydrogen fuel cell propulsion technology, known as “hydrail”, offers the possibility to eliminate all harmful emissions from operations as the exhaust is water, primarily in vapor form, and therefore is considered a zero-emission option. NCDOT commissioned the Center for Railway Research and Education (CRRE) at Michigan State University (MSU) to assess the technical feasibility of a hydrogen fuel cell powertrain for the Piedmont service and estimate energy as well as emission impacts through the respective supply chain for diesel hybrid and hydrail options. Hydrogen is an energy carrier and, therefore, can be produced from many different feedstocks including fossil fuels, biomass, and electricity with varying impacts on emissions and energy consumption.

The authors utilized modelling tools to estimate feasibility, energy and emissions impacts. For train operations the CRRE single train simulator was adapted and modified; for the supply chain well-to-wheel (WTW) assessment, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was employed.

Route and train information were required inputs as well as efficiency maps for all major powertrain components, such as traction motors, generator, diesel engine, and fuel cell system. Where data was not available from NCDOT, pre-existing data in the modelling tools and information from literature was utilized. A traction motor map was developed at MSU.

The train configuration with a diesel-electric locomotive and CCU was used as the benchmark. The simulator was validated with recorded data made available from NCDOT; simulation results were within acceptable margins compared with recorded data. In total 25 train configurations were modelled including battery hybrids, and nine hydrogen production pathways evaluated in addition to the conventional diesel supply chain.

Primary results were that diesel hybrid options have the potential to reduce emissions and energy both from operations and on a WTW basis. However, implementation of the required propulsion components in an existing diesel locomotive is likely not possible due to space and weight constraints. Conversion of a CCU to house batteries or hydrail components appears to be a feasible choice. Zero-emissions cannot be achieved with a diesel hybrid as hydrocarbon combustion continues onboard the unmodified diesel locomotive.

A hydrail solution is feasible as it is likely that all powertrain components could be installed on a locomotive or converted CCU. Refueling after one roundtrip would be necessary if a single locomotive plus unconverted CCU train configuration were adopted while it is likely that two roundtrips could be completed if a locomotive and converted CCU or two locomotive option would be implemented. Continuing to follow existing protocols of plugging in trains every night upon return to Raleigh would reduce overall energy consumption if batteries were also recharged. The lowest energy reduction of feasible solutions was 14% for the diesel plus battery option. Lowest energy reduction for the evaluated hydrogen options was 19%, resulting from a fuel cell powertrain without batteries if the locomotive would haul a train with a non-operating diesel (as an emergency backup) on the other end. The highest energy reduction of all evaluated options is 48% achieved with a single locomotive fuel cell hybrid plugin powertrain. Options with a single locomotive and CCU configuration have higher energy reduction compared to a single locomotive and converted CCU options. However, the difference in energy reduction between these options is small.

An option where the powertrain is distributed across two vehicles is the only feasible option for hybridization with a diesel locomotive and would make implementation of a fuel cell system (FCS) and hydrogen storage tanks easier as more space is available and weight constraints are reduced. All hybrid options perform better than the corresponding version without a battery while all plugin options offer the highest reductions within a powertrain category. For the fuel cell hybrid options, a reduction in output from the powerplant (downsizing) has been considered with the objective of reducing the number of fuel cell systems to make more volume available for hydrogen storage and reduce capital cost. The impact on energy reduction from downsizing is small.

Operational risk could be reduced through an implementation program to better understand and gain operating experience with the new technology. An option would be to install the new powertrain components in the CCUs and operating diesel plus converted CCU trains until confidence with the technology is sufficient to fully retrofit diesel locomotives with hydrail powertrains, thereby achieving full zero-emission trains. This procedure is a standard practice when introducing new technology to an existing service.

The recommended hydrail configuration for the Piedmont service would be the two locomotive (i.e. converted CCUs) fuel cell hybrid downsized plugin, based on ease of implementation, refueling frequency, capital cost, and energy and emission reductions. Such a configuration would probably consist of two converted CCUs, each with 800 kW FCS power, a 1350 kWh battery, and 200 kg of hydrogen storage. If hydrogen storage were approximately doubled, it is likely that refueling after two roundtrips could take place rather than after one. Options are either two traction motors per converted CCU or four traction motors per converted CCU if power were limited during acceleration. A version where all eight wheelsets of the converted CCUs are not limited in power was also evaluated and would lead to an approximately 10 minute journey time decrease for a one-way trip, but energy reduction would drop from 45% to 28%.

The highest energy and emission reduction on a WTW basis are achieved when electrolysis at the refueling site would take place and the electricity would be produced entirely from non-carbon sources, such as renewables (e.g., hydro, solar, wind) or nuclear. Existing hydro powerplants are approximately 110 miles from a likely refueling location. For renewable hydrogen production from electrolysis at a central location with 110 mile delivery to the refueling site, emission and energy decrease are only marginally affected when transportation is as a gas; for the liquid hydrogen option emission reductions are also only slightly affected but energy consumption would increase by a small margin. Electrolysis with electricity from the SERC grid, of which North Carolina is a part, would likely lead to increases in energy consumption, greenhouse gases, and in some cases particulate matter emissions on WTW basis compared to the diesel benchmark. This option should only be used if a substantial decarbonization of grid electricity would occur as long as the primary objective is to reduce WTW emissions. Currently, most of the hydrogen is produced from natural gas in the U.S. through a process called steam methane reforming (SMR) and this option would lead to emission and energy reductions if produced at the refueling site and lower reductions if delivered. Production from biomass leads to similar results as SMR but with higher energy and emission reductions.

The results from the analysis show that a diesel plus battery train configuration would result in energy and emission reductions, and a hydrail option could be implemented on the Piedmont corridor, which would offer energy reduction and zero emissions in operations. On a WTW basis, emission and energy reduction are possible with several production pathways and a 100% renewable option could potentially be implemented. A phased technology adoption would be possible with the first phase being a diesel locomotive with battery CCU. At the same time, a proof-of-concept hydrail locomotive could be constructed to validate simulation results and test and demonstrate feasibility in actual operation.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS/GLOSSARY

Term	**Explanation / Meaning / Definition**
AC	Alternating Current
BATS	Blended After-Treatment System
BCRRE	Birmingham Centre for Railway Research and Education
BoP	Balance-of-Plant
CCU	Cab Control Unit
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CRRE	Center for Railway Research and Education, Michigan State University
DC	Direct Current
DOE	United States Department of Energy
EPA	United States Environmental Protection Agency
ESS	Energy Storage System
FC	Fuel Cell
FCS	Fuel Cell System
FRA	Federal Railroad Administration
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GWP	Global Warming Potential
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbons
HEP	Head-End Power
IEA	International Energy Agency
km	Kilometer (1 mile ~ 1.6 km; 1 km.~ 0.62 mile)
km/h	Kilometers per hour
LFP	Lithium Ferro Phosphate
LTO	Lithium Titanate Oxide
m	Meter(s)
m^3	Cubic meter

Term	**Explanation / Meaning / Definition**
mph	Miles per hour
MSU	Michigan State University
MU	Multiple Unit train
N_2O	Nitrous oxide
NCDOT	North Carolina Department of Transportation
NG	Natural Gas
NH_3	Anhydrous ammonia
NMC	Lithium Nickel Manganese Cobalt Oxide
NOx	Oxides of nitrogen
O_2	Oxygen
PEM	Proton Exchange Membrane
PM	Particulate matter
PTW	Pump-to-wheel
RSSB	Rail Safety and Standards Board in the UK
SAE	Society of Automotive Engineers
SBCTA	San Bernardino County Transportation Authority
SMR	Steam-Methane Reforming
SOC	State-of-Charge
t	Metric tonne(s) (1.016 US tons)
TIRCP	Transit and Intercity Rail Capital Program
USA	United States of America
WTP	Well-to-pump
WTW	Well-to-wheel

1 INTRODUCTION

The Piedmont passenger rail service connects Raleigh, NC, and Charlotte, NC and is maintained by the North Carolina Department of Transportation's Rail Division (NCDOT). NCDOT seeks to reduce the environmental impact of its operations, particularly exhaust emissions that impact local air quality, as well as overall Greenhouse Gas (GHG) emissions. NCDOT also wishes to reduce energy consumption, become a rail technology leader, demonstrate the State's commitment to innovation and technology capabilities, and highlight opportunities for further development.

In this report, the authors assess various low- and zero-emission powertrain technologies and associated energy supply chains that may be suitable for the Piedmont service and meet NCDOT's goals. A technical feasibility study utilizing simulation-based modelling was conducted with an emphasis on hydrogen fuel cell technologies applied to railway vehicles (hydrail) in combination with battery-based onboard energy storage. These options do not require continuous wayside power infrastructure such as overhead contact systems while eliminating harmful emissions at the point-of-use and enable a relatively long range of travel before refueling is required due to the high energy density of hydrogen.

The Center for Railway Research and Education at Michigan State University (CRRE) is the leading North American academic research resource with expertise in low- and zero-emission railway propulsion. NCDOT appointed CRRE to research and evaluate technical feasibility and performance of several powertrain configurations for the Piedmont service. CRRE conducted similar research for the San Bernardino County Transportation Authority (SBCTA) in California (MSU CRRE & BCRRE, 2019) with a focus on a multiple-unit passenger rail vehicle over a shorter route, which highlighted technical hydrail feasibility. However, the Piedmont service characteristics differ significantly to the SBCTA case, being locomotive hauled, having higher power requirements, and operating over a much longer route, which required an additional study considering these parameters. Nevertheless, general technology feasibility has been shown in the SBCTA feasibility study and through various prototypes and commercial service operation of multiple-units in Germany. Currently, the Piedmont service would be the hydrail project with the highest power requirement and longest operating route, therefore, offering the potential to demonstrate the technology on a larger scale.

1.1 Scope and Limitations

In the presented research, the authors evaluated several powertrain configurations covering diesel, hydrogen fuel cell and hybrids of these with battery technology where components are either installed in a single locomotive or split between two locomotives, one on either end of the train. In addition, a well-to-wheel (WTW) analysis was conducted to estimate the total energy an emission impact of various hydrogen supply options. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was employed to estimate emissions and energy requirements.

Power and energy requirements were determined using a single train simulation model. This also identified relative size of major powertrain components, such as energy storage systems, fuel cell system (FCS), and hydrogen storage tanks required for the Piedmont service and respective powertrain. A comparison between different options was then possible and high-level technical feasibility could be assessed considering NCDOT's current locomotives and cab control units. The focus of the technical feasibility was on utilizing existing equipment where possible.

Neither physical plant nor component testing was part of the project. Results were determined through single train computer simulation. Results enabled sizing of components in terms of volume and mass. Virtual integration of the new drive trains into the existing locomotive shell in computer-aided design (CAD) or through engineering drawings was not part of the work to be performed. Component selection and performance data is generic and not linked to a manufacturer. Information was sourced through literature and existing data in the simulator. Specific supplier product data may vary compared to the generic characteristics simulated. Data provided by NCDOT was utilized wherever possible. This project did not include simulation verification with experimental test but use of measured data, where available, was utilized to compare simulated results of the benchmark diesel-electric configuration with the provided data to calibrate the model.

The pump-to-wheel energy consumption resulting from the single train simulation was the basis to estimate point-of-use emission, well-to-pump, and WTW energy and emissions. The data, including decrease in GHG emissions for low- and zero-emissions motive power options reflect current fuel sources that could become less polluting over time thereby impacting the overall WTW supply chain. This is largely dependent upon factors such as the original production feedstock, and electricity production. No actual measurements or energy and emission audits where part of the work but the authors relied primarily on existing data in the GREET model.

All the work was conducted through literature review or modelling with information obtained from NCDOT, literature, or pre-existing data in the modeling tools, therefore all results are estimates. No detailed powertrain design or optimization of the powertrains and associated components has been performed as the objective of the work as to assess overall technical feasibility. More detailed work is required to design a prototype locomotive and the results contained in this report can be used as a start. Commercial considerations regrading price of energy and components have not been considered in any detail and only been incorporated through the potential of smaller powerplant in terms of power due to the current price differential between batteries and fuel cell system and the assumption that lower energy consumption from operations is desirable as less diesel, hydrogen, or electricity would have to be purchased. A more detailed economic feasibility study would be required to compare the various energy supply options and the value of emission reductions.

1.2 Structure of Report

Following this introduction, the report covers the background to the research consisting of information regarding the Piedmont service including equipment currently used, an overview of the current U.S. rail system energy use, regulated emissions resulting from railway operation, high-level information on GHGs, finishing the section with briefly highlighting previous NCDOT efforts to reduce emissions. Next an introduction to hydrogen and its application to railways is provided – a true zero emissions option when the hydrogen supply chain is powered fully by renewables. The report then continues with a description of the methodology employed to determine both energy requirements (simulation) for train operation and the tool utilized to estimate supply chain energy and emission impacts (GREET, using industry specific data). 23 primary powertrain configurations were assessed each with their applicable energy production method while several hydrogen supply options were considered for the applicable cases. production methods. Next, simulation results are presented and discussed before finishing with conclusions including key findings and recommendations. Detailed results are provided in the appendix for reference.

2 BACKGROUND

In this section, the authors provide information about the Piedmont service starting with the route followed by the current equipment employed before providing an overview of U.S. rail energy consumption and emission regulation. The section finishes with a summary of NCDOT's previous efforts to reduce emissions.

2.1 Piedmont Route Information

Figure 2-1: Illustration of the Piedmont Route (Harris, 2019)

The Piedmont service corridor is a 173-mile (~278 kilometers) one-way rail line with two terminal stations (Raleigh and Charlotte) and seven intermediate passenger rail stations. The route is illustrated in Figure 2-1. Table 2-1Each roundtrip is 348 miles (~560 route kilometers) and a one-way trip takes 3 hours and 10 minutes including nine total stops; the location of the stops and dwell time is presented in Table 2-1. The Piedmont service is marketed by Amtrak. Current service frequency is three southbound and three northbound trains spread across the peak travel hours of the day. Plans exist to increase daily service frequency by adding an additional roundtrip.

Table 2-1: List of Stations Locations and Dwell Time for a Roundtrip

Station	km	miles	Dwell time in minutes
RALEIGH	**0**	**0**	**2**
Cary	14	9	2
Durham	42	26	2
Burlington	97	60	1
Greensboro	132	82	2
High Point	154	96	1
Salisbury	210	131	1
Kannapolis	235	146	1
CHARLOTTE	**278**	**173**	**50**
Kannapolis	321	200	1
Salisbury	346	215	1
High Point	402	250	1
Greensboro	424	264	2
Burlington	459	285	1
Durham	514	319	2
Cary	541	336	2
RALEIGH	**560**	**348**	**2**

Maximum train speed on the route is 79 mph (~127 km/h), average speed is 63 mph (~100 km/h), and it is possible that in the future the maximum line speed will be raised to 110 mph (~177 km/h) in places plus potential for additional stops. The speed limit and speed profile of the train are presented in the Simulation Results and Discussion section. Topographic elevation changes result in several gradients along the route, both illustrated in Figure 2-2.

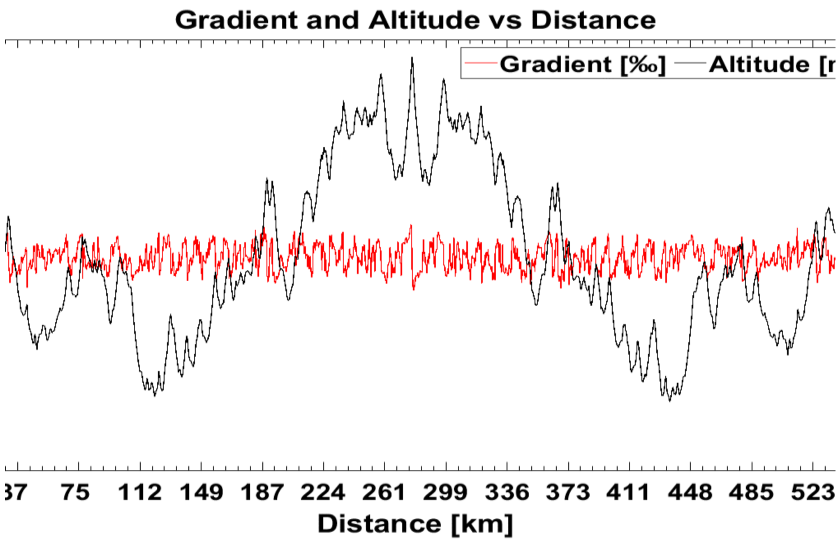

Figure 2-2: Gradient and Altitude Change of the Piedmont Route, starting at the reference point of Raleigh

Gradients have a significant impact on the resistance to motion encountered by the train and therefore significantly influence traction and braking requirements of equipment operated over the route.

2.2 Current Equipment on the Piedmont Route

The Piedmont service is provided by locomotive-hauled trains that typically consists of a locomotive, three or four intermediate passenger and luggage cars depending on daily ridership demands, and a second locomotive. NCDOT has a fleet of six F59PH and two F59PHI diesel-electric locomotives rated at 2.2MW (~3000HP). A train of the described configuration operates in pull-pull mode where the lead locomotive pulls the train in each direction, a standard passenger railroad operating practice. In Figure 2-3, examples of NCDOT's F59PH locomotives are shown.

Figure 2-3: F59PH Diesel-Electric Locomotive Employed on the Piedmont (Hoffrichter, 2013, 2019)

A F59PH has a weight of approximately 123t and has a fuel tank holding approximately 1,800 gallons (~6800 liters), as provided by Harris from NCDOT. The powertrain contributes approximately 42t (Electro-Motive Diesel, 1994) to the total.

Diesel-electric locomotives employ a diesel combustion engine connected to a generator to produce electricity that is utilized in traction motors to drive the wheels in truck assemblies. The current NCDOT locomotive flees utilized DC traction motors, more recent locomotives typically employ AC motors. In Figure 2-4 a block diagram of a diesel-electric powertrain with an AC traction motor is depicted. All major components and their respective efficiency maps or curves were considered in the train simulation, providing the pump-to-wheel part of the work.

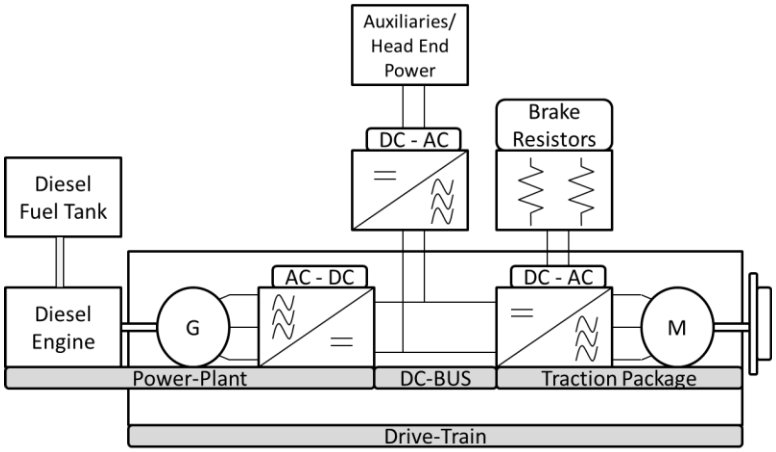

Figure 2-4: Block Diagram of a Diesel-Electric Powertrain with AC Traction Motors (Hoffrichter, 2013)

Passenger cars, typically three or four (depending on demand) in each train, provide space for luggage and have seats for customers. Power to the cars for lighting and climate control is provided by the locomotive, usually referred to as auxiliary, hotel or head end power (HEP). NCDOT's locomotives have a separate HEP diesel-generator-set that cannot be used for traction. The cars are pulled or pushed by the locomotive and cannot provide traction required for motion, which distinguishes them from multiple-units. In Figure 2-5 photos of the passenger cars employed on the Piedmont are depicted.

Figure 2-5: Exterior Photos of Passenger Cars Used of the Piedmont (Hoffrichter, 2013)

Cab control units are non-powered vehicles that offer a cab for the engineer and allow control of the locomotive on the other end of the train, similar to Amtrak's Non-Powered Control Units. Easier and faster operation at terminals is possible with this arrangement as the need to move the locomotive to the new head end of the train is eliminated while avoiding the requirement of a second locomotive on the train. Cab control units are converted from locomotives where the powertrain, at the end of its service life, is removed while driving controls retained.

Figure 2-6: Cab Control Unit
(Hoffrichter, 2018)

Cab control units (CCUs) offer NCDOT the opportunity to utilize the space previously occupied by the diesel-electric powerplant for components of an alternative powertrain, such as fuel cell systems or batteries. The volume available in a CCU is approximately 52.5m^3 if one of the two walkways would be eliminated (~41m^3 if both walkways were retained), determined by initial, high-level measurements conducted by Harris from NCDOT and Hoffrichter from CRRE. The weight of a CCU is approximately 82t, enabling a 41t powertrain if a similar weight to the locomotive is the target, and a powertrain weight of up to 48t would be possible if the maximum operating axle load on the route of 32.5t would fully utilized, according to Harris, but a lower weight would be desirable.

A further advantage of converting existing CCUs is the potentially lower cost compared to a new locomotive. In addition, redundancy is introduced as two powered vehicles would be present on a train; this is particularly useful if a new technology would be tested as the impact on the service in case of a malfunction would be limited.

2.3 Overview of Current Energy Use and Emissions in the U.S. Rail System

The two primary power provision options for railways are wayside electrification or on-board generation. Wayside electrification, often simply referred to as electric, requires continuous infrastructure on the right-of-way to supply electricity to the train. This is typically through either overhead wires or through ground-level third rail, the latter popular in subway systems. A modern, alternating current (AC) overhead contact system is shown in Figure 2-7.

Figure 2-7: Wayside Electrification with an Overhead Contact System in Denver (Hoffrichter, 2016)

In the U.S., on-board power generation is typically achieved with a diesel engine connected to an electricity generator. The resulting electricity is subsequently used to operate traction motors. This powertrain is diesel-electric, often simply referred to as diesel, and used in NCDOT's locomotives. Figure 2-4 illustrates a diesel-electric powertrain with a three-phase generator and three-phase traction motors, representing a typical modern arrangement for passenger and freight motive power vehicles in North America.

Energy consumption from diesel-electric motive power dominates in the U.S. while the remainder is provided by electricity from wayside infrastructure (ORNL, 2019). Electric motive power is primarily utilized in urban railways, such as the LYNX system in Charlotte, NC and high-density passenger operation, such as Amtrak's North-East Corridor (Washington, DC to Boston, MA).
In Figure 2-8 the energy consumption of the railway system in the U.S. is illustrated, and the dominance of diesel can clearly be seen.

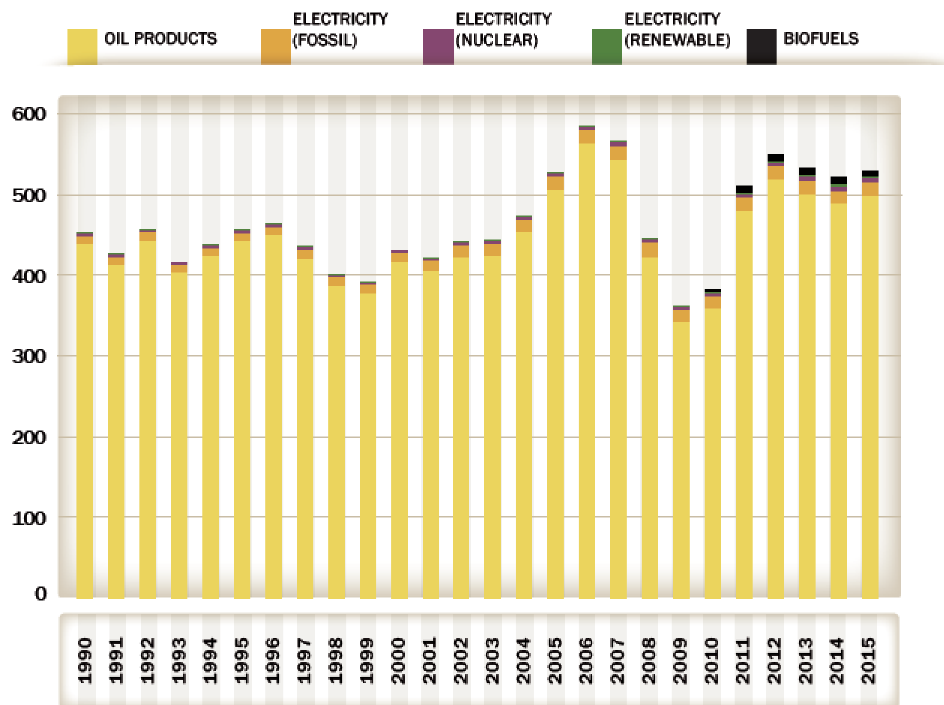

Figure 2-8: Railway Energy Consumption in Petajoules in the U.S. (IEA & UIC, 2017)

Wayside electrification eliminates emissions at the point-of-use but requires extensive infrastructure with associated significant capital expenditure. The overall environmental performance is dependent on the source utilized for electricity generation. Lower emissions compared to diesel can be achieved if primarily renewables are the source, or an increase is possible if coal is the primary source. Continuous wayside electrification is likely economically unfeasible for the Piedmont service due to the high capital expenditure and infrastructure installation along the right-of-way. Therefore, this option has not been considered further in this study.

During braking phases of the train, energy must be dissipated. All trains have a mechanical braking system, where brake pads or shoes are applied to the wheel or a brake disc controlled through pneumatic connections along the train with air provided by the locomotive. An alternative method is the utilization of the traction motors as generators where the resulting electricity is converted to heat in resistor grids, known as dynamic braking. With appropriate technology, most of the generated electricity from braking can be stored onboard of the train, an option known as regenerative braking. Figure 2-9 illustrates the theoretical potential for regenerative braking at the wheels as depends on stopping frequency and speed. It can be seen that the stopping frequency has a large impact than the speed of the train.

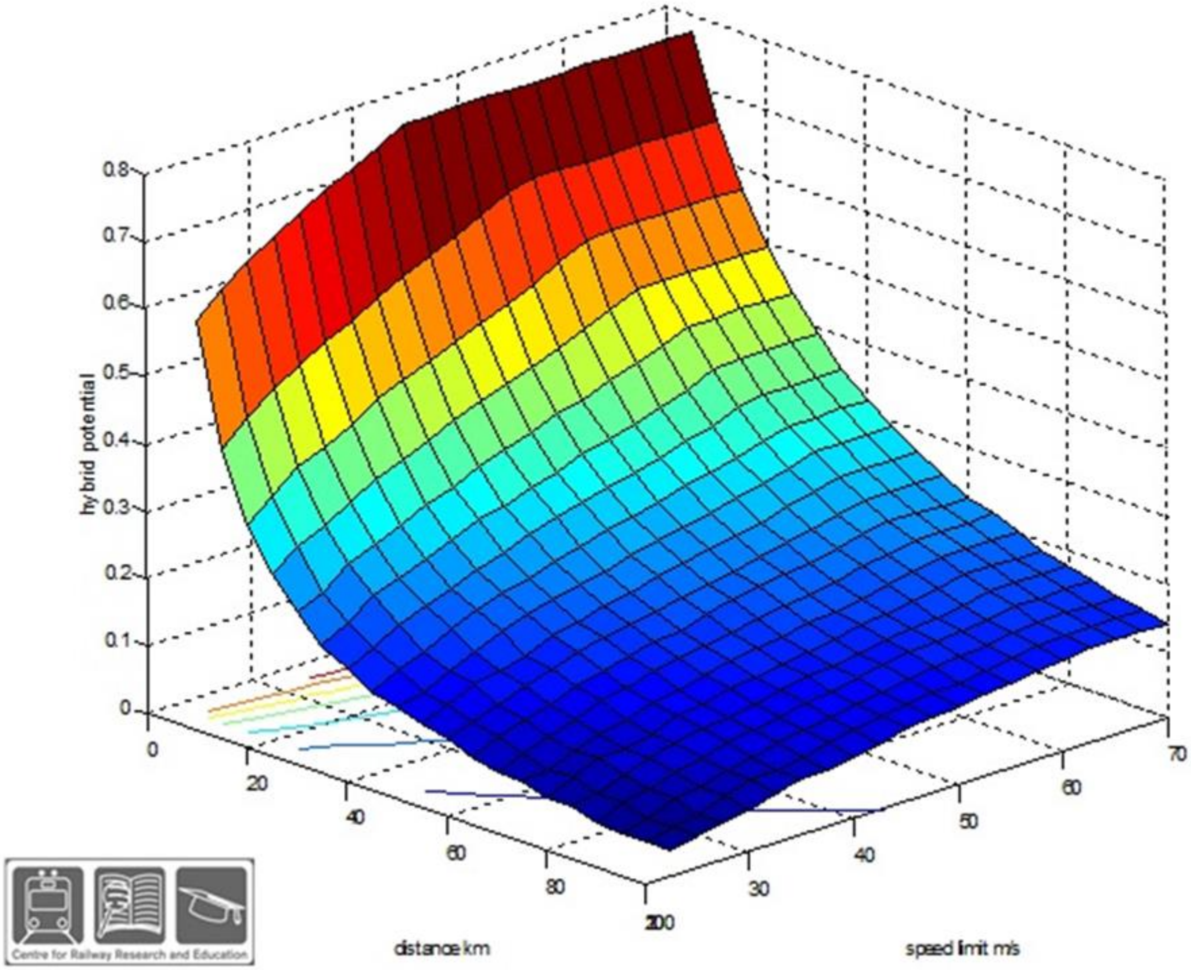

Figure 2-9: Potential for Regenerative Braking at the Wheels (Shaofeng Lu et al., 2008)

On-board energy storage systems (ESS) enable capture of energy resulting from braking, particularly on downhill segments and when approaching station stops, this energy can then the employed in the next acceleration phase decreasing the primary fuel requirement. The route characteristics of the Piedmont service feature elevation changes and several stops with relatively high-speed operation, therefore potential for regenerative braking is present. Installation of a battery-based ESS would enable regenerative braking and create a hybrid powertrain where the primary power plant would be either the diesel-generator-set or a fuel cell system. A further option is installation of the ESS in a CCU, effectively creating a battery locomotive if traction motors are added, both options are considered in the conducted work. In addition to charging the batteries through braking energy, they could be charged from an external source through a connection to the vehicle, creating a plugin version, which has been evaluated as part of the study. Several possibilities for charging equipment could the installed, such as charge bars, wireless power transfer or connection with a cable. Assessing the feasibility and appropriateness of the various charging infrastructure options are outside the scope of this study but should be evaluated if NCDOT would choose a plugin solution.

The space in a CCU could also be employed for an entire alternative powertrain consisting of hydrogen storage, fuel cell system, and traction motors with the potential option of adding batteries creating a hybrid powertrain. In the conducted work, both options including a plugin version are considered to estimate the impact on energy consumption and emissions.

More detailed information about the modelled options is provided in the Powertrain Technologies section.

2.3.1 Air Quality-Impacting Emissions

The combustion of hydrocarbons, such as coal, diesel, and natural gas results in emissions that impact air quality and greenhouse gas (GHG) emissions. The U.S. Environmental Protection Agency (EPA) regulates the allowable emissions resulting from hydrocarbon combustion on railway vehicles (EPA, 2016). Standards for exhaust emissions have become progressively more stringent, and the latest for railway motive power vehicles is Tier 4 effective for locomotives built from 2015 onwards. The applicable EPA standards (reflected in 40CFR1033) are depicted in Figure 2-10. NCDOT's F59PH locomotives currently achieve a Tier 0+ standard (Harris, 2019).

Locomotives: Exhaust Emission Standards

	Duty-Cycle [b]	Tier	Year [c]	HC [l] (g/hp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)	CO (g/bhp-hr)	Smoke (percentage) [m]	Minimum Useful Life (hours / years / miles) [n]	Warranty Period (hours / years / miles) [n]
Federal [a]	Line-haul	Tier 0	1973-1992 [d, e]	1.00	9.5 [ABT]	0.22 [ABT]	5.0	30 / 40 / 50	(7.5 x hp) / 10 / 750,000 [o]	1/3 * Useful Life
		Tier 1	1993-2004 [d, e]	0.55	7.4 [ABT]	0.22 [ABT]	2.2	25 / 40 / 50	(7.5 x hp) / 10 / 750,000 [o] (7.5 x hp) / 10 / -	
		Tier 2	2005-2011 [d]	0.30	5.5 [ABT]	0.10 [k] [ABT]	1.5	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 3	2012-2014 [f]	0.30	5.5 [ABT]	0.10 [ABT]	1.5	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 4	2015+ [g]	0.14	1.3 [ABT]	0.03 [ABT]	1.5	-	(7.5 x hp) / 10 / -	
	Switch	Tier 0	1973-2001	2.10	11.8 [ABT]	0.26 [ABT]	8.0	30 / 40 / 50	(7.5 x hp) / 10 / 750,000 [o]	
		Tier 1	2002-2004 [h]	1.20	11.0 [ABT]	0.26 [ABT]	2.5	25 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 2	2005-2010 [h]	0.60	8.1 [ABT]	0.13 [i] [ABT]	2.4	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 3	2011-2014	0.60	5.0 [ABT]	0.10 [ABT]	2.4	20 / 40 / 50	(7.5 x hp) / 10 / -	
		Tier 4	2015+	0.14 [j]	1.3 [j] [ABT]	0.03 [ABT]	2.4	-	(7.5 x hp) / 10 / -	

Figure 2-10: Locomotive Emission Standards (EPA, 2016)

California has ambitions to reduce emissions beyond the Tier 4 standard and developed a further progression, referred to as Tier 5, illustrated in Figure 2-11. Currently, this proposed standard is under consideration by the EPA and the suggested implementation date would be 2025. In addition to the emissions regulated in the previous Tiers, GHG have been added and a provision for zero-emission capabilities has been introduced. Definition of "designated areas" for air quality is not yet defined. It could cover all EPA non-attainment or even EPA maintenance areas, in which case most, if not all, of the Piedmont corridor would be affected.

Potential Amended Emission Standards for Newly Manufactured Locomotives and Locomotive Engines

Tier Level	Proposed Year of Manufacture	NOx		PM		GHG		HC		Proposed Effective Date
		Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[2]	Standard (g/bhp-hr)[1]	Percent Control[1]	Standard (g/bhp-hr)	Percent Control[2]	
5	2025	0.2	99+	<0.01	99	NA	10-25%	0.02	98	2025
		With capability for zero-emission operation in designated areas.								

Figure 2-11: Potential Tier 5 Emission Standards Applicable to Railway Motive Power as Proposed by California (Nichols, 2017)

A trend to reduce emissions further, even beyond Tier 5, could be implied with the goal of some states, such as California, to reach zero-emission railway operation. Current locomotives produced do not meet this standard, hence the focus on low- and zero-emission technologies. NCDOT has the desire to significantly reduce emissions with the potential implementation of zero-emission technology when feasible.

2.3.1 Greenhouse Gas Emissions

Combustion of hydrocarbons with oxygen (or air) leads to carbon-based emissions, such as carbon dioxide, which contributes to the greenhouse effect. Scientist found evidence suggesting that utilization of hydrocarbons by humans and the subsequent release of GHGs is leading to climate change resulting from global temperature rise (IPCC, 2020). More details about science of climate change can be found in publications of the Intergovernmental Panel on Climate Change (IPCC, 2020).

There are several GHGs. Their relative impact on the climate can be illustrated by the metric Global Warming Potential (GWP) (EPA, 2019). The primary GHGs related to transportation activity are the following compounds:

- Carbon dioxide (CO_2), which represents the baseline GHG with a GWP of 1. The compound results when hydrocarbons are combusted, which is the case in diesel engines and powerplants that rely on coal, natural gas, or petroleum, among others.
- Methane (CH_4) is the primary component in natural gas. Its GWP is 28 to 36. Methane's warming impacts dissipate relatively quickly, lasting about a decade, but this fact is considered in its GWP score. Methane is also a precursor to ozone, another GHG, and this factor is also reflected in its GWP score. Methane is commonly used in electricity generation and as fuel in some transportation applications.
- Nitrous Oxide (N_2O) is one of many by-products of combustion with air, such as in diesel engines, and its GWP is 265-298 times of CO_2, or approximately ten times that of methane.

Modal shift from road to rail reduces energy consumption and emissions from the transportation sector even if current diesel technology is employed. Efforts to introduce low- or zero-emission motive power options will increase the rail advantage and are necessary for the mode to remain competitive given lower emission options emerging in the road sector.

2.4 Previous NCDOT Efforts to Reduce Emissions

The Piedmont travels through many counties that were registered by the EPA for non-attainment of air quality standards in the past (EPA, 2020). As a public entity, NCDOT has a desire to limit their impact on air quality from rail operations and to achieve that objective, the Rail Division has previously examined use of alternative fuels for railway motive power. Efforts included testing of biodiesel and blends of petro- and bio-diesel, including B20 biodiesel, which demonstrated up to a 60% emissions reduction of CO, HC, PM2.5 with limited impact on NOx when these fuels where tested in three in-service locomotives (Frey, Graver, & Hu, 2016; Harris, 2019). Additionally, an EPA certified (JRPSK0710B01-001) Blended After-Treatment System (BATS) was implemented and improved emissions from Tier 0+ to Tier 3+ with Tier 4 upgrades planned for future systems (Harris, 2019). Figure 2-12 illustrates the results of the BATS testing in relation to the EPA emission standards.

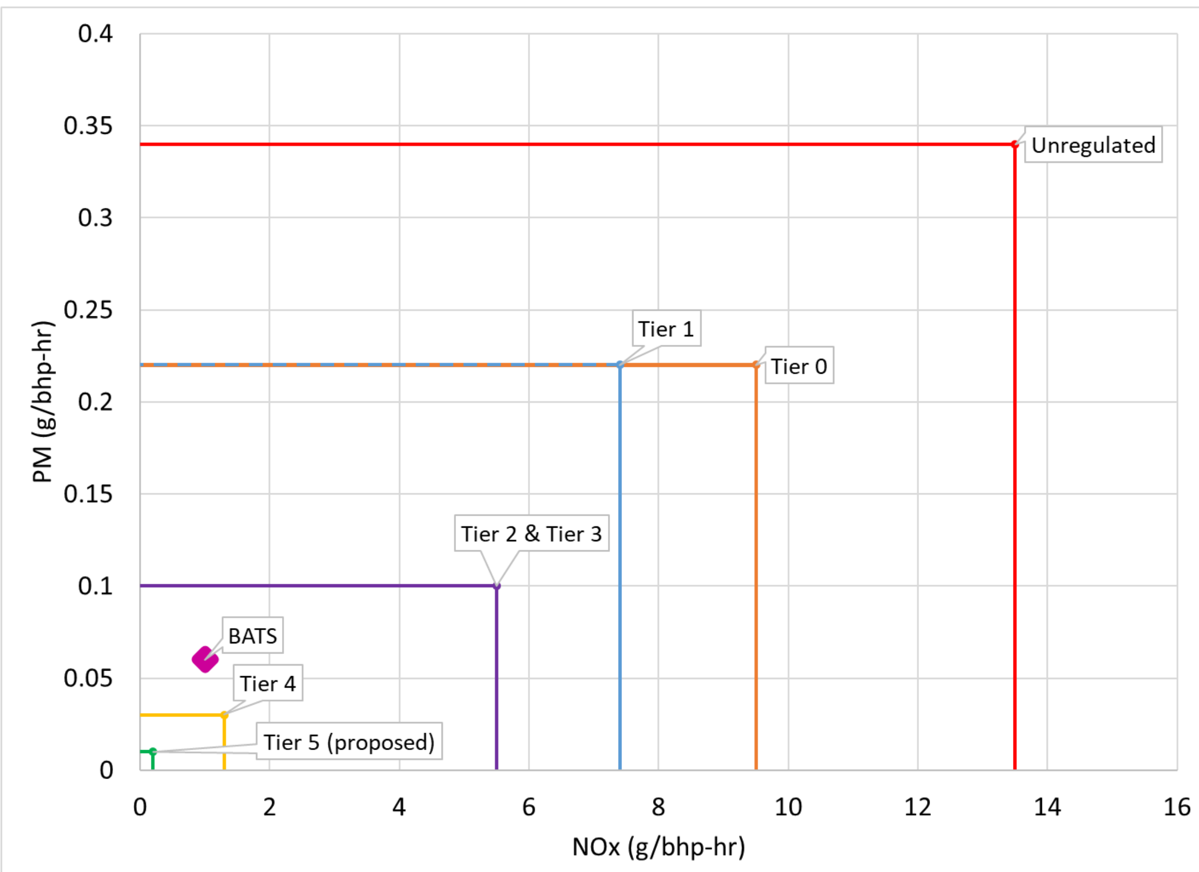

Figure 2-12: EPA Tiers and NCDOT Demonstration Project Performance (Cook, 2016 as quoted in Harris, 2019; EPA, 2016; Nichols, 2017)

Previous efforts of NCDOT have shown commitment to reduce emissions and willingness to trial new technology. A combination of options including BATS, biofuel, and a plugin hybrid powertrain are likely to result in significant emission reduction but will not lead to a zero-emission option. Therefore, investigation of hydrogen as a potential fuel for NCDOT's rail operation is warranted and complements previous efforts.

3 INTRODUCTION TO HYDROGEN RAIL TECHNOLOGY

This section describes hydrogen characteristics and hydrail applications. It includes production, storage, and transportation; hydrogen fuel cell systems followed by an overview of batteries. At the end of the section, examples of hydrail vehicles are provided.

3.1 Hydrogen Characteristics

Hydrogen (H_2) is the most common element in the universe and a common element on Earth, occurring in compounds such as water (H_2O) and hydrocarbons such as natural gas or petroleum. To obtain pure hydrogen, the associated compound must be split. Therefore, H_2 is an energy carrier (or vector) rather than an energy source, similar to electricity in this respect. As an energy carrier, it can be produced from many feedstocks enabling a zero-emission energy supply chain.

Hydrogen is a colorless, odorless gas at ambient temperature and the lightest element. It has the largest energy density by mass, ~120MJ/kg low heating value, of any fuel but low volumetric energy density. Thus, it requires compression or liquification to enable storage densities that allow practical travel ranges for vehicle applications. One kilogram of hydrogen has a similar energy as a gallon of diesel. Hydrogen is not a GHG and will escape into the atmosphere and eventually to space due to its buoyancy. Hydrogen combustion with air results in water and small amounts of NOx. The latter will be avoided when hydrogen is used in fuel cells.

Hydrogen is an attractive option for an alternative fuel since it does not contain any carbon. When utilized in fuel cells, it avoids all harmful emissions, has a relatively high energy density, and can function as large-scale storage. Currently, hydrogen is used in many industrial processes, such as petroleum refining and fertilizer (ammonia) production and is available as a gas or liquid for commercial purposes.

3.2 Hydrogen Production

Hydrogen, as an energy carrier, can be produced from many different sources, illustrated in Figure 3-1. Currently, the most common feedstock in the U.S. is natural gas. Water and natural gas are reformed to create hydrogen and CO_2. This method is known as Steam Methane Reforming (SMR), alternatively gas derived from biomass could be employed as a substitute for natural gas. SMR has been considered as part of the evaluation.

Another alternative method is electrolysis of water, where water is split into oxygen and hydrogen with an electric current, the opposite process to a fuel cell. Electrolysis is attractive as electricity from renewable power sources or nuclear power stations could be used for hydrogen generation, avoiding emissions from production with the possibility of an entirely renewable energy supply chain. Electrolysis where power is provided by the grid and an option where solely renewable sources are utilized are included in the study.

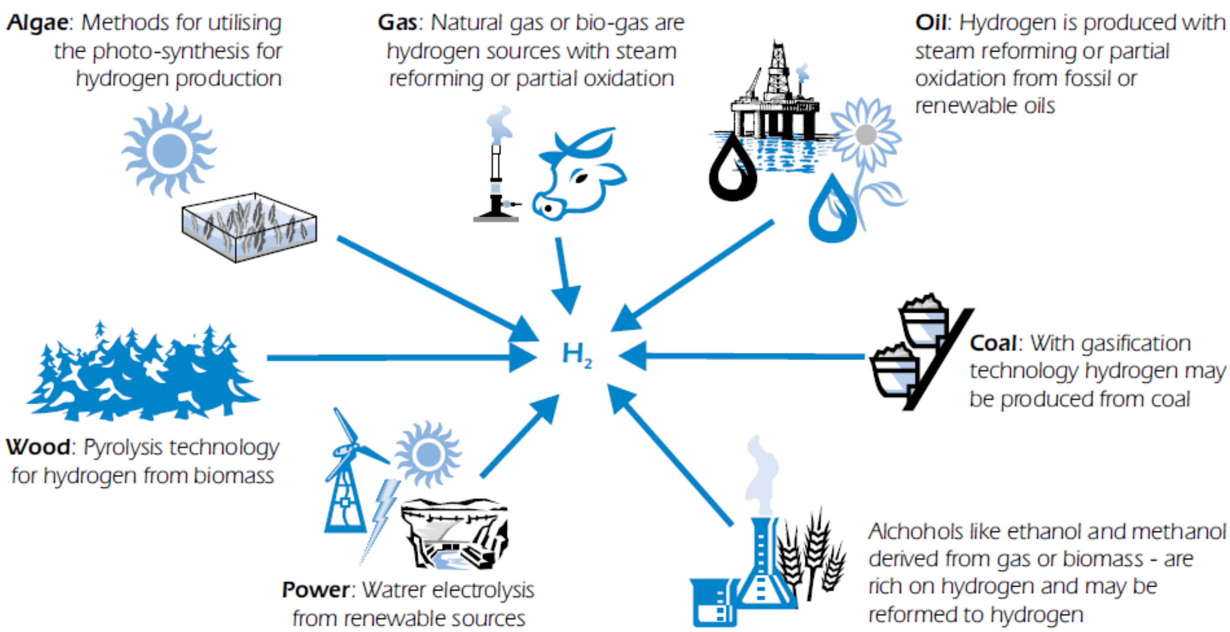

Figure 3-1: Illustration of Feedstock for Hydrogen Production (IEA, 2006)

A hydrogen production option from biomass has been evaluated as part of this study and could be an attractive possibility as renewable sources would be utilized, which may have a positive impact on emissions. More detail on hydrogen production methods can be found in the PhD dissertation by Hoffrichter (2013).

There are two possible production locations for hydrogen considered in this study: either a unit is constructed at the refueling site and hydrogen produced locally or hydrogen is produced at a central location and transported to NCDOT facilities. Evaluated onsite options include SMR, requiring a gas supply, and electrolysis, requiring a high-power electrical supply, while both require water. If hydrogen would be sourced from a central location, delivery is necessary and would most likely occur by truck as a liquid or in gaseous form, both options were considered. Hydrogen production locations in the U.S. are shown in Figure 3-2, and it can be seen that there is no major production in North Carolina currently, requiring transportation from out-of-state. However, it is possible that North Carolina could start producing hydrogen if the NCDOT opportunity was realized, because, for instance, both the Raleigh and Charlotte railyards are in close proximity to nuclear power plants, and hog farms (methane) and fertilizer production are major industries in eastern North Carolina and could be sources of hydrogen.

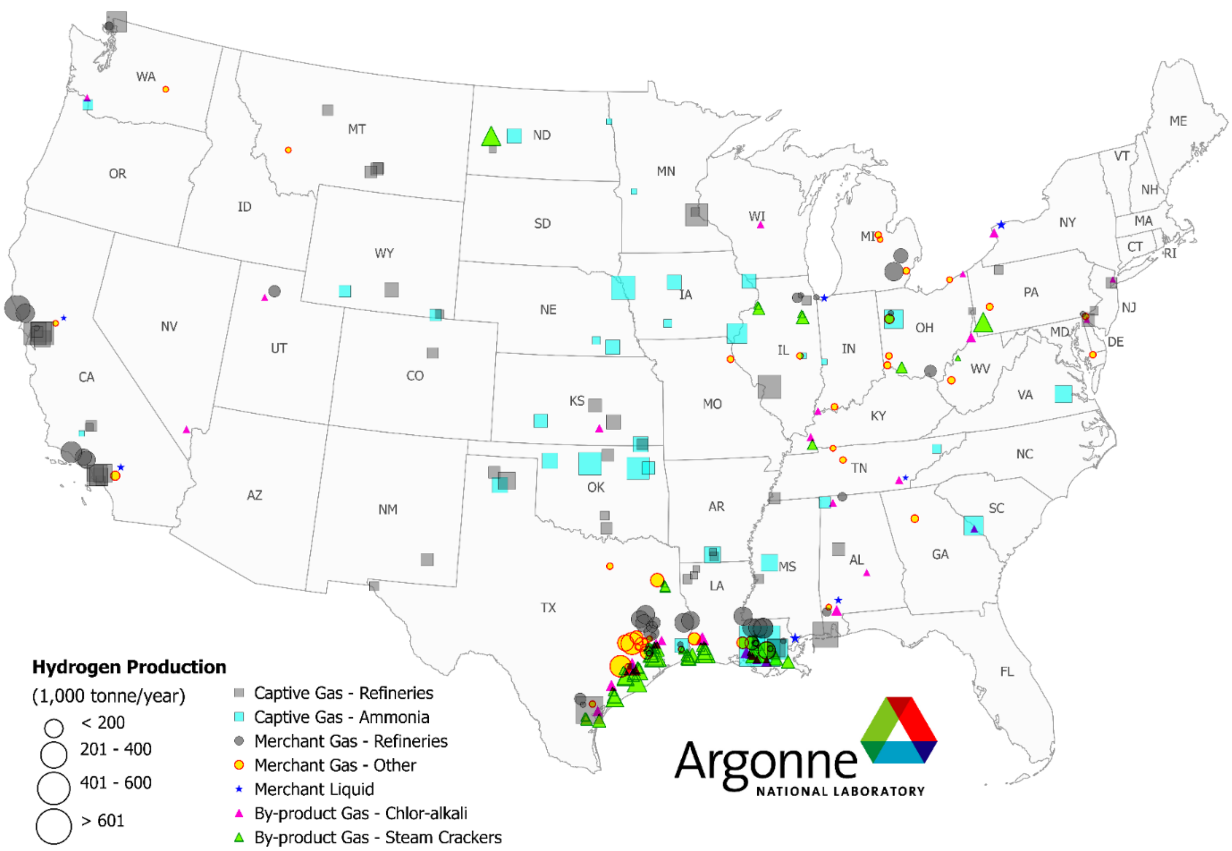

Figure 3-2: Current Hydrogen Production Locations in the U.S. (Satyapal, 2019b)

The various feedstocks and associated production methods have different impacts on hydrogen cost and environmental performance. Selection of appropriate hydrogen production pathways and sourcing will depend on NCDOT's objectives, availability, and price of H_2 and trade-offs are likely required.

3.3 Hydrogen Transportation, Distribution, and Storage

Hydrogen is produced as a merchant gas sold to customers through various methods, primarily dependent on the quantities required. The most common options are described in this section and several on the technologies employed for the transportation of hydrogen could also be utilized for on-board storage tanks on a locomotive.

In Figure 3-3 the volumetric and gravimetric energy density of various fuels and storage devices is depicted. The top right corner represents the highest energy density by mass and volume while the bottom left corner represents the lowest. It can be seen that liquid hydrocarbon fuels have the highest energy density, therefore requiring the least amount of space and are the lightest of all options. Batteries are at the opposite end with a relatively low energy density by mass and volume, thus being relatively heavy and requiring a significant amount of space in a typical rail application. Hydrogen has a lower energy density than hydrocarbons but higher than batteries, and if the mass of the diesel-generator-set is considered total weight of the powertrain between the diesel and hydrogen option is similar. Nevertheless, hydrogen requires approximately 3-4 times the volume for the same amount of energy stored as diesel. This higher volume requirement affects transportation vehicle design, delivery frequency, and onboard storage systems. Unlike the automotive industry, rail applications are less constrained by weight or space. NCDOT locomotives are likely to have adequate volume available if the diesel powertrain were removed to accommodate fuel cell systems, hydrogen storage and batteries. This makes hydrogen an attractive option for rail compared to utilization in road-based modes of transportation such as automobiles and trucks.

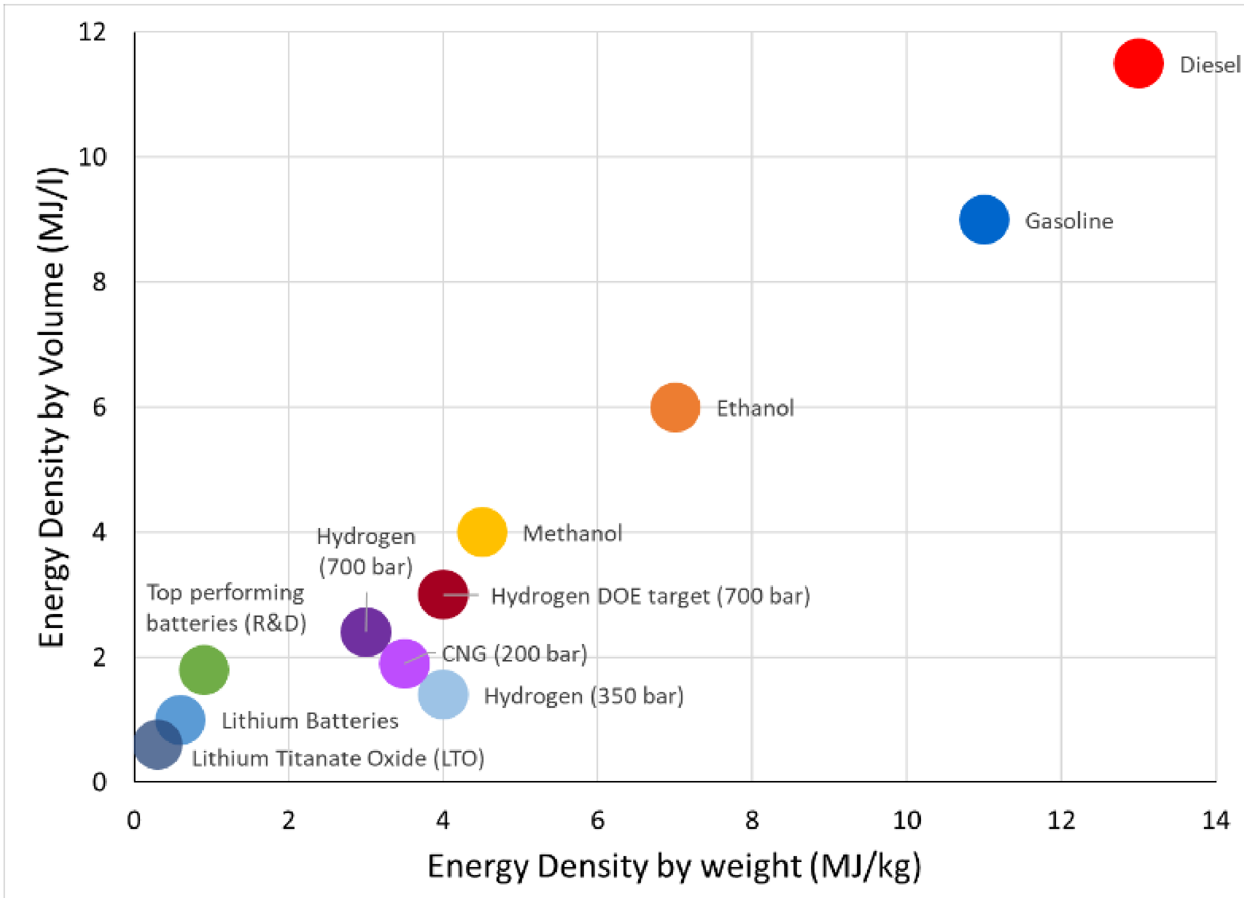

Figure 3-3: Energy Density of Various Fuels and Energy Carriers including tank system weight and volume and accounting for typical powertrain efficiencies (Hexagon, 2019; IEA, 2009; Johnson Matthey Battery Systems, 2017)

The relatively high energy density of hydrogen per mass and production capability from electricity make the element a suitable option for large-scale energy storage, see Figure 3-4, which is required if more renewables are to be part of the future electricity grid.

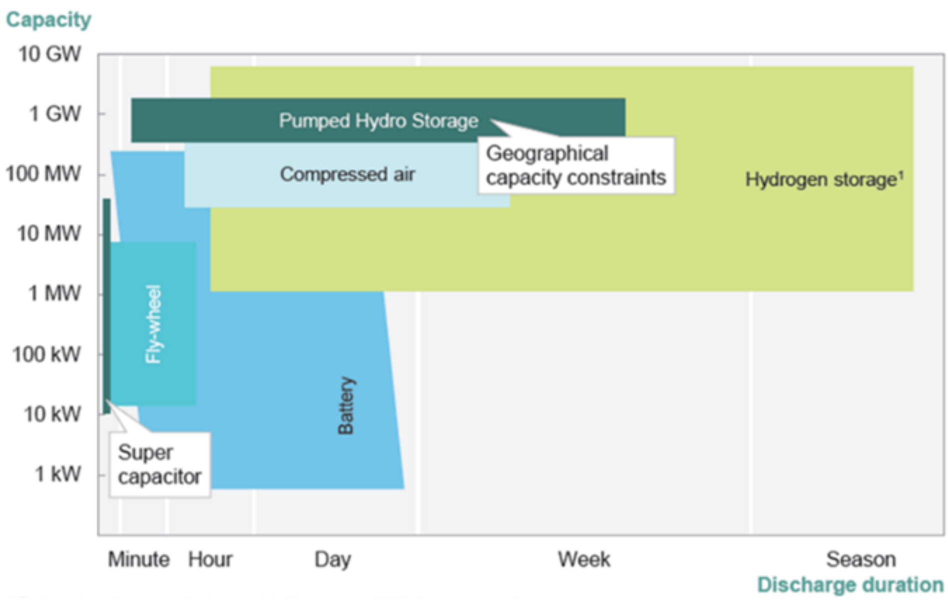

Figure 3-4: Large-Scale Energy Storage Options (Satyapal, 2019a)

The illustration also provides information about the suitability of ESS options that could be considered for rail applications, highlighting that supercapacitors would be useful for high power provision for short periods of time, while batteries could provide power and energy over medium time periods, but their weight presents a challenge (see Figure 3-3) while a hydrogen system could provide relatively high energy storage and power, which is required for the Piedmont service.

3.4 Hydrogen Transportation, Distribution and Storage

Hydrogen is utilized in large quantities for industrial processes. Thus, most hydrogen is transported, for the entire distance or in part, through pipelines. Where hydrogen is required in lesser quantities, not justifying a pipeline, transportation by truck is used (Gillette & Kolpa, 2008).

3.4.1 Pipeline

Individual large-user industrial sites are often linked by pressurized gas pipeline networks, see Figure 3-5, and there are approximately 1,600 miles of hydrogen pipeline in the U.S. (Satyapal, 2019b). Pipelines have a share of more than two thirds of the merchant hydrogen transportation market. Pipeline transport of hydrogen has been practiced since the 1930s in Germany (Winter, 2009) and is now common in many countries, including the U.S.

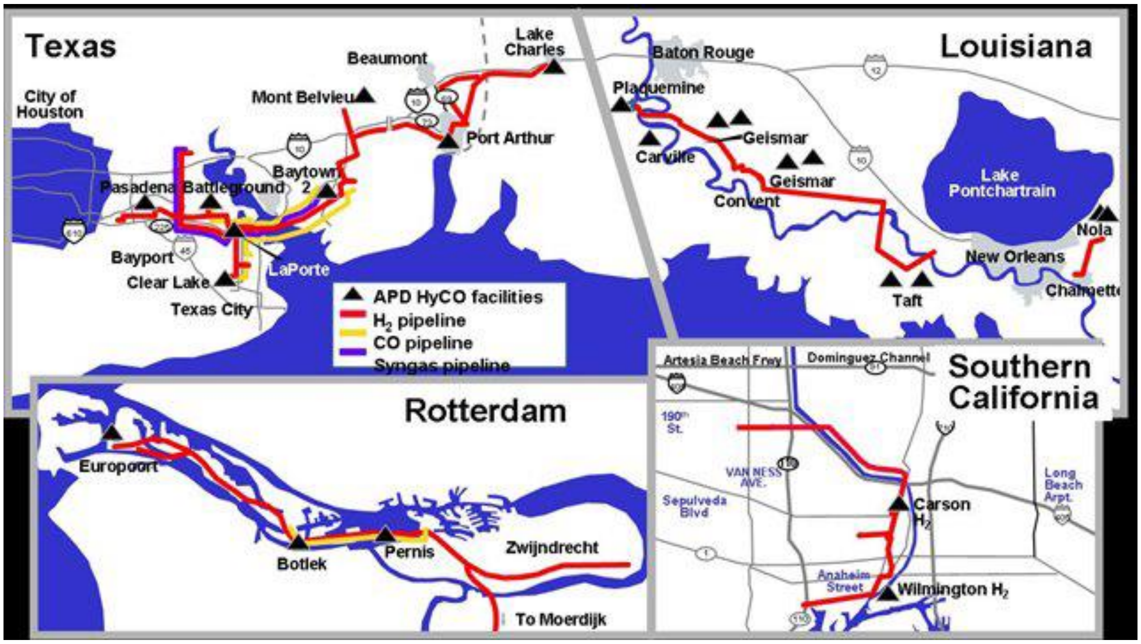

Figure 3-5: Example of Pipeline Networks in Industrial Areas,
H_2 pipeline shown in red (Miller et al., 2009)

About 16,000 km (~10,000 miles) of hydrogen pipeline exists globally, and many have a length up to 400 km (~250 miles) in several parts of the world. Most of the existing hydrogen pipelines have a diameter of 100 mm (~4 inches) with operating pressure up to 100 bar (Perrin, 2007).

The transportation capacity of pipelines carrying chemicals, such as hydrogen or natural gas is significant. Figure 3-6 illustrates a 600 MW capacity for a standard AC high voltage system and an appropriately sized hydrogen pipeline. Centralized hydrogen production and distribution to major customers through pipelines, as currently practiced in the petro-chemical industry, could be employed for railway applications where existing production facilities are in relative proximity to refueling sites.

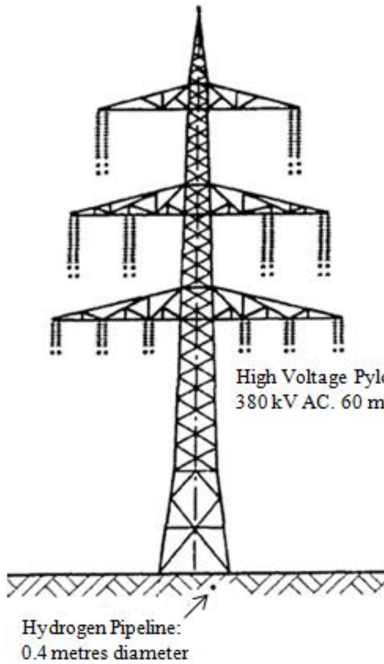

**Figure 3-6: Energy Transport of 600 MW each.
Drawing to scale. (Tetzlaff, 2008)**

Figure 3-6 shows that the impact of a hydrogen pipeline may be lower than an electrical energy transportation system and that underground installation is possible.

Traditionally, hydrogen pipelines are constructed of steel, but more recently, composites are being adopted within industrial plants. At a given pressure, hydrogen has about one-third of the energy density of natural gas but flows about three times as fast as natural gas at the same pipe diameter and pressure. Therefore, hydrogen pipeline sizes and requirements are similar to natural gas pipes.

The following example in Southern California illustrates central hydrogen production capacity, pipeline transportation, and railway refueling:

Vehicle Projects' Hydrogen-Hybrid Switcher locomotive, in collaboration with BNSF railway, was demonstrated from fall 2009 into 2010. Hydrogen for the trials was supplied by Air Products, which operates several SMR plants in Los Angeles connected to a pipeline distribution network petroleum refineries, see Figure 3-5. The hydrogen supplier stated that about 2% of the current production capacity in the Los Angeles area would be sufficient to fuel approximately 200 switcher locomotives, and that a connection to the pipeline network would be possible. At the time, the cost for hydrogen from the pipeline was between \$2 –3 per kg of H_2 (Miller et al., 2011), while retail diesel costs were \$3 -4 per US gallon (EIA, 2013). Thus, hydrogen was available at lower prices compared to diesel on an energy content basis.

The example shows that hydrogen production and distribution, as currently employed by the petrochemical industry could be adapted for railway requirements and that hydrogen can be available at competitive prices in specific circumstances.

For railway refueling sites in industrial areas, connection by pipeline to hydrogen producers seems the most suitable option. This might not always be possible or economical, especially for demonstration projects or a small fleet. No major merchant hydrogen production is located close to the Piedmont corridor and therefore a pipeline connection is unlikely and not considered further in this study. However other distribution methods currently employed to supply smaller quantities of hydrogen to customers could be suitable for NCDOT.

3.4.2 Transportation as a Gas or Liquid

Hydrogen, like other chemical fuels, can be transported in its storage medium on the road, railways, or boats. The main states in which hydrogen is currently stored to be transported are: (1) in gaseous form and (2) in liquid state. Another option is onsite generation of hydrogen at vehicle refueling stations as already described in the hydrogen production section. Hydrogen can be stored and hauled in cylinders at different pressures. Depending on the hydrogen quantity required, the gas tanks have different sizes, ranging from about one meter to truck trailer length. Pressurized hydrogen is often transported in a 200 bar tube trailer, 200 bar to 480 bar cylinder bundle, or a 500 bar dual-phase tanker (Williamson, 2011) described in more detail in the Liquid section of this report. The 200 bar tube trailer used for refueling of the Vehicle Projects / BNSF proof-of-concept locomotive is shown on the left in Figure 3-7, and a mobile refueler used for fuel cell trucks is shown on the right. Both might be options for NCDOT.

Figure 3-7: Hydrogen Distribution and Storage in Gas Tube Trailer
200 bar trailer on the left and 450 bar mobile refueler on the right (Hoffrichter, 2009, 2019)

Cylinder bundles usually consist of several individual gas tanks, a single steel bottle, installed in a hydrogen proof-of-concept locomotive, is shown in Figure 3-8. Cylinder bundles on a trailer are shown in Figure 3-9.

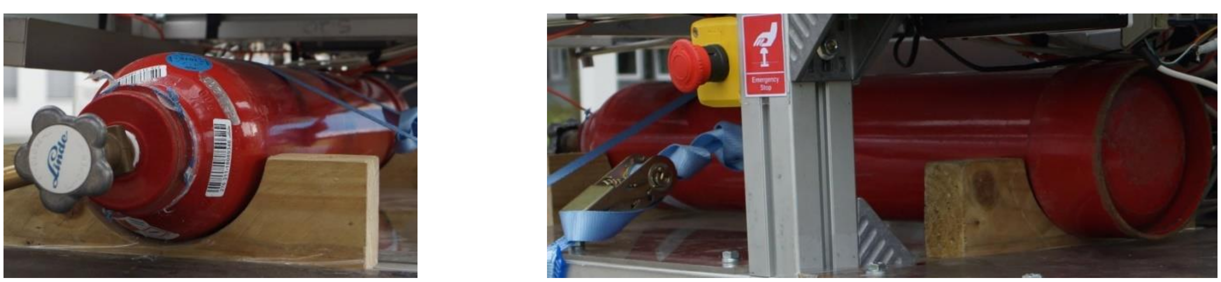

Figure 3-8: 200 bar Compressed Hydrogen Cylinder Installed in a Hydrogen Locomotive
Courtesy and Copyright Jonathan Tutcher, 2012

Figure 3-9: Trailer With Compressed Gas Hydrogen Cylinders in Bundles (Perrin, 2007)

Hydrogen gas trailers usually have a capacity of 180 kg to 540 kg (Air Products, 2013; Perrin, 2007). Transportation on the road as a pressurised gas is primarily suitable for relatively low daily energy requirements to reduce delivery frequency. As a feasible delivery option for NCDOT, transportation as a gas has been considered in this study.

Hydrogen can be transported in its liquid state requiring low temperatures of -253°C (-423°F) and therefore super-insulated trailer. A significant amount of energy of about 30 % to 40 % is lost in the liquefaction of hydrogen (IEA, 2006), having an impact on the overall supply chain, which has been considered in this study. Liquid hydrogen's advantage is its larger energy density per volume compared to compressed hydrogen: A super-insulated truck can transport up to 4,000 kg of hydrogen as a liquid (Air Products, 2013), more than six times the quantity of a compressed gas trailer allowing fewer deliveries and enabling more economical transportation over longer distances. A liquid delivery trailer connected to vaporizer located in a 40ft container combined with some high-pressure intermediate storage is depicted in Figure 3-10, as used to refuel a hydrogen multiple unit train in Germany. Delivery as a liquid is a feasible option for NCDOT and has been considered in this study.

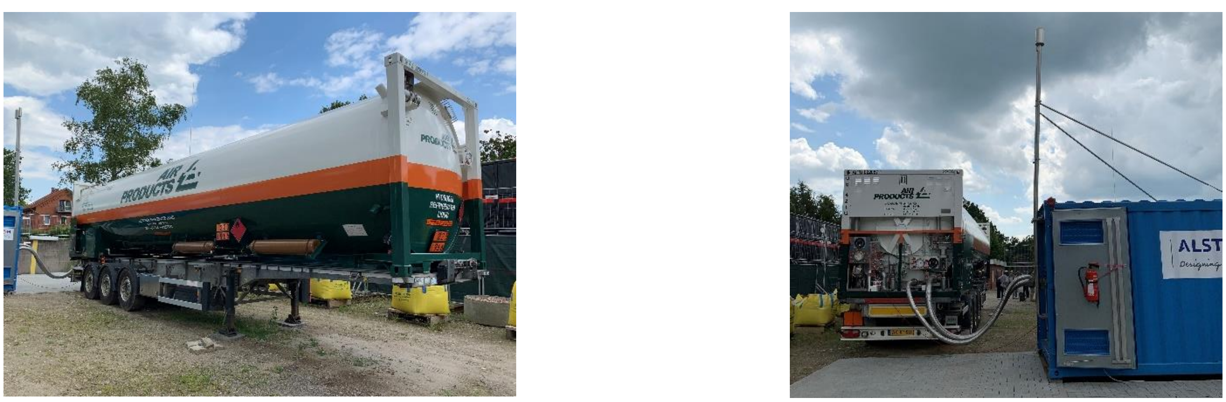

Figure 3-10: Liquid Hydrogen Trailer (Hoffrichter, 2019)

Most hydrogen stored on-board vehicles has been in pressurized cylinders. Therefore, conversion from liquid to gas form is necessary; a process that can take place at the fueling point/filling station or in case of a dual-phase tanker, on the vehicle (Ahluwalia, Wang, & Kumar, 2012). Air Products' dual-phase tanker delivering hydrogen to a filling station is shown in Figure 3-11.

Figure 3-11: Dual-Phase Tanker Delivering Hydrogen to a Filling Station (Williamson, 2011)

Hydrogen transportation and distribution processes are well-established. Delivery as a gas or liquid are suitable options for NCDOT together with onsite generation. Delivery is the most likely option for a prototype locomotive application.

3.5 Hydrogen Storage

Hydrogen can be stored in a variety of states and the employed method is usually dependent on the quantity of storage required. The primary two options for vehicle applications are storage as a gas or as a liquid, very similar to the hydrogen transportation options described in the previous subsection. All full-scale hydrogen-powered railway vehicles to date have employed storage as a gas, usually at 350bar and this would be the most likely option for NCDOT. Higher pressure gas storage, typically at 700bar is often used in cars and some trucks, and this could be an option for NCDOT. Lower pressure is preferable due to being technically less complex and lower capital requirements. Storage as a liquid would be a possibility if relatively large quantities of hydrogen would be required, but this option is technically complex and has a relatively large energy penalty as described in the previous subsection, therefore, the authors deem it less suitable for the Piedmont service and is not considered further in this report. More detail on hydrogen storage as a liquid can be found in Hoffrichter (2013). Should liquid storage be necessary for NCDOT's application, then a more detailed analysis would have to be conducted.

3.5.1 Common Gas Pressures for Vehicles

Hydrogen is always produced as gas, as shown in the Hydrogen Productions section, and therefore, storage in its gaseous form is an obvious choice. The low volumetric density of hydrogen at atmospheric pressure requires compression to achieve acceptable tank sizes. Common pressures are 200 bar, 350 bar, and 700 bar (Hexagon Lincoln, 2017; IEA, 2006; Williamson, 2011). In general, the move is towards higher pressures, and 700 bar is currently favored by the automotive industry due to space constrains while 350 bar is the preferred choice for heavy duty applications, including railways. However, at these high pressures hydrogen is outside the ideal gas region and a rise of pressure from 350 bar to 700 bar increases the energy content in the tank by 55 %, rather than 100 % and an additional 10% of energy is required to compress to 700 bar compared to 350 bar (Hansen, Sato, & Yan, 2010). For NCDOT's application it is likely that a 350 bar option would be employed due to the price and energy advantage but 700 bar is a possibility if available volume would be a challenge. In the study, hydrogen quantity is presented in kilograms so either storage pressure would be possible.

3.5.2 Hydrogen Tank Materials

Hydrogen tanks are traditionally manufactured from steel, and for lower pressures, up to 200 bar, it is still the most common cylinder material (Winter, 2009), see Figure 3-8, but composite tanks are more common at higher pressure and their weight advantage (IEA, 2006). An illustration of a typical composite tank designed for onboard usage is shown in Figure 3-12, while examples installed in a truck are depicted in Figure 3-13 on the left and on the right mounted on a train.

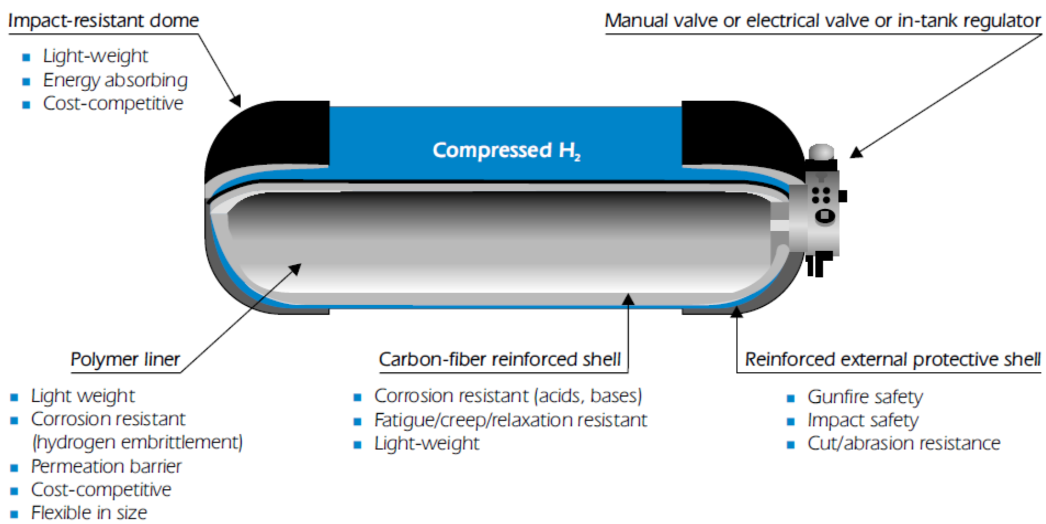

Figure 3-12: Schematic of a Typical Compressed Hydrogen Gas Composite Tank (IEA, 2006)

Figure 3-13: 350 bar Hydrogen Tanks
Left in a truck, right on a train (Hoffrichter, 2019)

The majority of railway vehicles powered by hydrogen, either as demonstrators or in-service, utilize compressed-gas storage, typically at 350bar. It is likely that a hydrogen solution for NCDOT would also employ compressed-gas storage at that pressure as the tanks are commercially available and already used in other railway applications. For this initial assessment, the authors assumed that approximately 24kg (~800kWh) of hydrogen could be storage in one cubic meter at a weight of 320kg based on a commercially available tank (Hexagon Lincoln, 2017). However, other tank arrangements might be possible enable more hydrogen storage in the same space at lower mass and a more detailed assessment would be required during a design phase for a proof-of-concept vehicle.

3.6 Hydrogen Safety

The properties of hydrogen are different to commonly used liquid fuels, such as gasoline or diesel, and some of these properties make it safer than the conventional fuels (Raj, 1997), such as being non-toxic and not resulting in toxic emission if combusted in air (i.e., no toxic smoke). The low radiant heat of burning hydrogen can also be an advantage as fewer areas are directly impacted. Additionally, hydrogen is the lightest element, significantly lighter than air, leading to relatively quick dissipation in case of release.

However, some of the properties require additional engineering controls for its safe use. The wider range of flammable concentrations in air and relatively low ignition energy result in easier ignition compared to conventional fuels. Adequate ventilation and leak detection are essential in a safe hydrogen system design. Flame detectors are required as hydrogen burns nearly invisibly. In addition, some materials including certain metals can become brittle when exposed to hydrogen for long periods of time. Appropriate material selection for hydrogen pipes and storage tanks is necessary. Hydrogen can also leak into other pipes, so hydrogen pipes should be installed above others to prevent this occurring.

Similar to natural gas, hydrogen is colorless and odorless making it difficult for humans to detect. It is possible to add an odorant, as the industry does for natural gas, however this contamination tends to damage fuel cells and is therefore not a feasible mitigation for NCDOT. Instead, hydrogen sensors have been used by the hydrogen industry for decades with success.

Hydrogen gas is typically stored and dispensed at very high pressures, as described in the previous subsections, which poses its own hazards. Careful design, certification, operation and inspections of vessels and dispensers used for hydrogen systems must be implemented. The Society of Automotive Engineers (SAE) has developed standards for hydrogen storage and dispensing equipment in automotive applications and these may be appropriate for use in a rail environment. Additional knowledge transfer can occur from bus applications and operation of the trains in Germany.

In many applications, including in railway vehicles, hydrogen is typically stored as a gas instead of a liquid. As such, hydrogen fuel's properties and resulting safety risks are different compared to diesel. Hydrogen requires a much higher temperature before autoignition occurs and higher concentration in air, as compared to diesel fuel. On the other hand, hydrogen requires a lower energy of ignition than does diesel fuel and has a wider range of composition in air in which it will burn. Hydrogen has been assessed as being safer compared to gasoline (Raj, 1997).

Due to its buoyancy, hydrogen tends to burn straight upwards if the leak has little pressure, otherwise, in the direction of the occurring leak. This characteristic can be used in risk mitigation, for example, through installation of tanks in designated areas that are well-ventilated in the upward direction and flame detectors.

In both production and storage, proper ventilation will support in mitigating hydrogen safety risks. Ventilation is especially important as hydrogen can permeate some of the materials that it may be stored in, for example, high-strength steel is subject to embrittlement. However, many other forms of steel and aluminum are unlikely to be affected given typical operating conditions, therefore appropriate material selection is essential. Embrittlement can lead to hydrogen escaping its container, and this means mixing with air. Limiting the rates and amounts of escape is a priority to keep the gaseous mixture below the flammability limits. Once a significant release occurs, avoiding sources of ignition will become key, as any explosion that could result is more dangerous than the more straightforward release of a hydrogen flame. More information on the optical and thermal sensors involved in flame detection can be found H_2Tools website (Pacific Northwest National Laboratory, 2019).

As with any fuel, periodic inspection and leak testing, will also be necessary. Leak testing is more complicated for a gaseous fuel than a liquid fuel. In addition, ensuring that venting is both large enough to relieve pressure yet small enough to limit size of any resulting hydrogen "cloud" is also crucial in design risk mitigation.

Dispensing of the fuel involves most of the same risks as the other aspects of hydrogen fuel handing, while also requiring regular inspection of the component parts, emergency off switches, and leak checks immediately prior to refueling. Leak check detection is often automated as part of the standard installation of hydrogen sensors at refueling equipment.

Currently, hydrogen is safely used as a transportation fuel in several different applications, for example, cars and forklifts. In the forklift case, operation is usually in enclosed facilities and the associated risk are managed. Further improving the safe use of hydrogen in partially enclosed and indoor facilities is subject of ongoing research. Initial findings by a group at the Sandia National Laboratories suggest that aiming some air flow at the vehicle while under repair (though this could also apply to refueling), even if the facility is fully enclosed, would greatly reduce the risk of flame occurrence.

A fully enclosed area is likely not ideal for hydrogen refueling while for maintenance work a partially enclosed area would be adequate or installation of appropriate ventilation systems. For NCDOT, fueling outside would be recommend, similar to the current practice of diesel refueling. During the refueling station implementation process, it is suggested to incorporate national standards developed by the National Fire Protection Association (NFPA). The NFPA 2 Hydrogen Technologies provides information relating to installation and handling (NFPA, 2019).

In total, there are now 40 public hydrogen refueling stations located in the U.S. (Satyapal, 2019a), the majority located in California. Experience with these stations will increase knowledge about safely handling hydrogen with subsequent improvements in safety.

For NCDOT it is likely that some new methods and procedures to handle hydrogen safely are required, but these are not likely to be particularly costly nor technologically new. For example, pressure sensors and leak detectors, along with related warning systems, will be necessary since hydrogen is an odorless and colorless gas.

Information on hydrogen safety is readily available and the Department of Energy has set up the H_2Tools website for educational purposes (Pacific Northwest National Laboratory, 2019). The website includes a link to a hydrogen incident database. The site also provides information regarding safe hydrogen handling and equipment implementation. For a more technical appraisal of the risks associated with hydrogen for a given production and refueling site, the Department of Energy has also set up a risk assessment model (Sandia National Laboratories, 2019). More information on the model, including instructions on how to access it, can be found at reference provided. Information from this tool could be incorporated in a detailed risk and mitigation design analysis.

Currently, SBCTA is going through the process of introducing a hydrogen-powered train in the U.S., which requires engagement and permission to operate from the Federal Railroad Administration (FRA). If NCDOT would implement a hydrogen solution there might be collaboration options with SBCTA and some of their learning and engagement with the FRA could be incorporated in the project.

In will also be necessary to inform the public about operation of a hydrogen-powered train. Due to the public's relatively limited experience with hydrogen as a fuel, along with an oversimplified understanding of its role in the Hindenburg disaster in the popular imagination, hydrogen fuel's public acceptance has been challenging, with concerns that the fuel is more dangerous than widely used fuel sources. But different risks are not necessarily greater risks and hydrogen can be safely employed in a rail application. Public education and outreach will be required prior to full implementation.

A more detailed safety analysis regarding NCDOTs case will have to be conducted as part of a proof-of-concept or prototype vehicle, including assessment of refueling procedures and the Rail Division's available facilities.

3.7 Fuel Cell Systems

Fuel cells consist of electrochemical devices where fuel, such as hydrogen, is combined with oxygen to produce electricity, heat, and exhaust in the form of water. While there are many ways to construct a fuel cell, the most popular way for vehicles is the proton exchange membrane (PEM), also known as polymer electrolyte membrane (DOE, 2016). Their efficiency, low operating temperature, start-up capabilities, and relatively long operating lifetime make them the preferred option for almost all vehicle operations, including all railway applications to date. An illustration of the operation of a PEM fuel cell is provided in Figure 3-14.

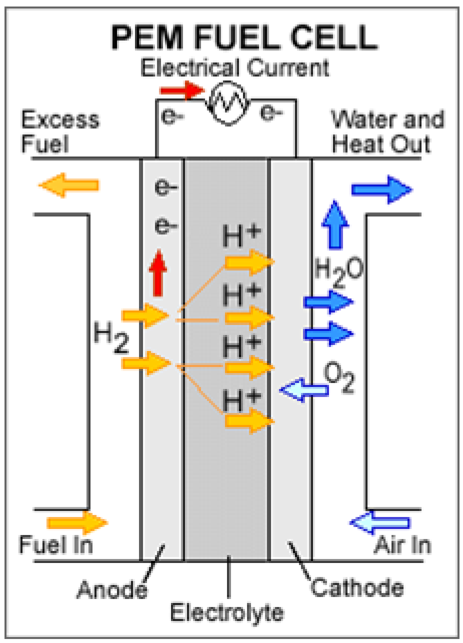

Figure 3-14: Illustration of a PEM Fuel Cell (DOE, 2011)

The process in a PEM has three primary stages (Schlapbach, 2009):

1. Hydrogen enters the cell at the anode side where the hydrogen molecule is split into atoms.
2. An anode catalyst separates the electrons from the atom creating hydrogen ions, which pass to the cathode, whereas the electrons move across an electric circuit to arrive at the cathode.
3. Oxygen from air is directed to the cathode, where it combines with the hydrogen ions and electrons to form water, which then leaves the cell.

For vehicle applications, several cells are combined in a stack to produce the required power. Hydrogen, air, and thermal management components, referred to as balance-of-plant, combined with one or more fuel stacks create a fuel cell system (FCS), also referred to a module, and the generic components are illustrated in Figure 3-15. In heavy-duty applications, power output levels are typically 30kW, 50kW, 80kW, 100kW, and 200kW. More power can be obtained by combining several FCS, which would be required for NCDOT's application.

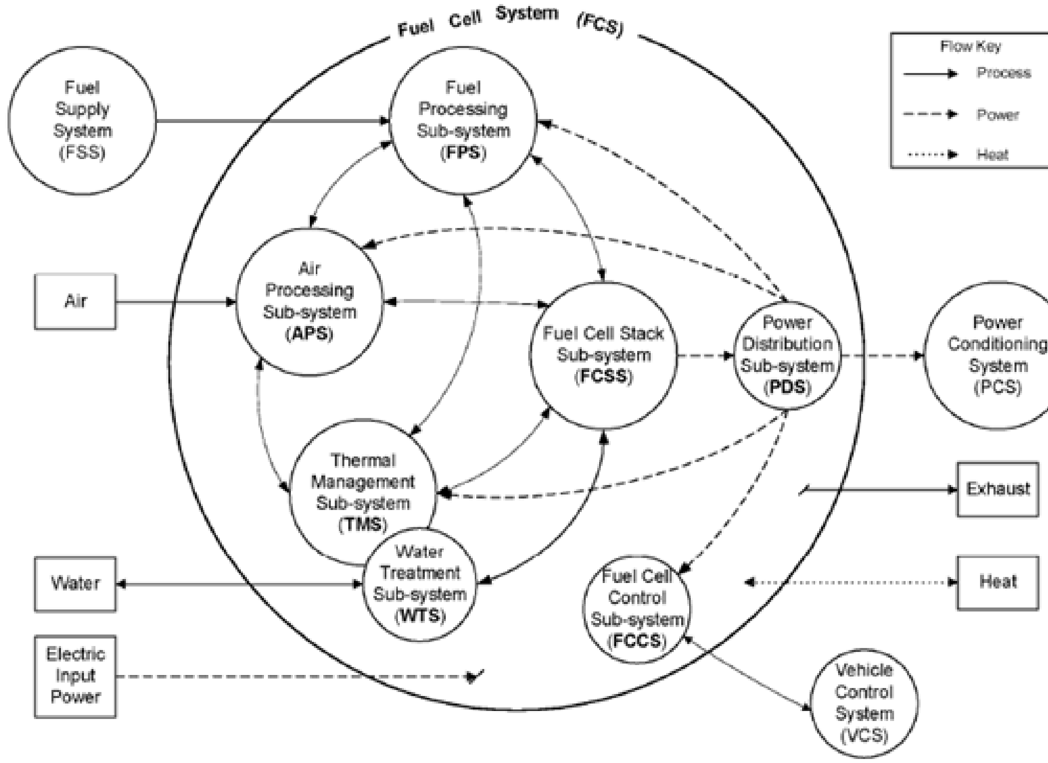

Figure 3-15: Illustration of the Components in a Fuel Cell System (SAE International, 2011)

Figure 3-16 shows train and truck FCS modules in use.

Figure 3-16: Examples of Fuel Cell Systems; train module (left) and truck (right) (Hoffrichter, 2019)

In addition to having pure water as exhaust, therefore eliminating all air pollutant and GHG emissions, FCS typically have a high efficiency over the entire operating range, as illustrated in Figure 3-17.

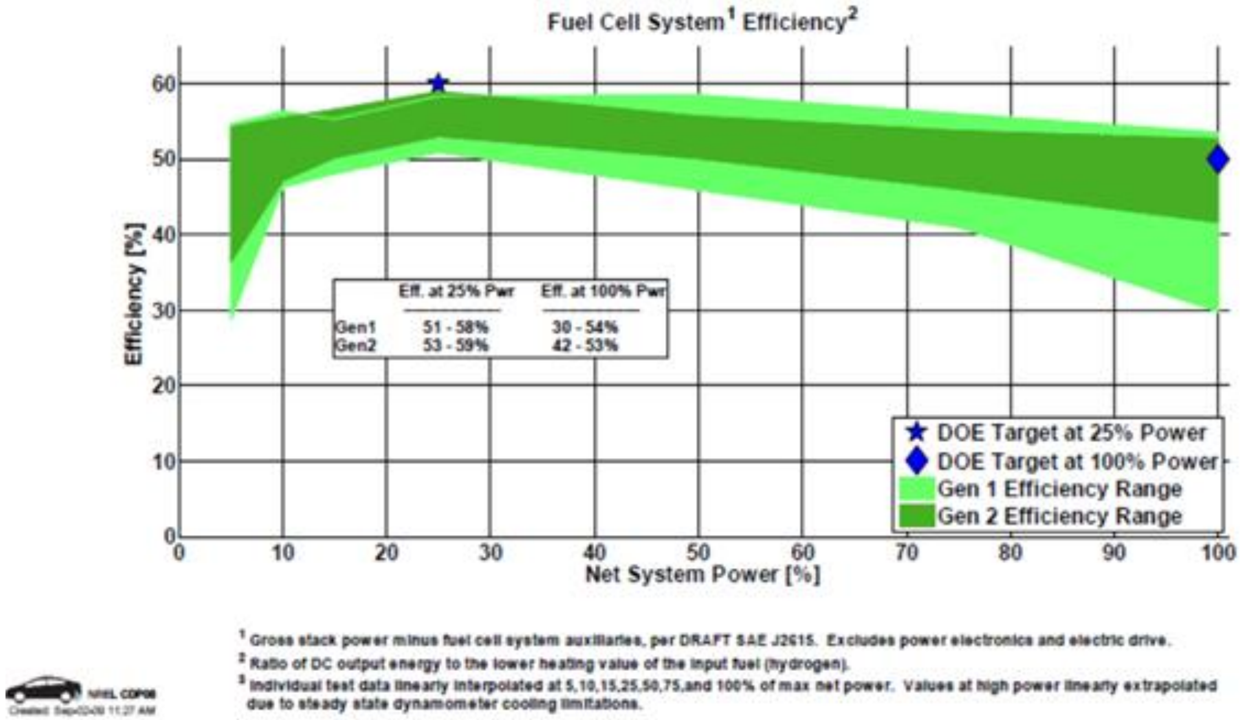

Figure 3-17: Illustration of Fuel Cell System Efficiency Curves in Light Duty Vehicles (Wipke et al., 2012)

The information presented in Figure 3-17 was obtained from the operation of FCS in cars, showing varying performance according to vehicle and FCS manufacturer. It can be seen that some of the tested systems never drop below 50% efficiency and further that the highest efficiencies occur at partial load. Efficiencies of heavy-duty systems are typically a few percentage points lower than for light-duty applications, therefore the curve is included for illustrative purposes only. Continued research and development efforts are increasing the efficiency of FCS in both types of applications.

In general, the efficiency of FCS is higher than for comparable diesel engine generator set, as illustrated in Figure 3-18. Only indicative values are shown as more precise data was not available in the public domain.

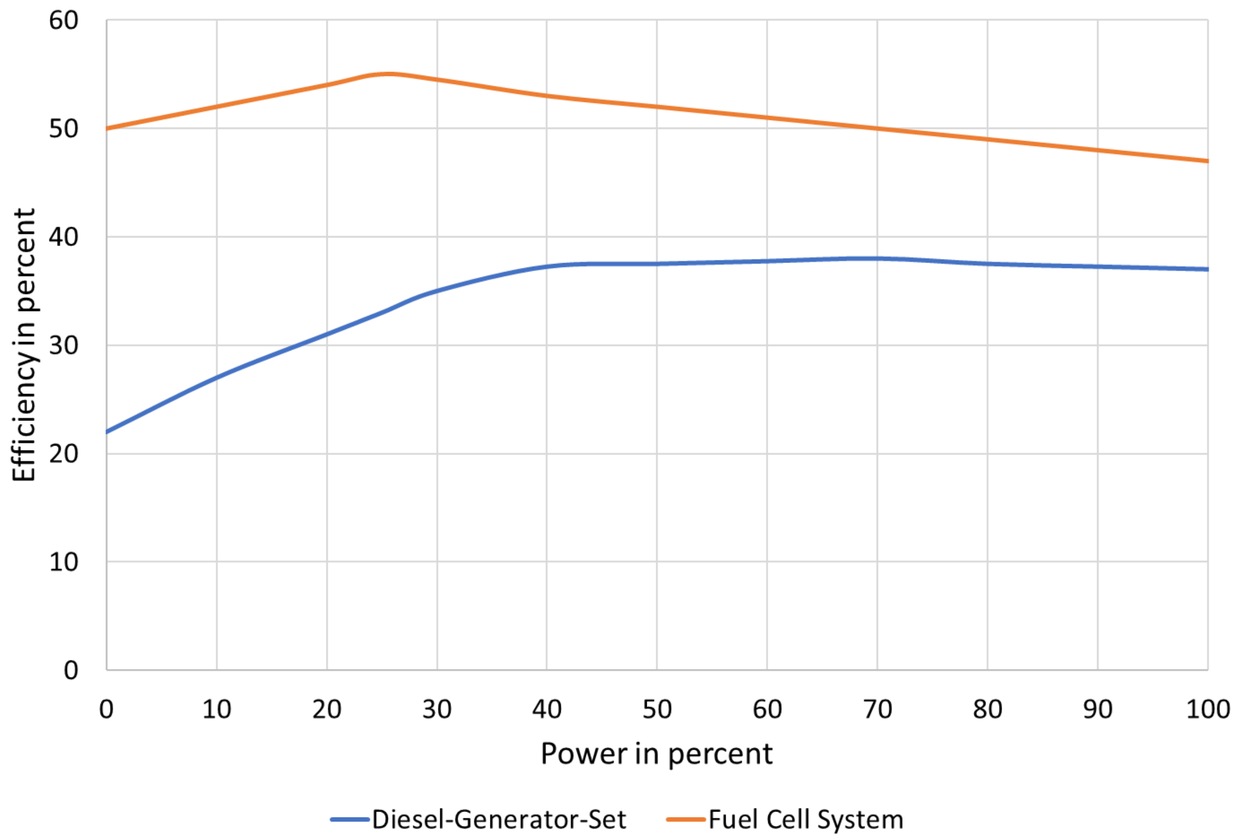

Figure 3-18: Indicative Heavy-Duty Diesel Generator-Set and FCS Efficiency Curves

The higher overall efficiency of FCS enables a reduction in energy consumption along with allowing for less on-board energy storage with comparable range to a gasoline or diesel vehicle. Efficiency curves for both diesel-generator-set and FCS have been included in the pump-to-wheel analysis as part of the simulation. Lifetimes of heavy-duty FCS have exceeded 30,000 hours (Eudy, 2019) and these are still in operation. Similar systems would be utilized in railway vehicle applications. For this assessment, the authors assumed that a FCS module could provide 200 kW while requiring a space of 0.7 m^3 with weight of 550 kg, actual power output, size, and weight vary with manufacturer and the assumed values are indicative.

3.8 Battery Technology Overview

ESS enables capture of regenerative braking as described in the Background section while allowing the possibility to operate the primary powerplant in its most efficient region, both reducing energy consumption and resulting emissions. Several ESS systems are possible but for NCDOT the most appropriate is a battery option. Batteries are electro-chemical devices where electricity is chemically 'stored'. Single use and rechargeable options are available and for NCDOT a rechargeable option would be required. Individual battery cells have a low voltage and are typically combined into large arrangements and combined with thermal and power management to create a battery system. Several different chemistries are available with varying performance regarding charge and discharge capability (C-Rate), lifetime, energy density, safety, and cost. The choice is usually a trade-off between these primary determinants. A comparison of energy density for various chemistries is illustrated in Figure 3-19, while the main characteristics of several lithium-ion options are show in Table 2-1. More detailed information about batteries can be found in the battery guide by Johnson Matthey Battery Systems (2017).

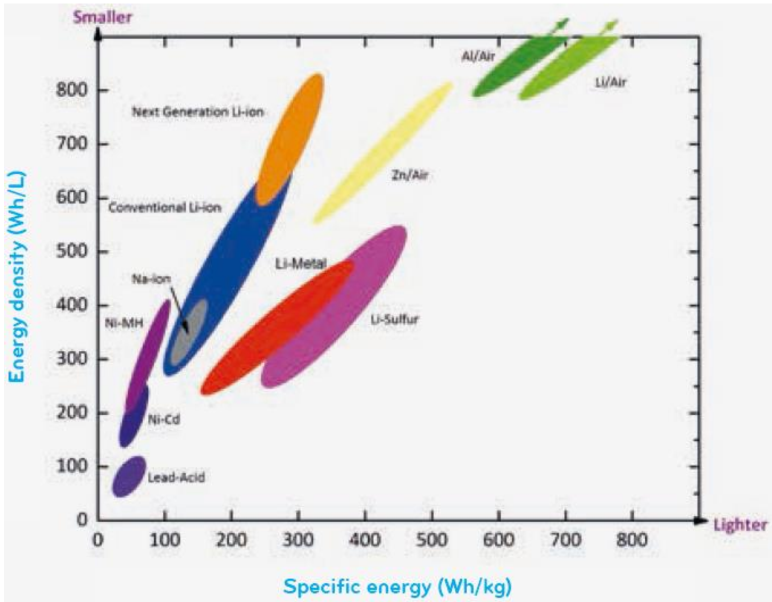

Figure 3-19: Illustration of Various Battery Chemistry Energy Densities (Johnson Matthey Battery Systems, 2017)

There has been a progression in energy density through the development of lithium-ion chemistries compared to more traditional options, such as lead-acid. Nevertheless, the energy density, particularly the specific energy, often prohibits sufficient energy storage for long range railway applications, as already illustrated in Figure 3-3.

Table 3-1: Characteristics of Main Lithium-Ion Battery Chemistries

Main Li-ion cell variants

	Cell level specific energy (Wh/kg)	Cell level energy density (Wh/l)	Typical power (C-rate)	Approx. safety thermal runaway onset	Typical nominal potential (V)	Typical temp. range (ambient)	Year of introduction into market
LCO	175-240	400-640	~1C	150°C	3.6	-20 to 60°C	1991
NCA (EV)	130-240	490-670	2-3C	150°C	3.6	-20 to 60°C	1999
LFP (EV/PHEV)	90-150	190-300	5C cont 10C pulse	270°C	3.2	-20 to 60°C	1996
LFP (HEV)	70-110	100-170	30C cont 40C pulse	270°C	3.2	-30 to 60°C	1996
NCM (EV/PHEV)	100-200	260-400	3C cont 6C pulse	210°C	3.7	-20 to 60°C	2008
NCM (HEV)	70-100	150-200	10C cont 40C pulse	210°C	3.7	-20 to 60°C	2008
LTO	90-130	170-230	10C cont 60C pulse	Not susceptible	2.4	-30 to 75°C	2008
LMO (EV/PHEV)	150-240	240-360	3-10C	250°C	3.8	-20 to 60°C	1996

In hybrid applications, where batteries are either charged periodically from wayside infrastructure, such as the QLine streetcar system in Detroit, or are combined with a primary power plant, such as in hydrail multiple units (MSU CRRE & BCRRE, 2019), these ESS have been successful in reducing energy consumption and providing autonomy from continuous wayside infrastructure. Most railway applications that have a powertrain with substantial batteries employ lithium-ion technology, example include: Alstom iLINT with lithium nickel manganese cobalt oxide (NMC or NCM) (Akasol, 2018), TIG/m streetcars utilizing lithium ferro phosphate (LFP) (Read, 2019; TIG/m, 2020), and some Siemens trains using lithium titanate oxide (LTO) (Reidinger, 2018).

When analyzing different forms of battery technology, multiple factors must be considered when making a decision based on the use case. For example, the energy/power density relates the volume and mass of a battery to the respective output The power rate of a battery determines how quickly a battery can be discharged/charged to allow a locomotive to accelerate and how effectively it can charge from regenerative braking. Safety is also a major concern on locomotives as overcharging or a damaged battery can bring harm to those on board. The FRA has published a report about battery utilization for railway vehicles in the U.S. (Brady, 2017). Other factors include volume, weight and cost of a battery system.

The battery type assumed in this study is LTO due to its superior safety characteristics; performance, including a large temperature range of operation and charge/discharge rates; and lifetime (Brady, 2017; Cowie, 2015; Johnson Matthey Battery Systems, 2017). It is likely for these reasons that this chemistry is increasingly utilized in railway vehicles in both passenger and freight (Barrow, 2019; Reidinger, 2018; Zasiadko, 2019). The main downsides to LTO are a lower energy density and a higher price compared to other chemistries. In this initial assessment, the authors assumed that between 108 kWh/m^3 to 230 kWh/m^3 at a mass of 1.4t to 2t could be stored in a battery (Akasol, 2018; Altair Nano Technologies, 2016; Johnson Matthey Battery Systems, 2017), the more conservative values were utilized for the first assessment. Other chemistries might be suitable for NCDOT's application and selection of an appropriate battery-type would be part of a more detailed vehicle design for a proof-of-concept / demonstrator locomotive; another possible option would be NMC due to superior weight and price considerations compared to LTO.

3.9 Examples of Hydrail Vehicles and Related Projects

The information presented in this section illustrates that hydrogen fuel cell or hydrogen fuel cell hybrid powertrains can be implemented in railway applications. Several relevant examples are presented but not all previous projects are covered. Other heavy-duty applications would also provide information about technology feasibility, which can be found in publications of the Department of Energy, specifically the Fuel Cell Technology Office. Regular reporting is provided about buses (Eudy, 2019) and cars (Kurtz, Sprik, Ainscough, & Saur, 2017), while information about trucks and rail applications is to be published soon. Dr. Isaac's PhD dissertation (Isaac, 2019) provides hydrail studies in a U.S. context while a report published by SBCTA (MSU CRRE & BCRRE, 2019) provides details for a multiple-unit case.

3.9.1 Commercially Available Vehicles

Currently, there are only a few hydrail vehicles that are offered commercially or are in service operation. The most significant is the Alstom iLINT multiple unit train, which has been in service in Germany since 2018 (Alstom, 2018). The train consists of two passenger cars with a hybrid powertrain where the PEM FCS provides a combined power of 400kW while the NMC batteries offer 450kW enabling a maximum speed of 140km/h (~87mph). A range of up to 1,000km (~620 miles) achieved with approximately 180kg to 260kg of hydrogen. Refueling takes about 15min. Figure 3-20 depicts the train.

Figure 3-20: Alstom Corodia iLINT
(Hoffrichter, 2019)

The project was successful for Alstom, with several orders pending in Germany, the UK, the Netherlands, France, among others. In addition, other major manufactures are developing similar vehicles, such as Siemens and Stadler.

CRRE is offering hydrail streetcars / light rail vehicles in China. Development started at the beginning of the last decade with trials in Qingdao and Tangshan (Barrett, 2017). Commercial operation started in late 2019/early 2020 in Foshan (Metro Report International, 2019). The in-service vehicle is depicted in Figure 3-21.

Figure 3-21: CRRC Hydrail Streetcar in Foshan
(Metro Report International, 2019)

The CRRE trams have a maximum speed of 70km/h (~44mph) and will operate on a 17.4km long line; eight have been ordered.

TIG/m is a manufacturer of streetcars in Chatsworth, CA and the company offers self-powered, zero-emission vehicles. Among the powertrain choices are hydrogen-hybrids with PEM fuel cells and LFP batteries (Read, 2019). The company has sold hydrail streetcars to Aruba, Dubai, and Qatar and offers heritage and modern style options. Examples of TIG/m trams are depicted in Figure 3-22.

Figure 3-22: TIG/m Streetcars
Heritage style on the left, modern style on the right
(Read, 2019)

The company offers various power-levels and options that are fully battery operated. The powertrain selection is dependent on the duty-cycle of the vehicles.

All vehicles that are currently in service or are commercially sold are of a multiple-unit configuration and operate at significantly lower power than NCDOT's service. The closest vehicle is the iLINT and components could likely be scalded to meet the requirements of the Piedmont service.

3.9.2 Proof-of-Concept/Demonstrator Vehicles

Several proof-of-concept or demonstrator hydrail vehicles have been constructed and a selection is presented here.

Vehicle Projects together with BNSF in a project funded by the Department of Defense demonstrated a switcher locomotive in the Los Angeles area in 2009-2010. The locomotive weighed 130t and stored 68kg of hydrogen in 350bar tanks, peak power of 1.5MW was provided by a 240kW PEM FCS consisting of two modules, and lead-acid batteries (Miller et al., 2011). The project demonstrated that a locomotive option is feasible with hydrail technology. Figure 3-23 depicts the locomotive and FCS.

Figure 3-23: Vehicle Projects and BNSF Proof-of-Concept Switcher Locomotive (Hoffrichter, 2009)

In 2012, a team at the University of Birmingham developed, designed, and constructed the first practical hydrogen-powered locomotive in the UK, called hydrogen pioneer (Coombe et al., 2016) and Hoffrichter was the systems engineer for the project. The locomotive had a PEM fuel cell and lead-acid battery and could be operated from a metal hydride or compressed gas tank. It was a scaled version of a full-sized locomotive and demonstrated that the hybrid powertrain concept with a hydrogen FCS is technically feasible. The project started development of further vehicles in Europe and a full-scale demonstrator multiple-unit train, called Hydroflex, was constructed in 2019. Hydroflex has a PEM fuel cell and lithium ion batteries. Both are depicted in Figure 3-24. More details about the Hydrogen Pioneer can be found in (Andreas Hoffrichter, 2013; Andreas Hoffrichter, Fisher, Tutcher, Hillmansen, & Roberts, 2014)

Figure 3-24: Hydrail Proof-of-Concept Vehicles in the UK
Hydrogen Pioneer on the left in 2012, Hydroflex on the right in 2019
(Hoffrichter, 2012, 2019)

In Japan multiple-unit proof-of-concept vehicles where constructed and demonstrated in 2008. Japan East Railway (Kawasaki, Takeda, & Furuta, 2008) had a project and the Railway Technical Research Institute (Yamamoto, Hasegawa, Furuya, & Ogawa, 2010) had a project. Both were successful and employed PEM FCS and lithium ion batteries. Neither entered commercial operation but recently Japan East Railway started a project for a new hydrail train (Railway Gazette International, 2019).

3.9.3 Ongoing Projects in North America

In North America several hydrail projects are ongoing. The most advanced a two-car multiple-unit produced by Stadler for SBCTA. The train will be a hybrid with a PEM FCS and lithium-ion batteries, most likely LTO. More information about the project can be found on SBCTA’s website and in associated reports (MM, MSU CRRE, & SBCTA, 2019; MSU CRRE & BCRRE, 2019). In Canada, Metrolinx in Toronto has a program to electrify part of their operations and hydrail technology is being considered instead of conventional wayside electrification (CH2M Hill, Ernst & Young, & Canadian Nuclear Laboratories, 2018). Initial feasibility of hydrail has been suggested in the report. This application would be similar to the Piedmont as high-power locomotive-hauled trains would be used. Further initiatives are ongoing in British Columbia, where Prof. Lovegrove is leading two hydrail projects, one involves the conversion of a switcher locomotive and the other, longer-term project, involves a multiple-unit passenger train (Lovegrove, 2018). A prototype hydrail speeder is currently being constructed and application for funds to convert the switcher have been submitted.

The previous examples demonstrate that hydrail technology is in principle feasible for the Piedmont service. However, it is necessary to consider the Piedmont service context in more detail to estimate if the technology would be suitable. The first step in a technical appraisal is often modelling to determine the most suitable options before construction of proof-of-concept vehicles.

In the next section, the authors describe the modelling approach employed in this study, followed by the considered train configurations, and the results of the simulation.

4 METHODOLOGY

The primary objective of this study is to determine the technical feasibility of a zero-emission powertrain installed in the existing locomotives or CCUs or both. To evaluate possible options, the energy consumption and power requirements of various components must be established with the premise that the exiting performance of the diesel-electric locomotives can be matched or could be exceeded. The first phase of such an undertaking is modelling of configurations, which would be followed by the construction of a proof-of-concept or prototype vehicle; the latter is beyond the scope of this study. A further part of this study was to estimate the energy and emission impacts of a motive power change throughout the respective supply chain. Both employed modelling tools are described in more detail in this section.

4.1 Single Train Simulator

Single train simulation (STS) has been utilized in this study to establish tank-to-wheel energy consumption, journey time, and to size major components regarding power and energy. STS has been employed extensively in the past to estimate the impact of powertrain changes on railway vehicles (A. Hoffrichter, Hillmansen, & Roberts, 2016; S. Lu, Hillmansen, & Roberts, 2010; Meegahawatte et al., 2010; Winnett et al.; Zenith, Isaac, Hoffrichter, Thomassen, & Møller-Holst, 2019). It is a frequently utilized tool by railway vehicle manufactures in the development of new vehicles and to ensure that current vehicle options in their portfolio meet performance requirements over existing routes.

The STS utilized for this project was developed at CRRE in collaboration with the Birmingham Center for Railway Research and Education and the WMG at the University of Warwick. It was constructed of well-established tools at these institutions and modified to model the various diesel, hydrogen fuel cell, and battery hybrid options relevant to the Piedmont service. Results of the simulation represent an estimate to enable the evaluation of various options and offer a suitable tool in the development process but simulations remain an approximation and construction of a prototype or proof-of-concept vehicle with associated instrumentation to validate performance is still required, especially if new technology such as hydrogen fuel cells and batteries are combined for such an unprecedented rail application as the Piedmont service.

The simulator discretizes distance, where the route is divided into sections, e.g., one-meter segments, and the movement of the train along the route is modelled until it reaches the terminus to complete the simulation. The next step is a backward-facing quasi-static pump-to-wheels (PTW) model to determine the requirements of various powertrain components considering the duty cycle resulting from service provision over the Piedmont route.

Speed limits, gradient profile, and station locations and service specifications such as desired journey time and dwell times at stations are required for the simulation. Further, characteristics of the train and its major powertrain components are necessary for the PTW portion of the simulation. The researchers made every effort to obtain data and accurately utilize that information for the simulation but some assumptions and estimates where nevertheless necessary. An example is the assumption that the train would travel as fast as allowable along the route and that all drivers would handle the operation of the train in the same manner. An illustration of the modelling process to obtain at-wheels values of energy consumption and braking energy as well as journey time is provided in Figure 4-1.

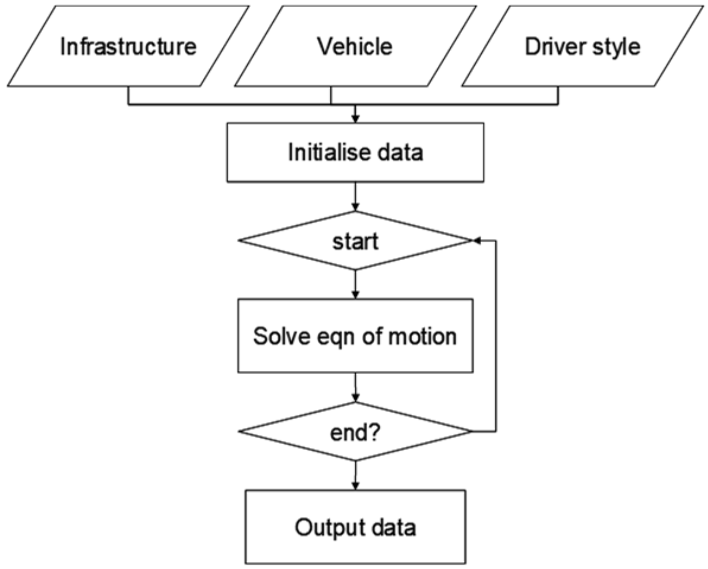

Figure 4-1: Flow Diagram of the Single Trains Simulator (Hoffrichter, 2012)

The characteristics of the major powertrain components for the PTW are also required. These were obtained from literature, provided by component suppliers, or estimated by the research team. Specifically, a traction motor efficiency was not available and developed at MSU, employing the process described in the indicated subsection below. Some manufactures provided confidential data and therefore only indicative values are presented in this report.

4.1.1 Traction Motor Map Development

The F59PH locomotives employed on the Piedmont service have DC traction motors. An efficiency map was not available for modelling, therefore the authors used the facilities at MSU to create an electric motor map. An induction motor was chosen as most modern locomotives have these installed and NCDOT might consider an upgrade. However, the work remains valid if DC motors would be retained.

Induction motors are a low cost, mechanically robust and mature technology. They have high overload capabilities and are more power dense than DC motors (Becker & Boggess, 1990). Induction motors are also capable of group drives; a single inverter can drive more than one motor. These motors have replaced DC motors in new locomotives over the past few decades and are projected to continue to dominate in this industry for another decade (Nategh et al., 2020) while permanent traction motors might be introduced in specific applications such as high speed trains. Figure 4-2 shows the torque speed curve of a typical induction machine. Field oriented control provides full torque at zero speed, quick acceleration and deceleration as well as smooth operation over the wide speed range.

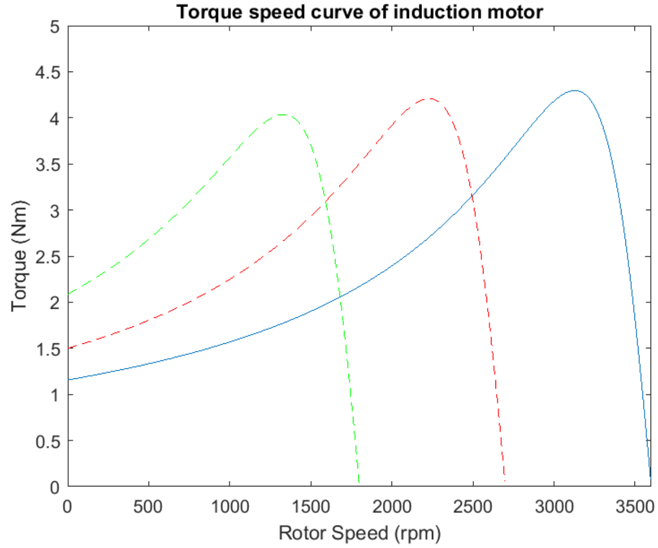

Figure 4-2: Example Torque Speed Curve of an Induction Motor (Foster, 2020)

Motor efficiency is merely the ratio of output to input power, as described in (1). Here, η, P_{out}, P_{in} and P_{loss} are efficiency, output power, input power and power loss, respectively. There are five common sources of power loss in motors: ohmic, core, friction, windage and stray losses. Ohmic losses are a result of current in conductive materials. Core losses have two components: hysteresis and eddy current losses. Core loss is dependent upon the motor operating point and quality of the electrical steel. Friction losses are due to the force required to overcome drag and are proportional to the operating speed. In an air-cooled motor, windage losses are caused by turbulence in the air acting against rotation. Stray losses include everything else. For this work, windage, friction and stray losses are neglected.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out}+P_{loss}} \tag{1}$$

An equivalent circuit shown in Figure 4-3 describes a single phase of a three-phase induction motor, including ohmic and core losses. Here, R_1 and R_2 are the stator and rotor resistances, respectively. X_1 and X_2 are the stator and rotor leakage reactances. X_m is the magnetizing reactance and R_c is the core loss resistance. Slip, s, is the difference between the actual motor speed and the synchronous speed, described in (2). Torque is described in (3) where Pg is the portion of the power converted to mechanical power, represented by losses across resistance $R_2 \frac{(1-s)}{s}$.

$$s = \frac{\omega_s - \frac{p}{2}\omega_m}{\omega_s} \tag{2}$$

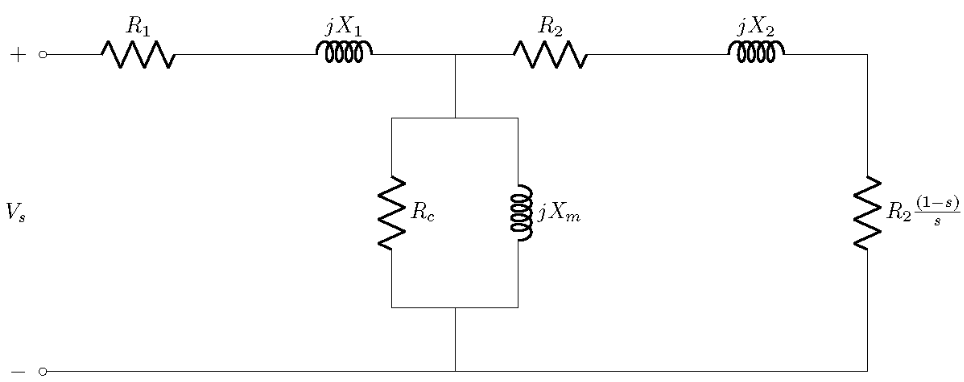

Figure 4-3: Induction Motor Equivalent Circuit of one Phase (Foster, 2020)

$$T = 3\frac{P_g}{\omega_s} \tag{3}$$

The maximum torque was determined from the tractive effort demand estimation of the locomotive. The maximum linear speed of the locomotive and the gear ratio were used to calculate the required speed range of the motor. Torque and speed requirements, together with the available DC voltage, were used to identify an AC induction motor. The parameters of this motor were used to populate an analytical model of the motor in MATLAB. The efficiency was calculated for operating points. The core loss was negligible. The resulting efficiency map, shown in Figure 4-4, was included as a look-up table in the simulator.

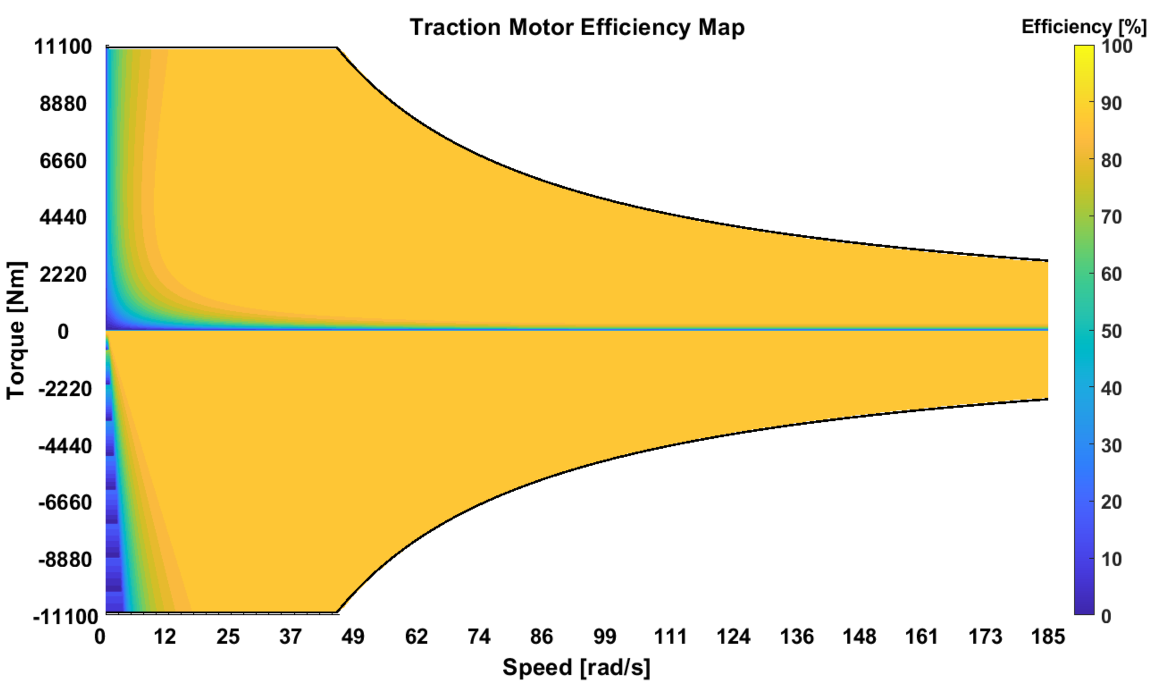

Figure 4-4: Traction Motor Efficiency Map (Foster and Madovi, 2020)

4.1.2 Simulator Validation

Some recorded data from NCDOT was available, such as the speed over the route and total diesel fuel consumption for a roundtrip. This data was used to validate the simulation results, which is illustrated with the speed profile along the route in Figure 4-5.

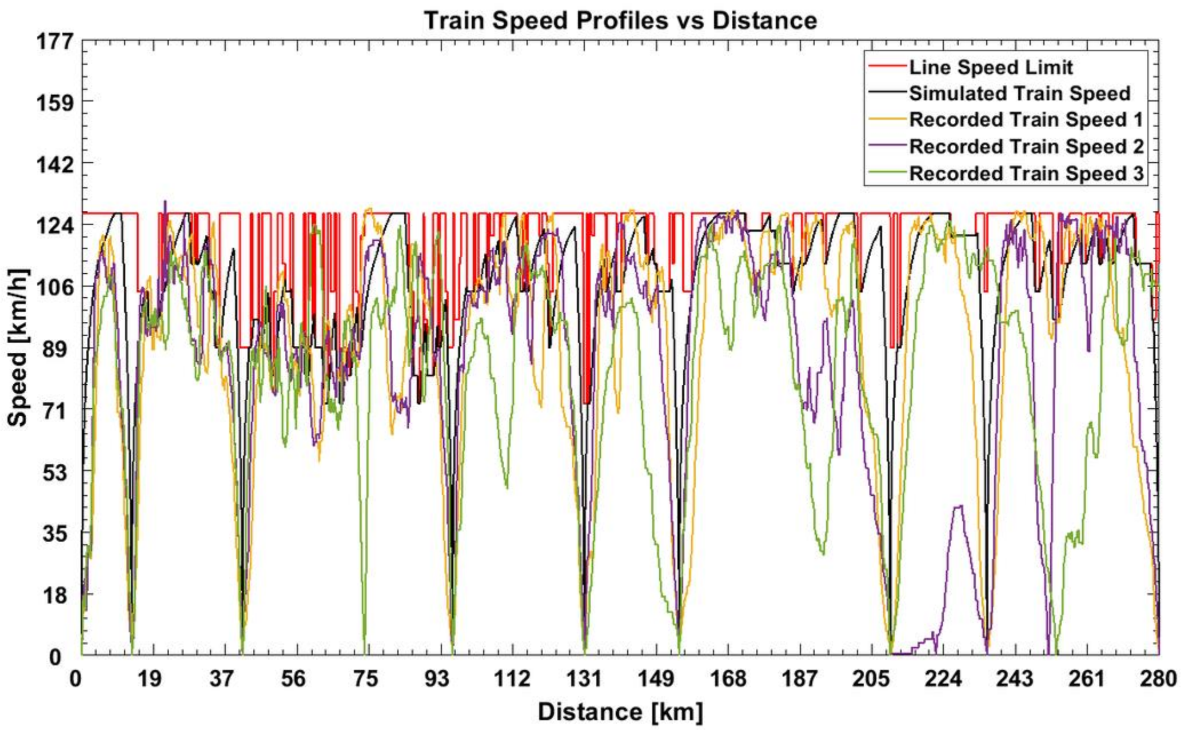

Figure 4-5: Simulated Train Speed Compared to Recorded Speed for a One-Way Journey Raleigh to Charlotte

Comparing the data in Figure 4-5, the simulated performance of a single-locomotive train and the recorded speed profiles are similar and the difference between the data is within the boundaries of variations in driving style. Further, the overall fuel consumption resulting from the simulation of approximately 640 gallons was similar to the NCDOT provided diesel fuel consumption of approximately 650 gallons. Therefore, the simulations provide a reasonable estimate of performance and energy consumption, and the impact resulting from a powertrain change can be equally estimated, enabling a comparison between the different technologies to allow feasibility assessment.

4.2 Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model

The GREET model is a tool to estimate energy consumption and emission of vehicle and fuel combinations considering the entire energy supply chain. Typically, a full fuel life cycle analysis is split into two parts: (a) pump-to-wheel and (b) well-to-pump (or tank-to-wheel and well-to-tank) and the combination is referred to as a well-to-wheels (WTW) analysis. The first part considers the powertrain technologies and duty cycles while the second part provides information about the fuel production and delivery. The GREET model was developed by Argonne National Laboratories, operated the UChicago Argonne, and is updated and maintained by that organization of behalf of the U.S. Department of Energy (Argonne National Laboratory, 2019). Figure 4-6 shows a high-level illustration of the GREET model well-to-wheel cycle. Additional information about GREET is available of the Argonne website (Argonne National Laboratory, 2019). In this study, the energy consumption of the first, PTW, part was determined with STS as describe in the section above. The GREET model was then applied to estimate emissions resulting from fuel combustion on the vehicle in the diesel cases and was utilized for the supply chain impacts, pump-to-tank (WTP), for energy and emissions impacts for diesel, hydrogen, and electricity. Some modifications to the GREET model where necessary to account for the specific NCDOT case. WTP energy is consumed, and WTP emissions are generated, during the process of resource extraction, transportation of the resource to a processing facility/powerplant, fuel refinement/conversion/power generation, and delivery or transmission of the final fuel product to the point of use or vehicle fuel tank(s). A more detailed description about the methodology utilized for this study can be found in the PhD dissertation of Raphael Isaac (Isaac, 2019).

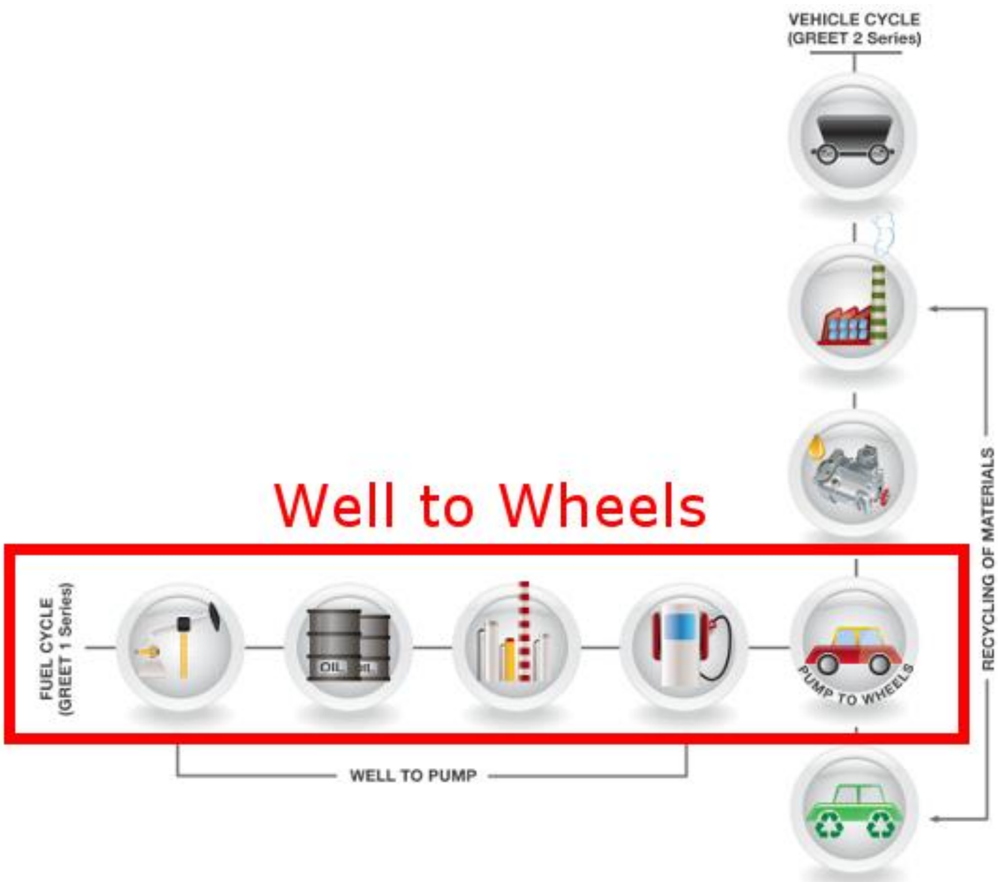

Figure 4-6: Illustration of Well-to-Wheel Cycle
(Argonne National Laboratory, 2019)

5 POWERTRAIN TECHNOLOGIES AND HYDORGEN PRODUCTION

In this section, the authors describe the various train configurations including the different simulated powertrains as well as the assessed hydrogen production pathways while providing information about the assumed electricity grid.

5.1 Powertrain Options

All modelled configurations have at least one locomotive, a lounge car which has baggage storage and booth seating for passengers, and three passenger cars. The motive power provision options vary between a single locomotive and an un-powered CCU and two locomotives, one on each end of the train. For most options four axles are powered to compare the results with the benchmark single locomotive option. In the cases of single hydrogen locomotive, the impact of hauling a separate diesel locomotive that is not operating for redundancy purposes has been included in the modelling.

For both the diesel and hydrogen options, hybrid powertrains have been considered in the simulation with batteries installed either in the same motive power vehicle as the primary power plant or in a separate converted CCU. Batteries with an LTO chemistry have been modelled but others such as NMC would be a possibility for implementation. The hybrid options have two variants, one where all the power required to charge the batteries is provided by the power plant and the second is a plugin version, where the batteries are recharged after each roundtrip. The depth-of-discharge has been limited to ~50% as a proxy for safe operation and reaching a satisfactory lifetime of the batteries.

Power output reduction version for the fuel cell hybrid options were modelled, with the objective to reduce the number of required fuel cell systems to decrease capital cost and provide additional volume for hydrogen storage. The hydrogen options also include a version where the powertrain is split between two locomotives or between a locomotive and converted CCU providing additional volume to install equipment.

Fuel savings for any particular journey can be realized through efficient driving. Many railroads deployed driver advisory systems that provide engineers with information to balance fuel usage with schedule requirements. This has not been taken into account in this study as the emphasis was on the comparison between different powertrains.

In a later phase of the project, optimization of component sizes including energy efficient driving could be undertaken to find the most appropriate combination for NCDOT, however this was beyond the scope of this comparative study, which aimed to determine technical feasibility and provide a comparative assessment between many potential powertrain options.

Results for each modelled option are provided in the Appendix along with an illustration of the train configuration. Examples of train configurations are shown in Figure 5-1. A summary of the train characteristics is provided in Table 5-1.

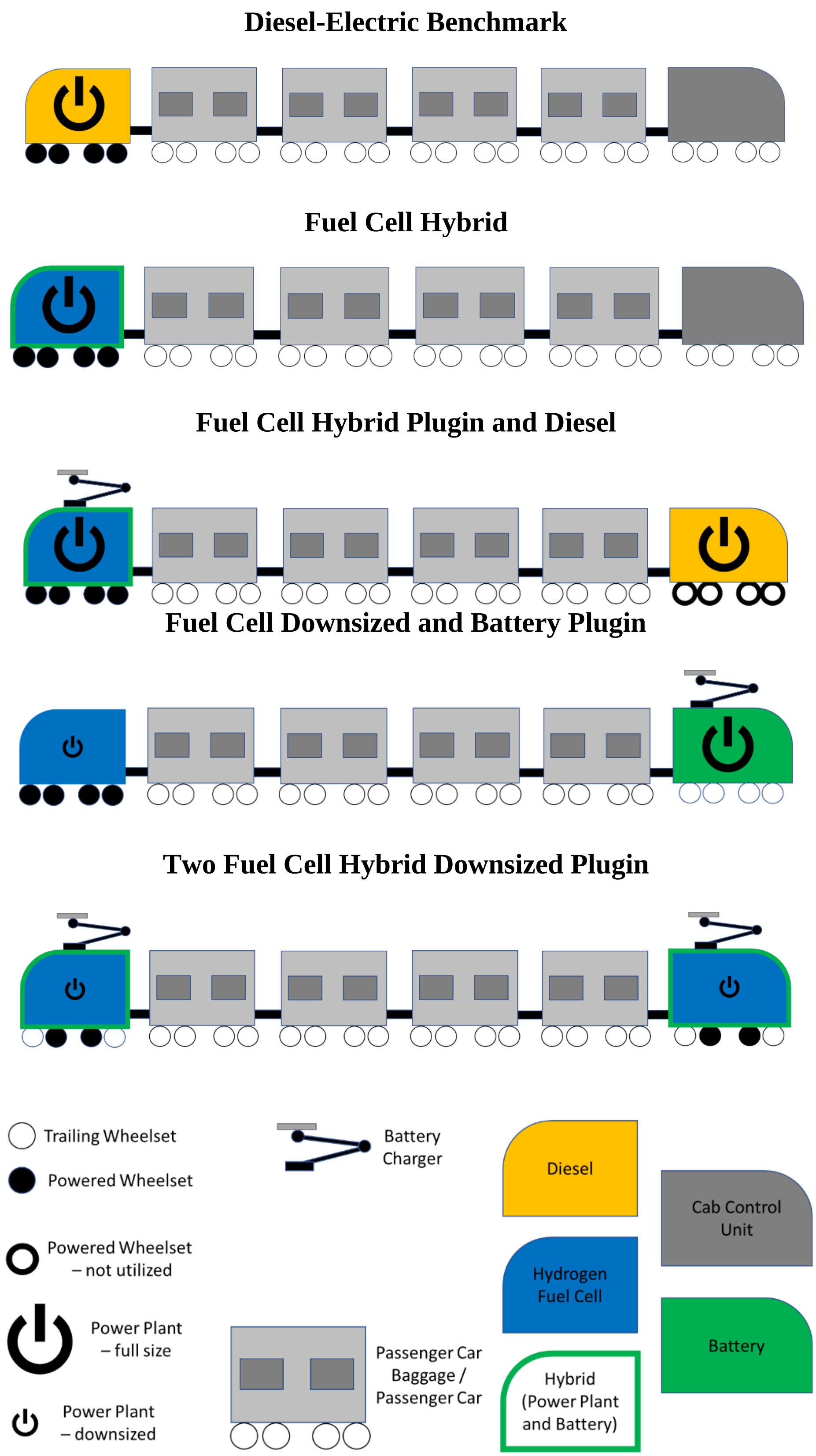

Figure 5-1: Illustration of Train Configuration Examples

Table 5-1: General Characteristics of the Modelled Trains

	Single Locomotive	Single Locomotive Hybrid	Two Locomotives	One Locomotive Hauling a Diesel
Weight in t	472	517	613	656
Resistance to Motion Parameters				
A in kN	5.787	6.042	7.103	7.346
B in kN/(m/s)	0.139	0.152	0.180	0.193
C in kN/(m/s)^2	0.03	0.03	0.03	0.03
Power at Wheels in kW	2000			
Maximum Speed in mph (km/h)	79 (127)			
Maximum Acceleration and braking in m/s^2	0.6			
Battery Capacity in kWh (if a hybrid)	-	2,700		

Resistance to motion parameters where not available and have been estimated with the Canadian National formula (AREMA, 2018) and PRIIA specifications. The aerodynamic component in the resistance to motion parameters is the same for all configurations as the authors assumed the same general aerodynamic shape as the current train. A hybrid locomotive configuration is heavier than a conventional with an impact on the resistance to motion parameters, which can also be observed for the other two configurations.

All two locomotive options are evaluated with the premise that four traction motors are installed or operated to provide comparative results to the diesel benchmark train. Additional motors could be installed, which would have an impact on acceleration, speed, journey time, and energy consumption. This impact has been evaluated for the option with two locomotives and a hydrogen downsized hybrid plugin powertrain to illustrate the effect on energy consumption.

5.2 Hydrogen Production Alternatives

Hydrogen production methods were described in the Introduction to Hydrogen Rail Technology section. A summary of the considered options in this study is provided in Table 5-2.

Table 5-2: Hydrogen Production and Delivery Options

	Onsite Production	Central Production and Delivery as a Gas	Central Production and Delivery as a Liquid
SMR	Yes	Yes	Yes
Electrolysis using grid electricity	Yes	Yes	Yes
Electrolysis using 100% renewable electricity	Yes	Yes	Yes
Biomass	No	No	Yes

The U.S. electric grid is divided into several regions to ensure reliability and North Carolina is part of SERC, see Figure 5-2. In these regions, the share of the various fuel source for electricity generation vary, and the production mix used for the well-to-pump assessment is illustrated in Figure 5-3.

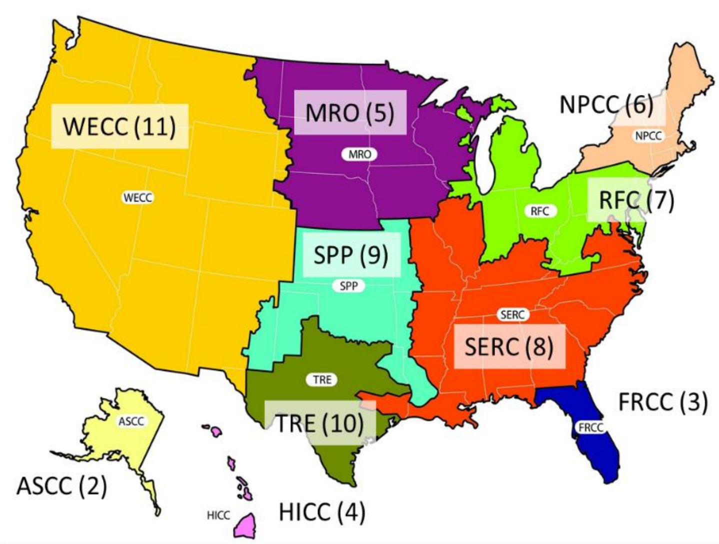

Figure 5-2: Regional Reliability Corporations for the Electric Grid in the U.S. (UChicago Argonne & Argonne National Laboratory, 2019)

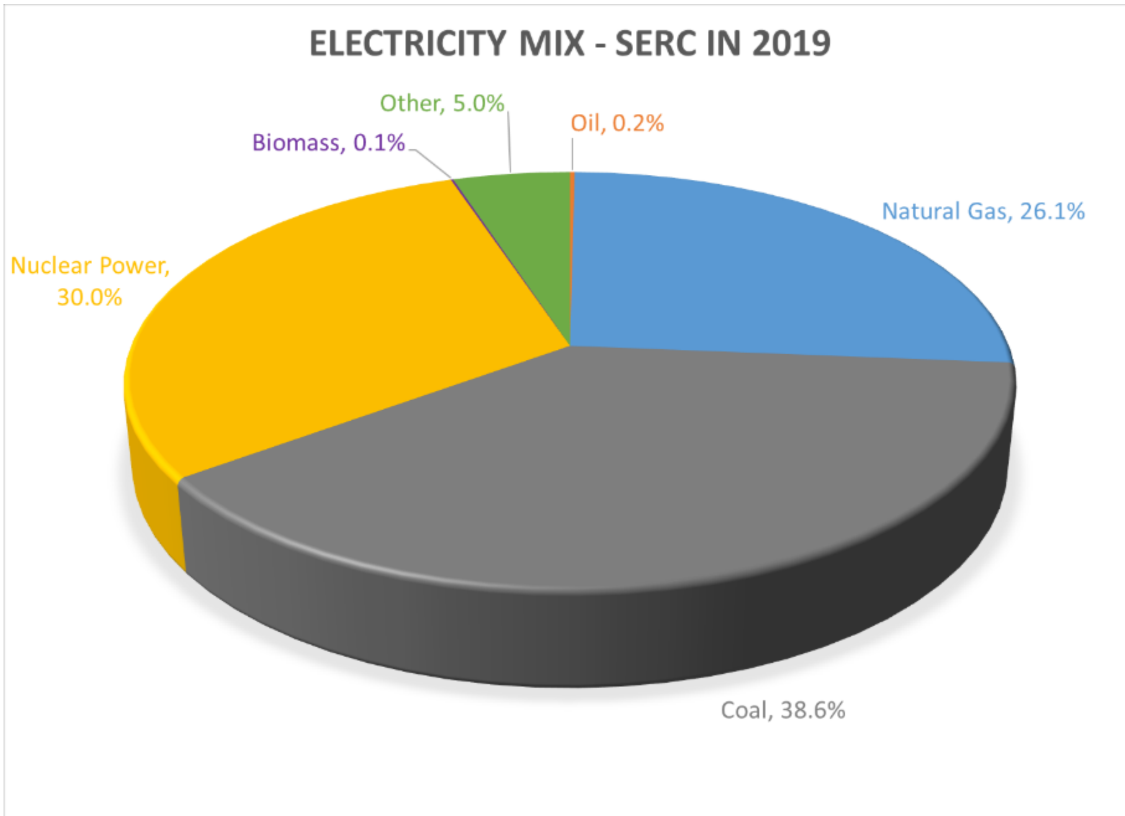

Figure 5-3: SERC Electricity Production Mix in 2019 (UChicago Argonne & Argonne National Laboratory, 2019)

Electricity production in the SERC region, see Figure 5-3, relies significantly on fossil fuels with coal and natural gas contributing almost a third. There is also a substantial contribution from nuclear power. North Carolina's five nuclear plants make this power source a viable GHG-free option. The high fossil fuel contribution, particularly coal, has an impact on WTW emissions, which becomes particularly clear for the hydrogen electrolysis options, regardless of onsite production or delivery. However, it is expected that a societal-level shift from coal to other sources, such as natural gas and renewables will occur, having a positive impact on emissions. This shift is driven by price differences between the power sources and societal expectations to reduce emissions.

There are several hydro power plants in North Carolina, in relatively close proximity to the Piedmont corridor. One to the operators, Ontario Power Generation, expressed and interest to produce renewable hydrogen at these facilities. A further hydrogen production method uses biomass as a feedstock and initial conversations of NCDOT with a potential provider have started. A 110-mile delivery distance was estimated for the biomass and renewable hydrogen options, based on the possible production locations.

Currently, there is no large-scale merchant hydrogen production in North Carolina, but significant production potential exists due to current industries in the state (see section 3.2 above). Currently, delivery would have to occur from out-of-state for the SMR options and the default distance for delivery as a liquid in GREET of 800 miles was used in the assessment (UChicago Argonne &

Argonne National Laboratory, 2019) and the same distance applied for transportation as a gas. This delivery distance would enable sourcing from neighboring states that have merchant hydrogen production.

6 SIMULATION RESULTS AND DISCUSSION

Comparative results from the assessment are provided in this section while more details about any single train configuration are provided in the appendix.

6.1 High-level Technical Feasibility

Technical feasibility was primarily dependent on the ability of the powertrain to provide the needed power and the space and weight constraints of the CCU. Detailed energy results are presented in the Appendix. Simulations were conducted as a trip from Raleigh to Charlotte and back.

The most challenging configuration is where the entire powertrain has to be installed in a single locomotive as all the weight of the components has to be carried by the four wheelsets and the components have to be installed in the volume available on one vehicle.

The options with “Two Locomotives” include configurations where (a) a diesel locomotive is hauled for backup, (b) the powertrain is distributed across two vehicles, one locomotive and one converted CCU or two converted CCUs. In both cases under option (b), the total of eight traction motors could be operated at a maximum of half their possible power, thereby being equivalent to the characteristics of four traction motors. The last modelled options (c) have two locomotives or converted CCUs where all eight traction motors operate at their full capacity.

Hauling an additional locomotive for backup has a limited impact on energy consumption as can be seen in Figure 6-6. A diesel hybrid in a single vehicle is not feasible due to the volume and weight constraints. A battery would require a substantial volume and add a significant amount of weight, neither of which can likely be accommodated. Therefore, a two locomotive solution would have to be implemented. Nevertheless, single locomotive diesel hybrid options are included in the energy and emission analysis for comparative purposes. High-level space and mass feasibility for the fuel cell options is shown in Table 6-1.

Table 6-1: Feasibility of Single Locomotive Fuel Cell Options

Configuration	Powertrain Volume in m^3			Powertrain Weight in t		
	Two Walkways	One Walkway	Feasible	Same as Locomotive	Higher Limit	Feasible
Available in CCU	41	52.5	-	41	48	-
Fuel Cell	34		Yes	15		Yes
Fuel Cell Hybrid	49		Yes	47		Yes
Fuel Cell Hybrid Plugin	45		Yes	46		Yes
Fuel Cell Hybrid Downsized	48		Yes	46		Yes
Fuel Cell Hybrid Downsized Plugin	44		Yes	44		Yes

As can be seen from Table 6-1, the fuel cell option is feasible while the hybrid options are possible if one of the walkways were eliminated, or the volume of the CCU otherwise expanded, such as raising the roof line. The impact of the battery weight can be seen in the hybrid options and all would be heavier than the current locomotive. The same weight as a current locomotive might be achievable if the mass of non-powertrain components of the converted CCU could be reduced. Sufficient energy (hydrogen or batteries or both) could be carried onboard the converted CCU for one roundtrip before refueling and recharging would be necessary. A two locomotive option would likely allow refueling after two roundtrips as more space and weight would be available on the train. Battery size could be reduced if charging were possible after a one-way journey, reducing implementation complexity subject to operating requirements.

The tractive effort, resistance to motion, and resulting force for acceleration is illustrated in Figure 6-1 and it can be seen that the maximum speed the train could reach is approximately 83mph (~133 km/h).

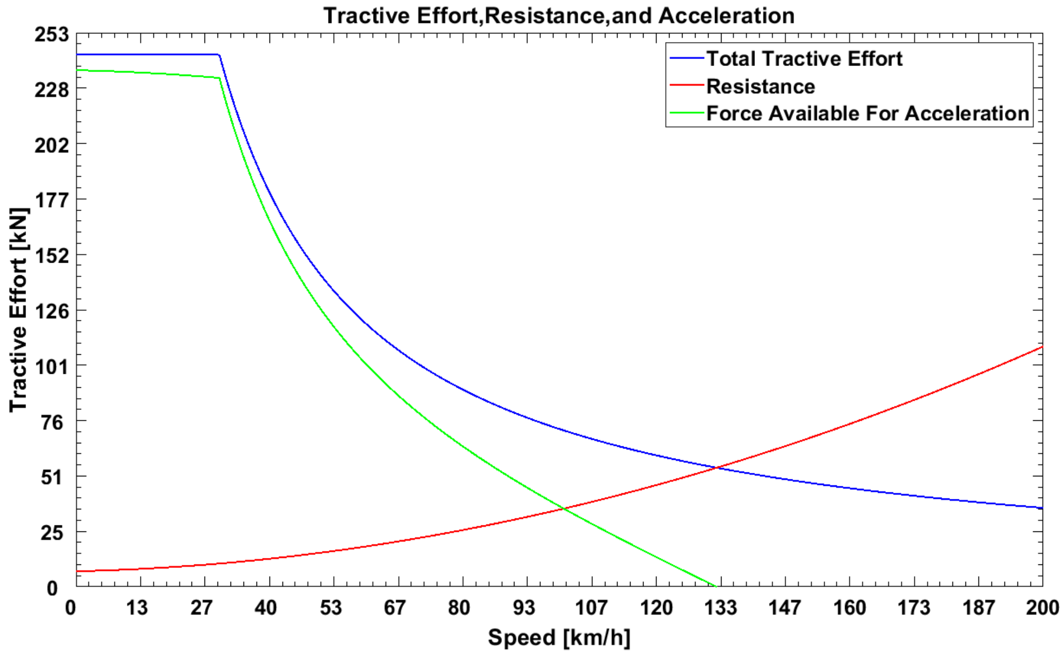

Figure 6-1: Tractive Effort, Resistance, and Acceleration Force for a Single Locomotive Configuration

Figure 6-2 illustrates the impact of adding four traction motors operating at full capability. It can be seen that the maximum tractive effort doubled and that the train could now reach approximately 108 mph (173 km/h). The additional tractive effort combined with the relatively small impact on resistance of the second locomotive (or converted CCU) leads to maximum values for both acceleration and braking to 0.9 m/s^2, which has a positive impact on journey time but with an energy penalty. Additionally, there is a positive impact on regenerative braking where the full-power eight-motor option enables more energy capture, as illustrated in the Appendix.

The speed profile compared to the line speed limit for a single locomotive train is depicted in Figure 6-3 with the corresponding running diagram illustrated in Figure 6-4. The train reaches the line speed limit frequently and acceleration and braking phases are shown, but most are difficult to identify. Dwell time at station stops can be seen in the running diagram, Figure 6-4, by the flat section. The 50 min dwell in Charlotte is easily visible.

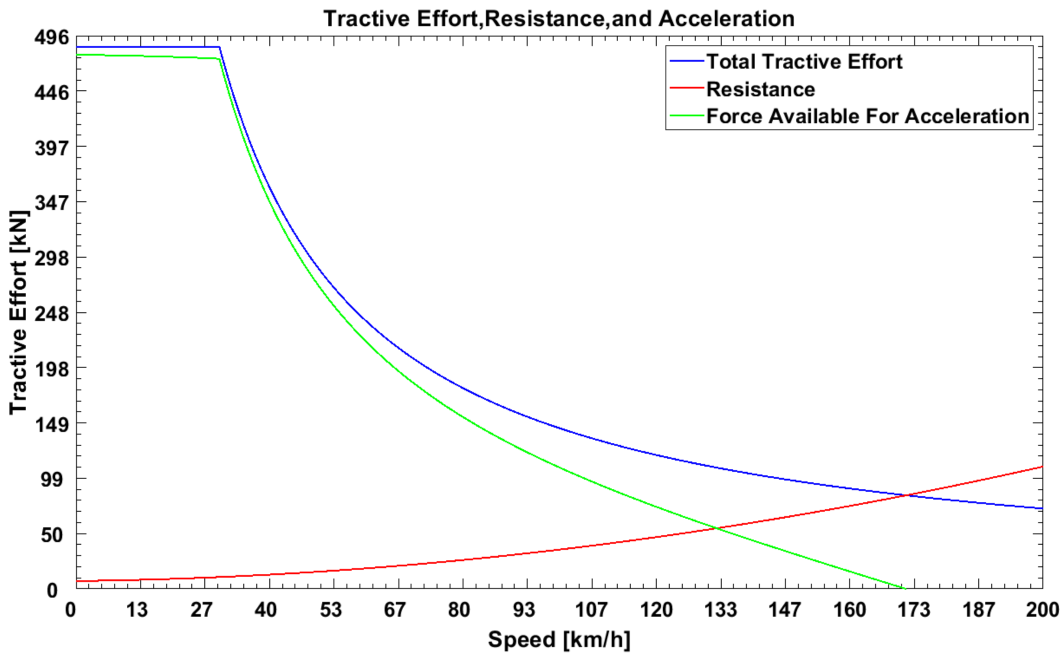

Figure 6-2: Tractive Effort, Resistance, and Acceleration Force for a Two Locomotive Configuration with Eight Traction Motors

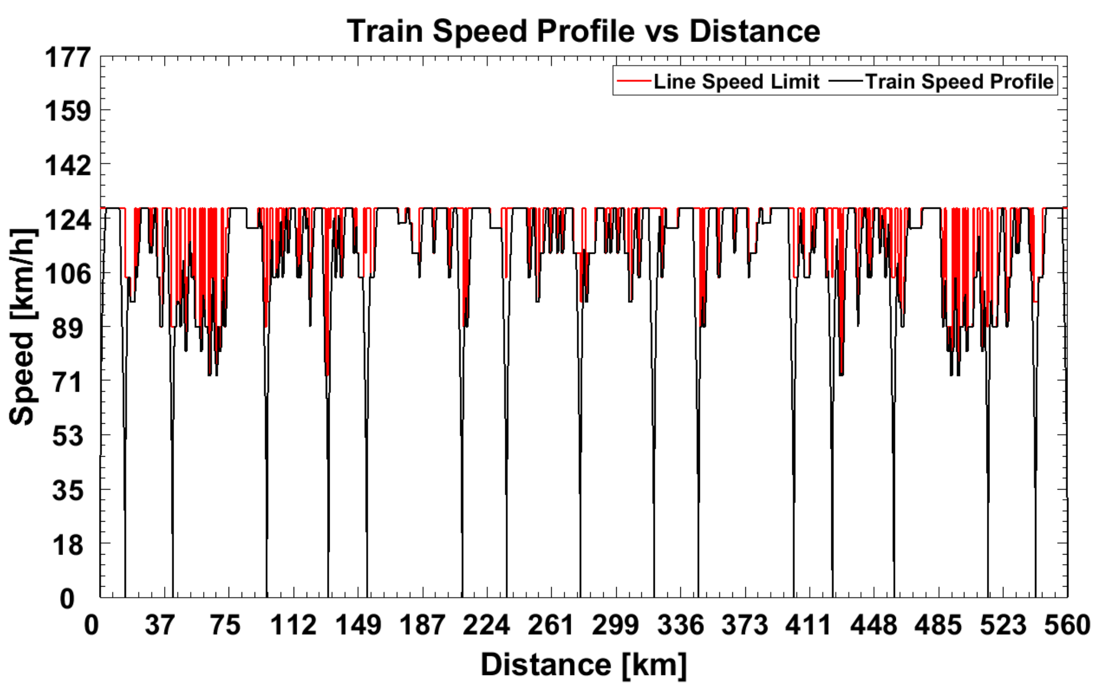

Figure 6-3: Simulated Speed Profile of a Single Locomotive Option over a Roundtrip

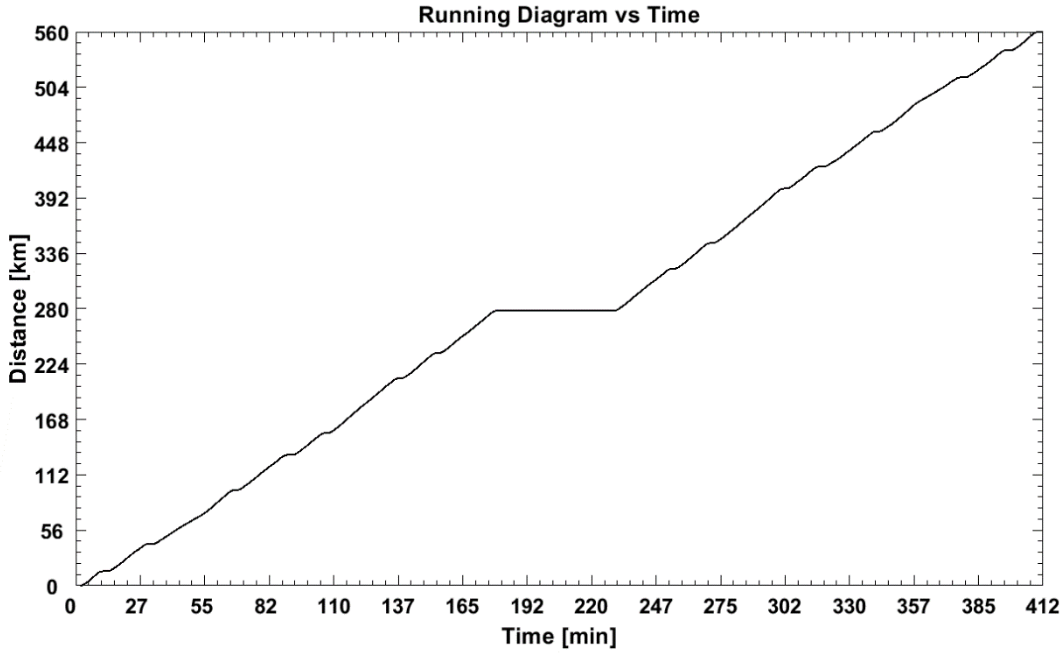

Figure 6-4: Simulated Running Diagram of a Single Locomotive Option over a Roundtrip

The simulated one-way journey time from Raleigh to Charlotte, for a configuration with a single locomotive and a CCU, is three hours and three minutes, while the addition of a locomotive (e.g. hauling a diesel locomotive) would extend the journey by five minutes. If both locomotives (or converted CCUs) were powered with eight traction motors operating at full capability, a journey time of two hours and fifty-three minutes would be achieved, giving a reduction of 10 minutes compared to the single locomotive options (or eight traction motors operating at half capability). To achieve that reduction, additional energy is required, illustrated in Figure 6-6.

6.2 Pump-to-Wheel

Energy consumption and emission resulting from operation are presented in this section as a comparison to the diesel-electric benchmark (single diesel locomotive with CCU). Detailed results for any individual option are presented in the Appendix.

The hydrogen fuel cell options would not have any harmful emissions as part of operations and, therefore, offer a 100% reduction. The impact on emissions from the diesel hybrid options is illustrated in Figure 6-5. Emissions from electricity production to charge the plugin options are considered as part of the WTP analysis. A discussion of the diesel options is provided in the “Well-to-Wheel Energy and Emission Impact” subsection.

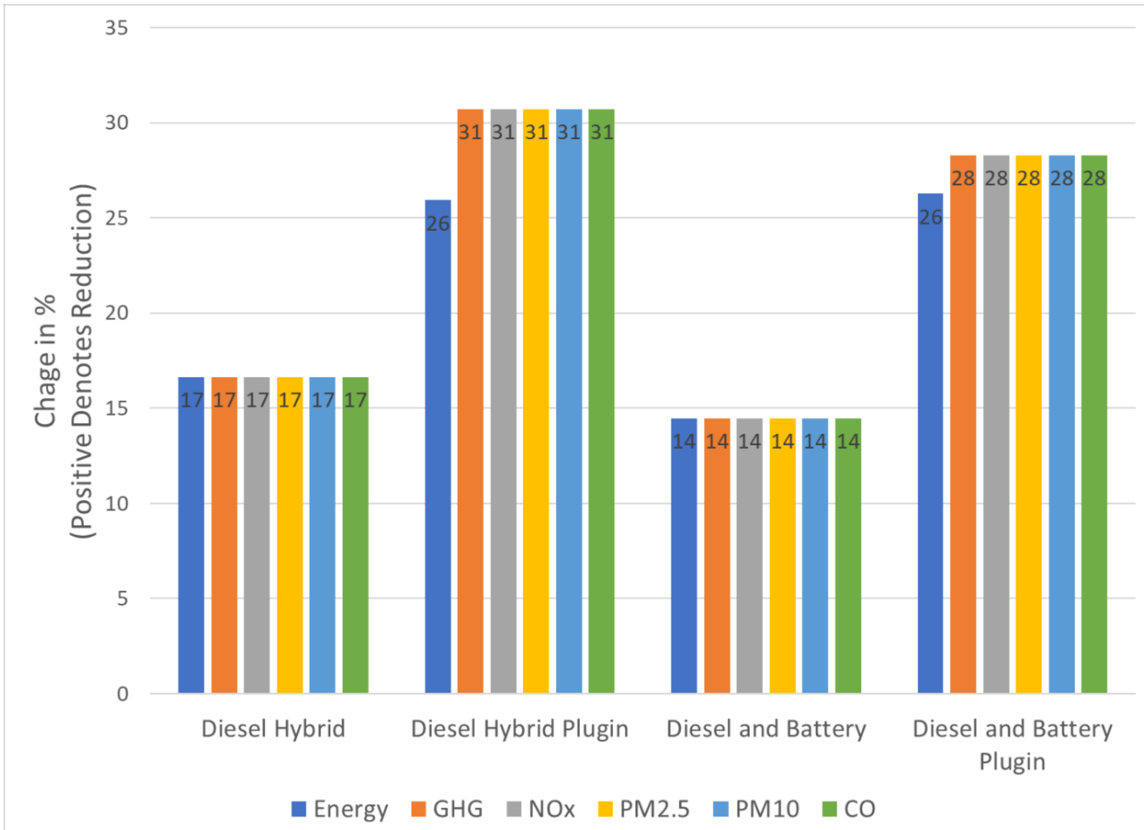

Figure 6-5: Impact of Diesel Hybrid Options on Energy and Emissions from Operation

In Figure 6-6, the energy reduction resulting from operations compared to the diesel-electric benchmark is illustrated. All options offer reduction potential. It should be noted that while the single locomotive options offer the highest reduction, these are the most difficult to implement due to weight and space limitations, and are not feasible for the diesel hybrid options and are shown for illustrative purposes only. Significant reductions are possible with several configurations, in the 50% range, which could have a positive impact on operating cost as long as hydrogen is available at a competitive price.

Splitting the powertrain between two different vehicles has no major impact on energy and subsequent emissions while hauling an additional locomotive, such as a diesel, has a minor impact compared to a CCU option. This is expected as addition of a comparatively small mass does not impact railway energy consumption significantly due to physical characteristics such as the firm interface between the wheels and the rail. Both primary fuel consumption reduction, i.e., diesel or hydrogen, and impact of energy required for battery charging are illustrated. The highest energy reduction potential was achieved with a fuel cell hybrid plugin option, as expected because the FCS can operate in its most energy efficient region while batteries can be charged from the grid. Reducing the number of FCS and resulting power output has minor impact on energy consumption but would enable capital cost reduction and easier powertrain implementation.

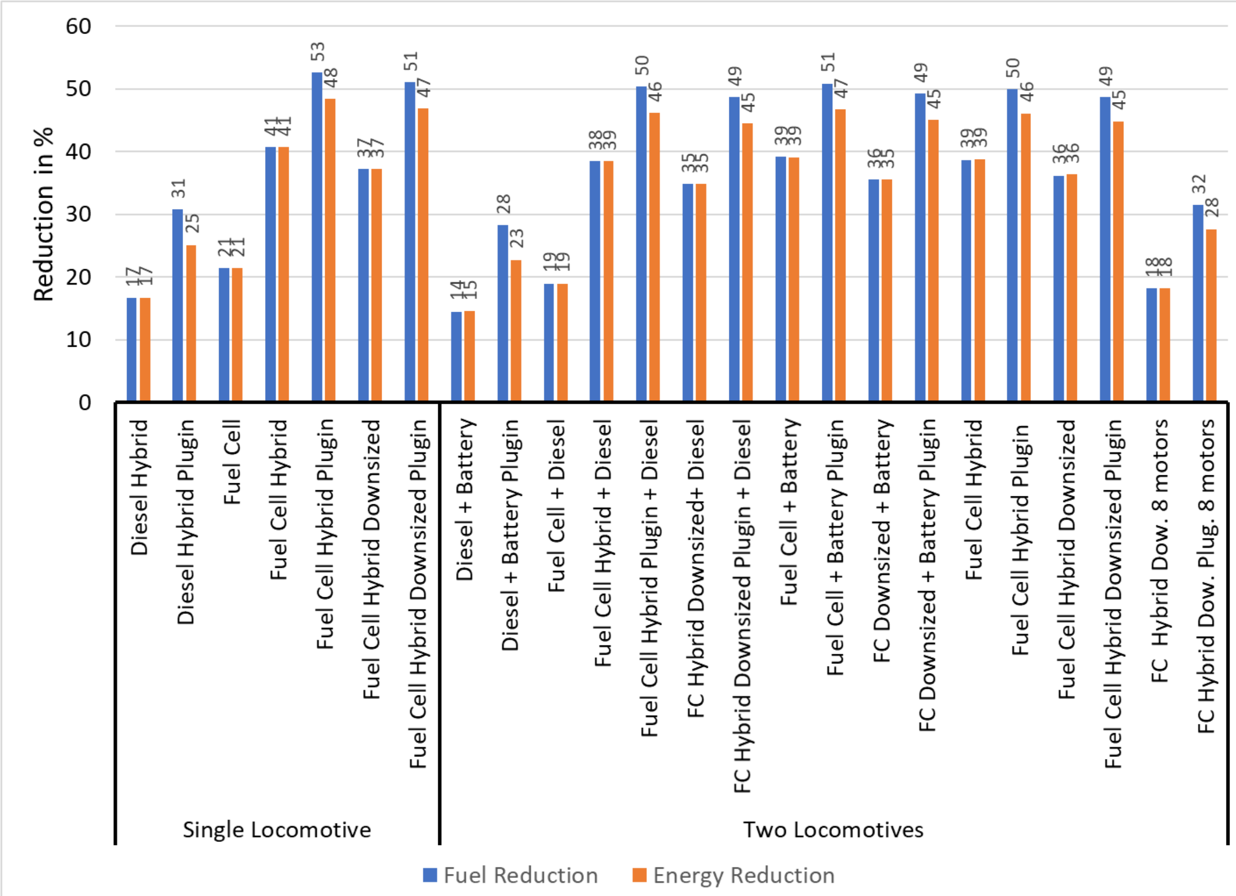

Figure 6-6: Energy Reduction Compared to the Diesel Benchmark

A further observation is the relatively significant impact on energy reduction potential if both locomotives would have powered wheelsets (or all eight traction motors would operate at full power if implemented). A trade-off would have to be made between a faster journey time and impact of energy consumption. Given the current line speeds, the additional capabilities of eight traction motors per train offer limited journey time improvements. Therefore, if a CCU would be converted to a locomotive, careful consideration should be given before all wheelsets are powered. A further possibility would be to limit the power during traction phases but utilize the capabilities of all motors for braking, which would likely lead to energy improvements and smaller journey time reduction.

The two-locomotive option with four powered wheelset (or eight operating at half-capability) and a fuel cell downsized hybrid plugin powertrain appears to be the most feasible option. Reasons for this assessment are the weight and volume constraints of a single locomotive and the high potential to refuel after two roundtrips compared to one; the high energy reduction potential; and the capital cost decrease opportunity in relation to a full-power FCS option. A motive power vehicle of this two-locomotive option would have approximately the following major components: 800 kW FCS, a 1350 kWh battery, 200 kg of hydrogen storage, and two traction motors (or four traction motors operating at half-power). Doubling of the hydrogen storage capacity would likely enable refueling after two roundtrips instead of one. Reduction of the battery size might additionally be possible if recharging could occur after a one-way journey, impacting ease of on-board equipment implementation and capital cost. Addition of two traction motors to a total of four would be possible enabling more regenerative braking but traction power should be limited to not negate that impact; a trade-off with capital expenditure would be necessary.

6.3 Well-to-Wheel Energy and Emission Impact

In this section a comparison of the WTW impact respective to the benchmark diesel-electric is presented. Well-to-pump emissions are shown in the Appendix together with detailed results for each configuration. Figures have been produced for all diesel-powered options, the single locomotive fuel cell options, and for the two locomotive fuel cell hybrid downsized plugin version to illustrate the impact.

Diesel hybrid options offer noteworthy reductions in WTW energy and emissions, as illustrated in Figure 6-7. Only the two locomotive options are feasible, and the plugin version performs better than the diesel and battery locomotive option. A large proportion of the emissions occur during operation due to diesel combustion on the locomotive and zero-emissions cannot be achieved, nor is an emission-free energy supply chain possible with current technology for the diesel options. Conversion of a CCU to hold a battery thereby forming a diesel hybrid train consist would be a suitable option to reduce air pollutants and energy consumption.

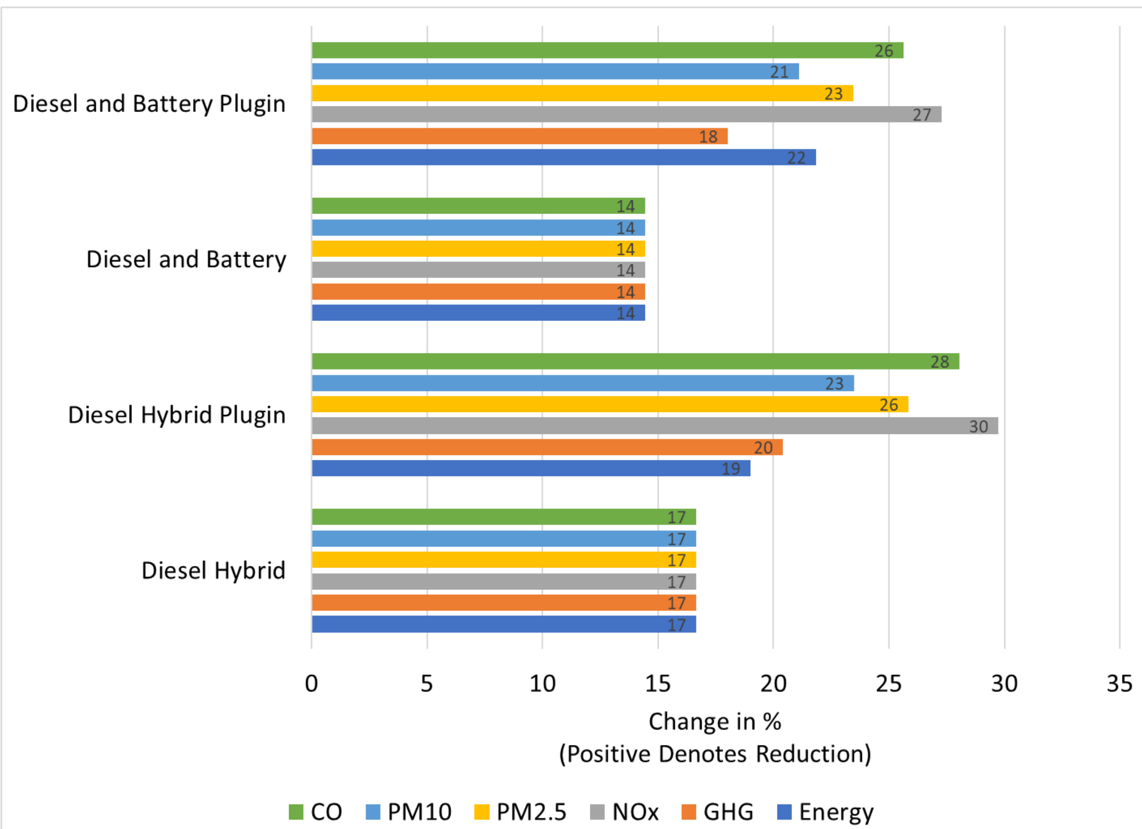

Figure 6-7: Diesel Hybrid Options WTW Energy and Emission Impact

The next graphs show the impact of single locomotive hydrogen fuel cell options on a WTW basis. Figure 6-8 illustrates the energy impact, followed by Figure 6-9 showing GHG emissions, impact on criteria pollutants are presented in Figure 6-10 to Figure 6-13. All emissions would occur as part of the energy supply chain as hydrogen options are zero-emission during operation.

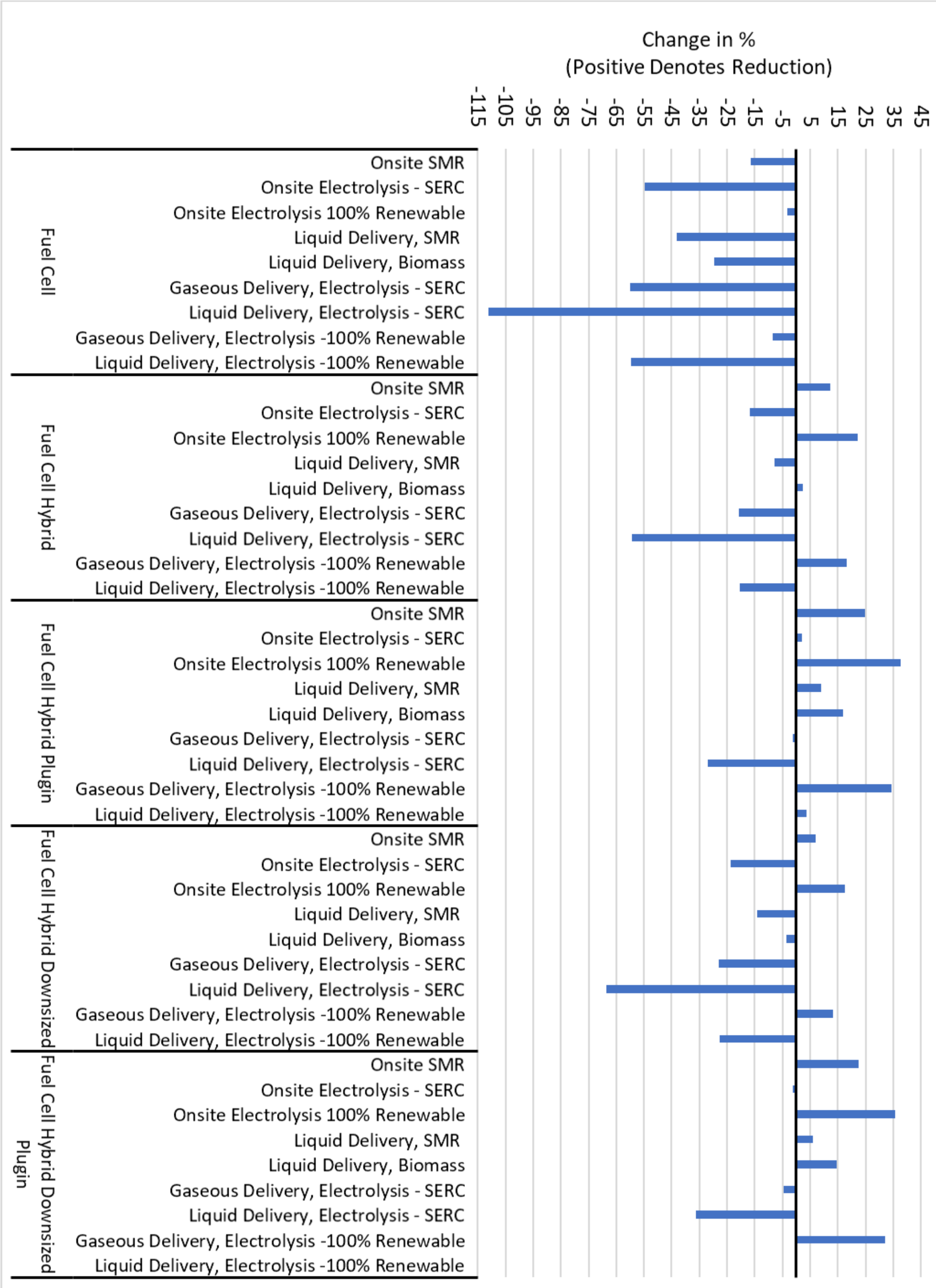

Figure 6-8: Single Locomotive Fuel Cell Options WTW Energy

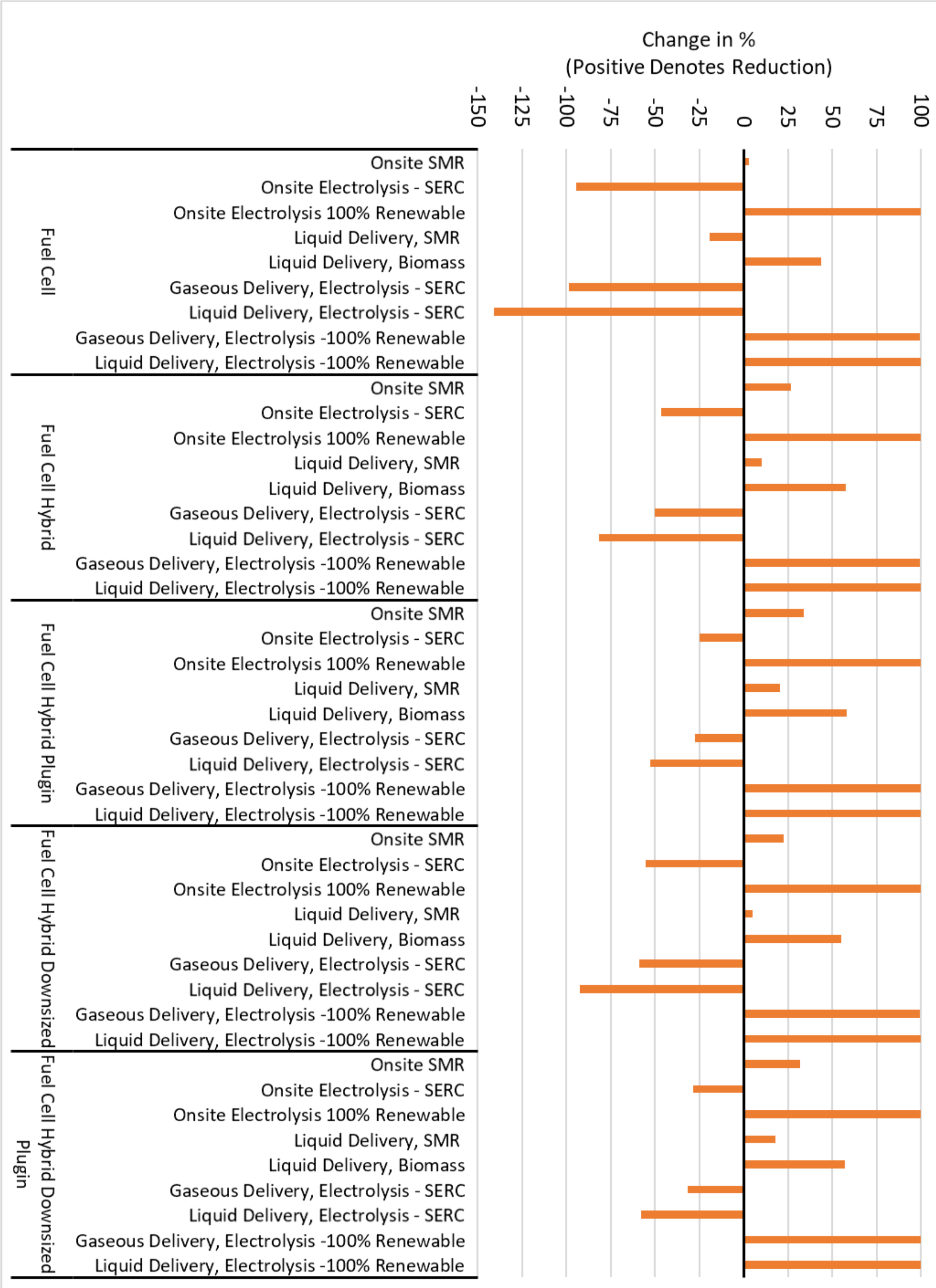

Figure 6-9: Single Locomotive Fuel Cell Options WTW GHG

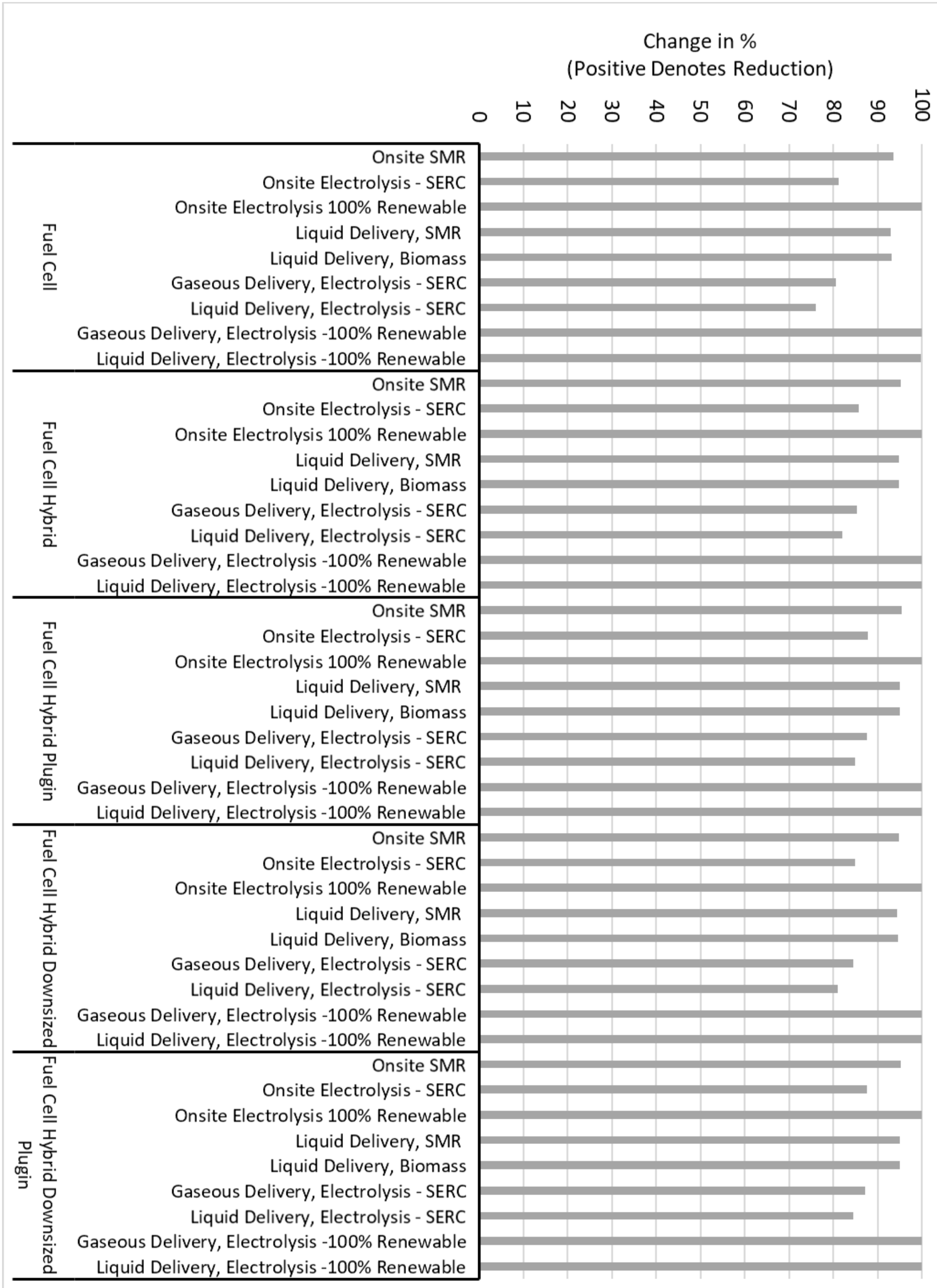

Figure 6-10:Single Locomotive Fuel Cell Options WTW NOx

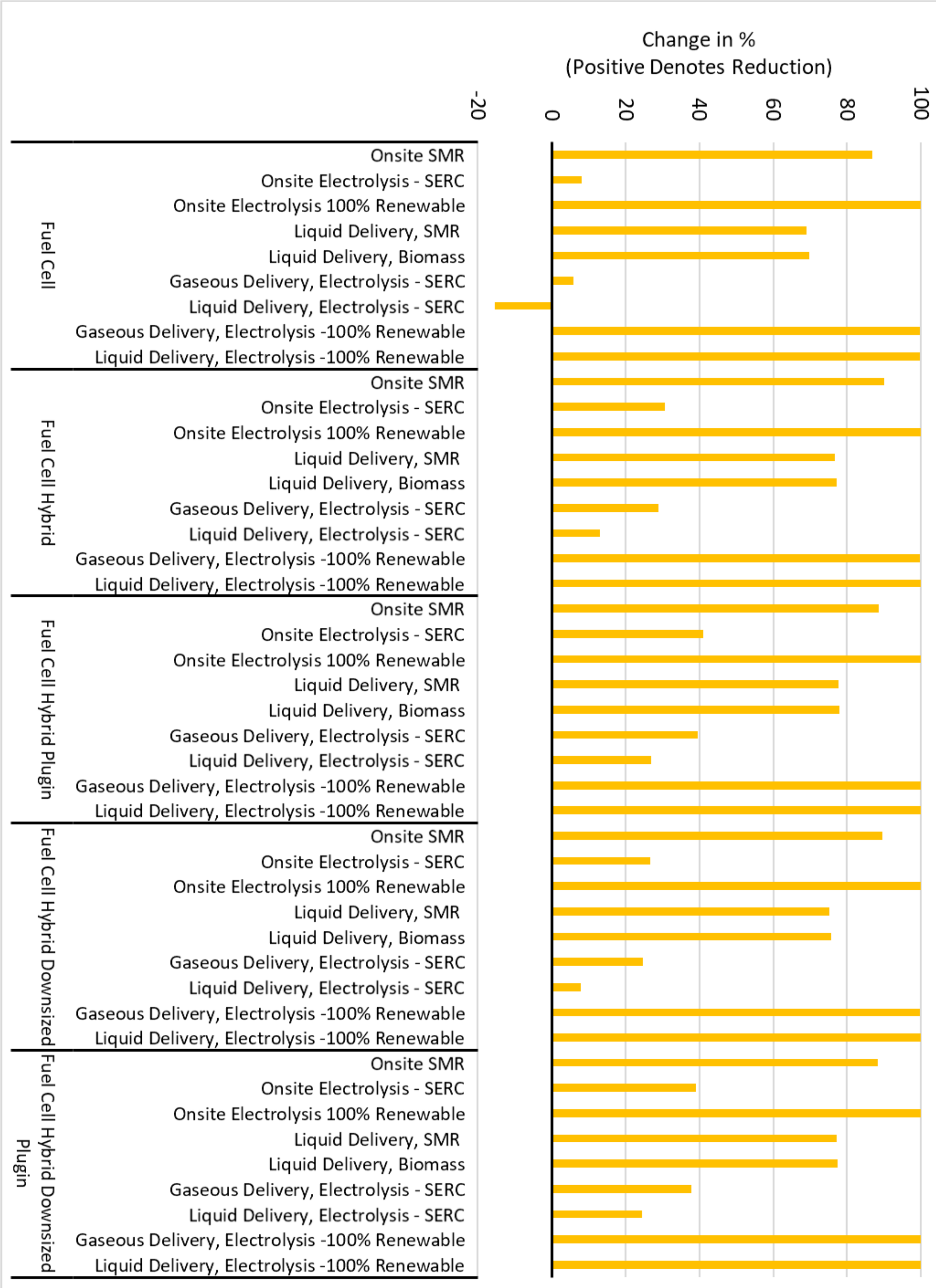

Figure 6-11: Single Locomotive Fuel Cell Options WTW PM2.5

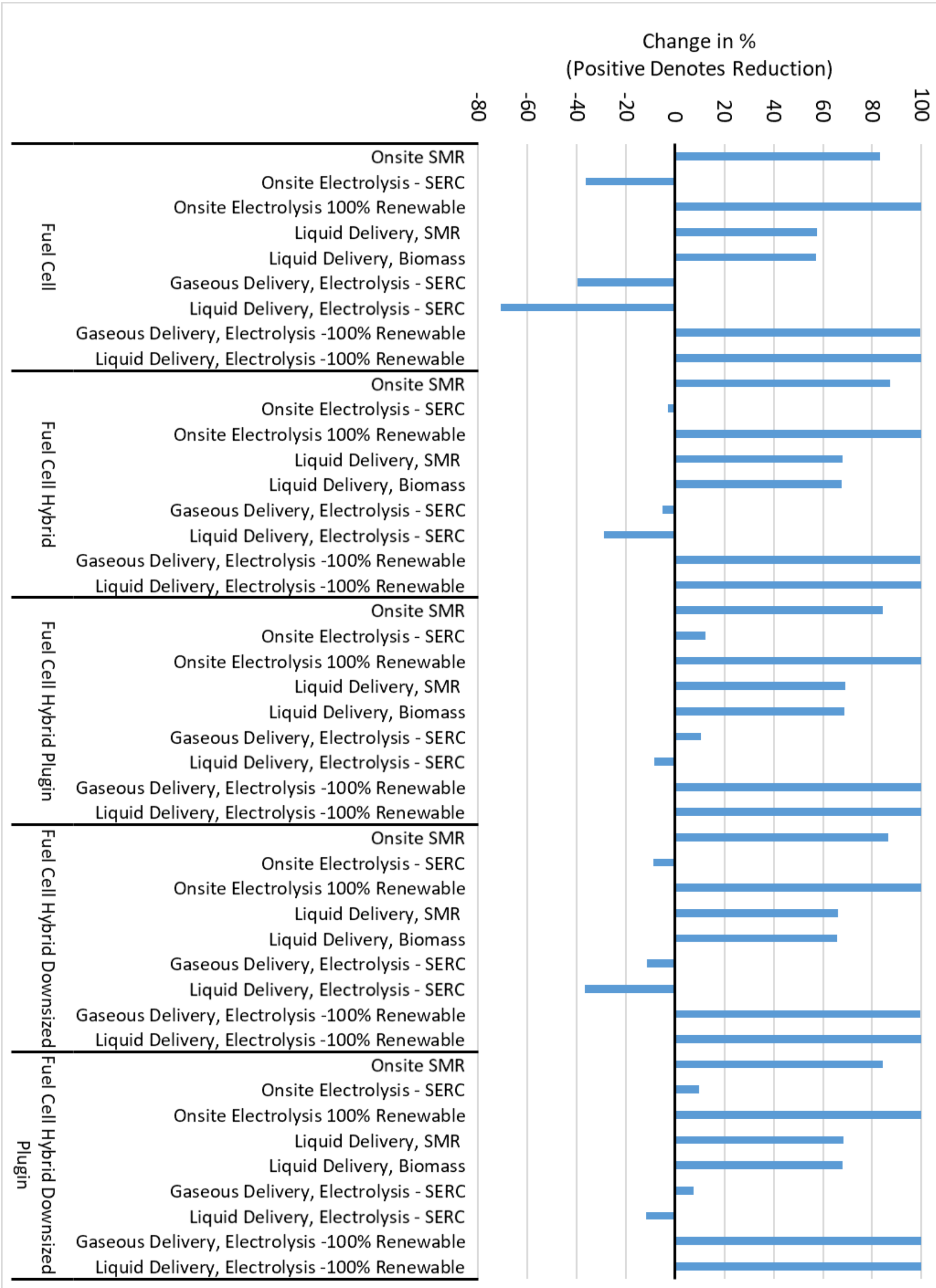

Figure 6-12: Single Locomotive Fuel Cell Options WTW PM10

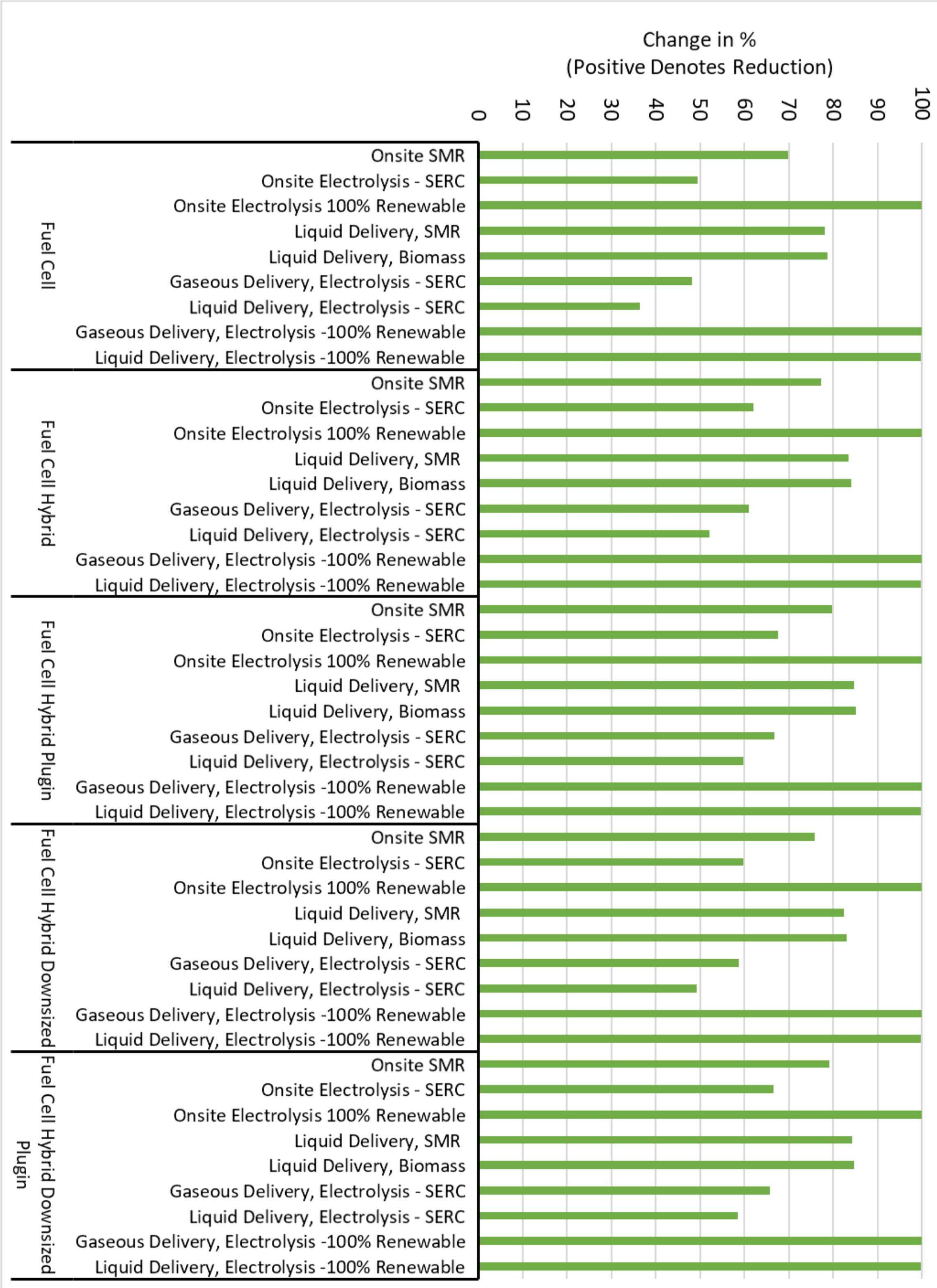

Figure 6-13: Single Locomotive Fuel Cell Options WTW CO

All options and supply chain pathways lead to a reduction in NOx and CO while the impact on energy, GHG, and PM are dependent on the pathway and increases are possible. PM reduction is important, especially at the point of use, as the EPA uses this pollutant to calculate large-scale health benefits (Harris, 2020). Thus, an option with a positive PM reduction is desirable. The fuel cell hybrid plugin offers the highest reductions as expected from the operational results, while the fuel cell option offers the lowest reductions of all considered hydrogen configurations.

The high contribution of fossil fuels in the electricity mix directly affects GHG and PM and has an impact on overall energy consumption. This production option should be avoided unless the electricity mix will become substantially less carbon intensive.

The best emission and energy reductions can be achieved with electrolysis and 100% renewable electricity mix as expected. There is a small difference between onsite production and delivery in the renewable electrolysis options but transportation of hydrogen has a minimal impact over the short distances considered; delivery as a gas offers higher reductions than as a liquid due to the high energy penalty for liquification. From a practical implementation perspective, the delivery by truck option might be especially attractive during the demonstration and early implementation phases when only a few hydrail vehicles are in use. NCDOT would not need to consider building an on-site hydrogen production plant until a later phase when comfortable with hydrail technology.

Hydrogen production from SMR offers substantial reductions in criteria pollutants and the onsite option offers the highest. The biomass option is also attractive, with reductions typically between SMR and electrolysis with 100% renewable electricity. Results for the two locomotive options follow a similar pattern as WTW emissions are dependent on energy consumption resulting from operations. The options of a single locomotive hauling a diesel have lower energy and emission performance while the two locomotive hydrogen options with four traction motors (or eight traction motors operating at half their capability) have similar but slightly less energy improvement, both illustrated in Figure 6-6, with the corresponding impact on the supply chain. An example of the WTW impact of a two locomotive option (either four traction motors, or eight traction motors operating at half their capability) is depicted in Figure 6-14.

The preferred train configuration and powertrain from the operational and implementation perspective as described in the High-level Technical Feasibility and Pump-to-Wheel section was the two locomotive fuel cell hybrid downsized plugin. In Figure 6-14, the results for that configuration are illustrated.

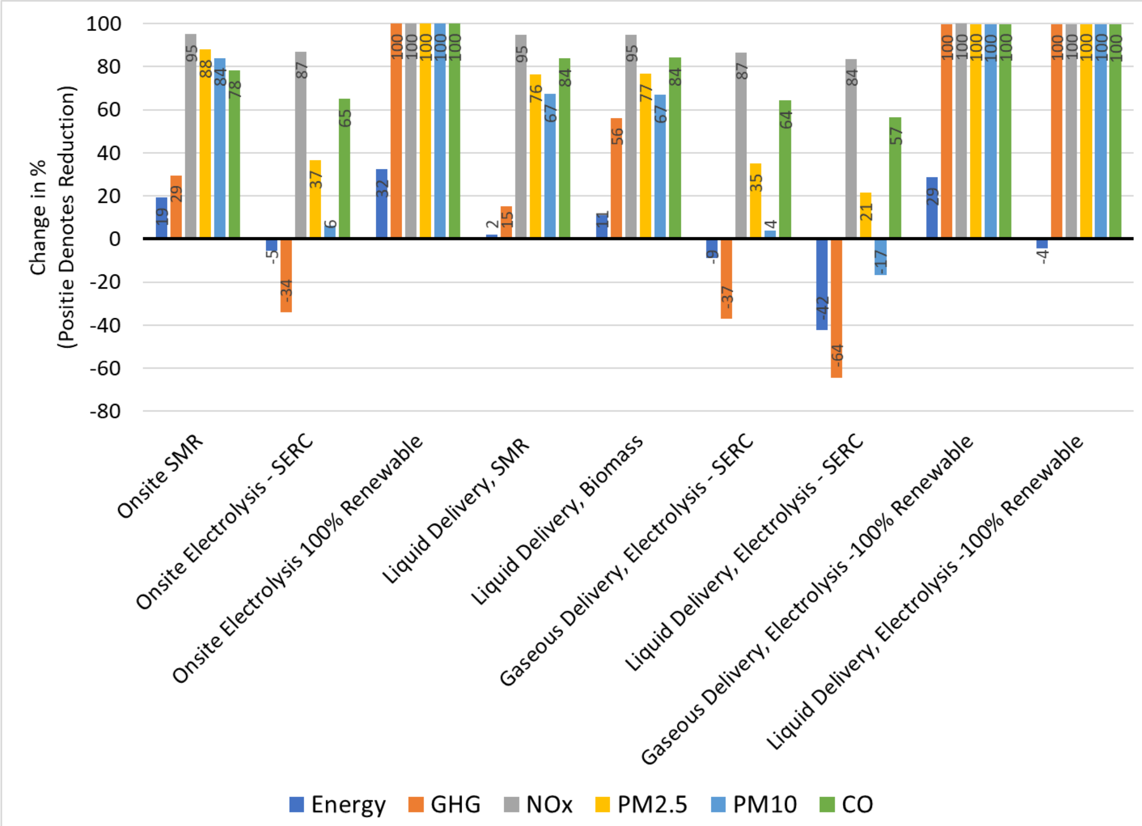

Figure 6-14: Two Locomotive Fuel Cell Hybrid Downsized Plugin WTW Energy and Emission Impact

The general pattern across the various hydrogen supply options is the same as for the other fuel cell configurations. The best emission and energy reductions are achieved with onsite electrolysis with a 100% renewable electricity mix, followed by the delivery options with that production method. Both SMR options offer reductions in all categories while the biomass option performs better than the SMR delivery pathway. Hydrogen production through electrolysis from SERC grid electricity is the option with the lowest reductions and increases in WTW energy and GHG emissions and, therefore, should be avoided unless the carbon intensity of electricity production can be substantially reduced. For the SECR electrolysis pathways: onsite electrolysis performs best, followed by delivery as a gas, while delivery as a liquid offers the lowest emission reduction in NOx, PM2.5, and CO combined with an increase in energy consumption, GHG, and PM10. The high carbon content in the electricity production mix combined with the energy demands for liquification are the primary causes for that result.

NCDOT may wish to consider a phased approach towards powertrain conversion to reduce implementation risk, become more comfortable with new technology, or due to budget constraints. A possibility would be to replace one of the diesel locomotives in the current consist with a converted CCU housing a battery, therefore creating a diesel hybrid train consist. In the next phase, the battery CCU could be upgraded with hydrogen fuel cell technology. Subsequently, the remaining diesel locomotive would be replaced with a hydrail vehicle.

Overall a hydrail option is feasible and offers zero-emissions resulting from operation with the potential to reduce WTW energy and emissions depending on the hydrogen production pathway. Given NCDOT's ambitions, a hydrail solution may be a cost-effective path forward to reduce emissions, ideally coupled with renewable hydrogen production, but a biomass or natural gas option would also result in emission and energy reduction in many train configurations, including the preferred option from an operational and implementation perspective.

7 CONCLUSION

The two incumbent powertrain technologies for railway motive power in the U.S. are electric where power is supplied through continuous wayside infrastructure and diesel-electric where power for the traction motors is produced onboard, the latter is the dominant in North America and the option used by NCDOT. Combustion of hydrocarbons, including diesel, leads to exhaust with air pollutants and GHGs. The Piedmont service route is located in counties that have previously been in air quality non-attainment and NCDOT has a desire to reduce, ideally eliminate, emissions from their rail operations if technically and economically feasible. Previous efforts of the Rail Division in that direction included testing of biodiesel and installation of aftertreament systems to the existing locomotives. New technologies such as diesel battery hybrids and hydrogen fuel cells offer the potential to reduce energy consumption and emissions, the latter avoiding harmful emissions completely at point of use. Additionally, hydrogen enables significant decreases in emissions throughout the energy supply chain. The conducted work compared technical feasibility of diesel battery hybrids and hydrail technology for the Piedmont service.

Diesel battery hybrids and hydrail vehicles have been successfully demonstrated in locomotive applications and are operating in service as multiple unit configurations. However, neither technology is currently in operation for a service with NCDOT's demands and, therefore, assessment of technical feasibility is necessary. Twenty-three train configurations have been modelled as part of the study, ranging from a diesel-electric benchmark through diesel hybrid options to various hydrail powertrains. Plugin variants were part of the investigation, i.e. the battery system can be charged from the grid after a roundtrip. As an energy carrier, hydrogen can be produced from many different feedstocks and nine production pathways have been considered in this analysis. Single train simulation and well-to-wheel assessment tools were employed to assess feasibility and indicate options suitable for the next phase(s), which could include construction of a demonstrator vehicle(s). Key findings and recommendations are provided in this section.

7.1 Key Findings

A diesel hybrid option offers reduction in energy consumption and emissions both in operations and throughout the supply chain. Installation of the required battery system in the same vehicle as the diesel-generator-set is not feasible due to the volume and mass implications but converting a CCU to house the battery system would be possible, offering reductions.

Hydrail technology has been in commercial operation in multiple unit trains in Germany for over two years. The assessment finds that hydrail technology is feasible for implementation on the Piedmont corridor. Sufficient power can be provided by either a fuel cell powertrain or a fuel cell hybrid powertrain to meet speed expectations and journey time. Fitting a CCU with a new powertrain to create a locomotive is probably a cost-effective option. The volume available in a CCU could likely accommodate all required equipment and hydrogen storage if refuelling after one roundtrip is possible; however, a more detailed design assessment would be required. Results from the assessment indicate that hydrogen storage at 350 bar is feasible but pressure could be increased to allow installation with a smaller volume requirement if necessary. Distributing the powertrain across two locomotives (or converted CCUs), one on each end of the train, would likely enable a refuelling frequency after two roundtrips. A journey time improvement of approximately 10 minutes could be achieved if all eight axles of these vehicles would be powered and operating at full capacity but energy reduction compared to the benchmark would be lower than with other options; a decrease of approximately 18% for the hydrogen hybrid option and 28% for the respective plugin version. From this initial assessment, the two locomotive (or converted CCUs) fuel cell downsized hybrid plugin with four traction motors (or eight traction motors operating at half capability) appears to be the most preferable for the Piedmont service, considering weight and volume requirements, refuelling frequency, number of FCS, and energy and emission reduction potential.

A phased technology implementation approach could be considered by NCDOT, where a CCU is converted to battery and operated with a diesel locomotive in a consist creating a diesel hybrid offering energy and emission reductions. Although this may be suitable approach from a budget and funding perspective, it is not the best option for long-term emissions reduction. However, the converted battery CCU could be further modified by installing a hydrogen fuel cell system with associated tanks. Alternatively, if budget and propensity to take risk is acceptable, a hydrogen fuel cell hybrid powertrain could be implemented in the CCU from the outset thereby eliminating harmful emissions at the point of use.

Energy reduction from operations compared to the diesel-electric benchmark range from 15% to 48%, the lowest decrease achieved with the diesel and battery option and the highest with the single locomotive (or converted CCU) fuel cell hybrid plugin. The two locomotive (or converted CCU) options offer an approximate two to three percentage point lower reduction compared to the single motive power vehicle variants but enable easier implementation and the possibility to refuel after two roundtrips instead of one. The likely preferred option of NCDOT based on this assessment would offer a 45% energy reduction in train operation.

Of the nine considered hydrogen production pathways, the highest energy and emission reductions are achieved with onsite electrolysis supplied by a 100% renewable (or carbon-free) electricity mix, followed closely by the same production method at a central location and hydrogen delivery as a gas while delivery as a liquid would result in energy increases but emission reduction. The lowest reductions and increases in WTW energy requirements and GHG as well as PM in some configurations are the result if hydrogen would be produced by electrolysis from SERC grid electricity. Onsite production performs better than central and delivery. SMR offers reductions in emissions and energy in most cases with the onsite option performing better than delivery. Production of hydrogen from biomass and delivery has similar results as SMR but offers higher GHG and energy reduction.

7.2 Recommendations

Hydrail is feasible for the Piedmont service based on the criteria assessed in this work. The likely best train configuration for NCDOT from an energy and emission reduction perspective is the option with two locomotives (or converted CCUs) employing a hydrogen fuel cell hybrid downsized plugin powertrain with four traction motors (or eight traction motors operating at half their capability). The rationale for that choice is a combination of space and weight considerations, likely making implementation of a hydrail powertrain easier, the probable refuelling frequency after two roundtrips instead of one, the high energy and emission reduction potential, and the cost reduction possibilities through fewer FCS requirements. If charging after a one-way journey would be possible, additional component size reductions with associated cost savings are likely. To address possible technological concern and funding availability, batteries could be added to a CCU to provide a diesel battery hybrid train consist offering energy and emission reductions.

Following this technical feasibility study an economic and life-cycle cost assessment of a hydrail system for the Piedmont service should be conducted. , This would enable NCDOT to choose the most appropriate powertrain and hydrogen delivery pathway commensurate with their criteria. Trade-offs between emission reduction, energy savings from operations, capital investment, and operational expenditure will have to be made and could be identified in that project.

Construction of a proof-of-concept vehicle is recommended to validate simulation results and demonstrate feasibility on the actual route, as any modelling offers estimates only. The primary powertrain components of such a vehicle (converted CCU) could be an 800 kW FCS, a 1350 kWh battery with plugin capability, 200 kg of hydrogen storage, and two traction motors (or four traction motors, cost permitting); it would represent one motive power vehicle of a two locomotive (or converted CCU) consist train. Refueling after one roundtrip should be achievable with this design. Additional hydrogen storage might be required for redundancy purposes. A more detailed design would have to be part of the project, which would enable component size and hydrogen storage quantity optimization.

If a hydrail system were implemented and WTW emissions reduction were prioritized, then production via electrolysis from an electricity mix consisting of 100% renewable sources should be chosen. For this case, hydrogen production could either be onsite or elsewhere and delivered to the fueling station, over a relatively short distance. SMR, the most common current hydrogen production pathway, offers emission reductions on a WTW basis with hydrogen delivered to the refueling station, rendering this option likely for a demonstration project.

In summary a hydrail option is feasible on the Piedmont service and suitable to achieve emission reduction goals while also decreasing energy consumption in train operations. In a next phase a proof-of-concept or demonstrator should be constructed and tested.

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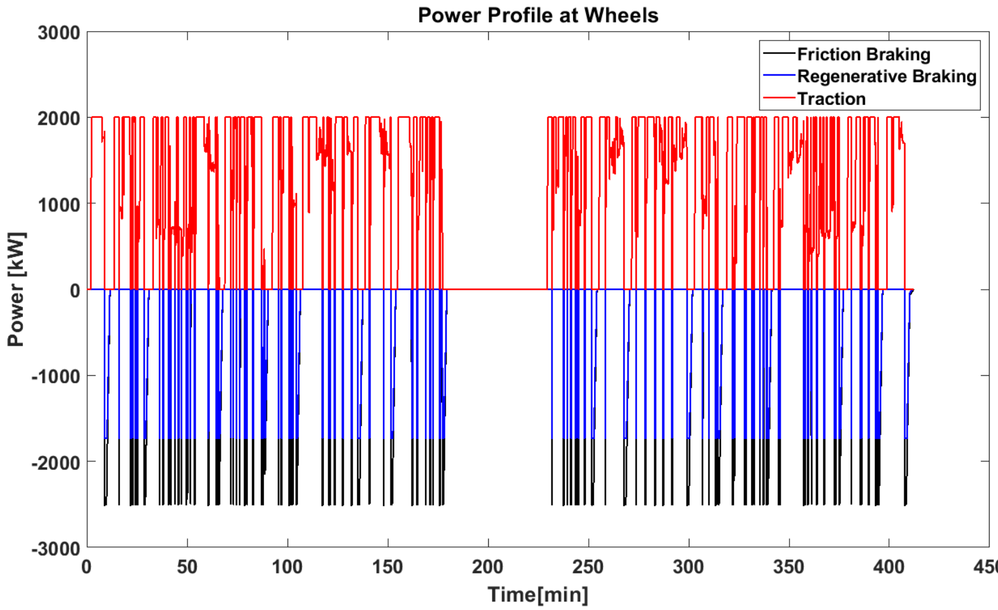
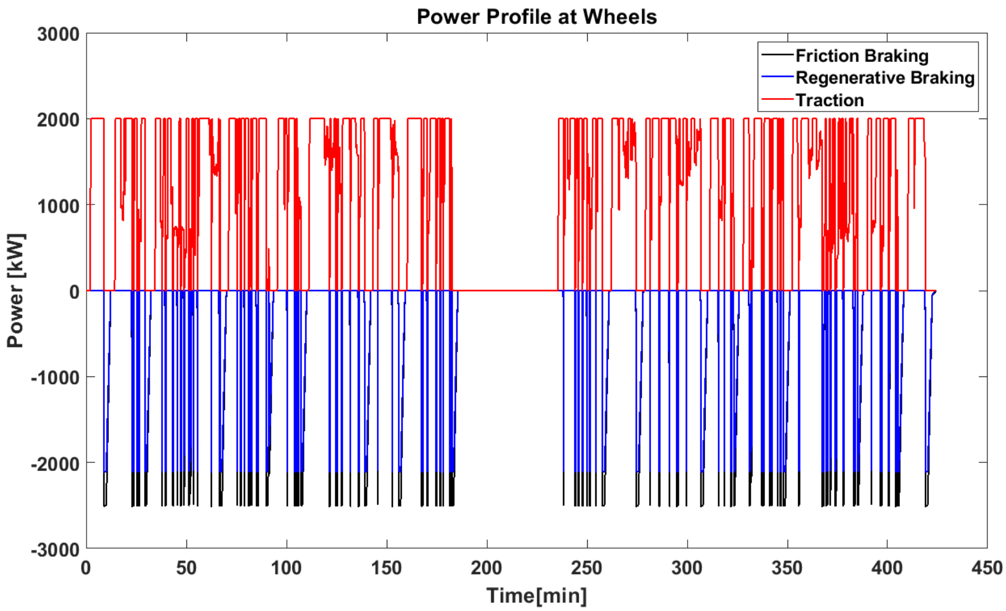
9 APPENDIX

9.1 Regenerative Braking Illustrations

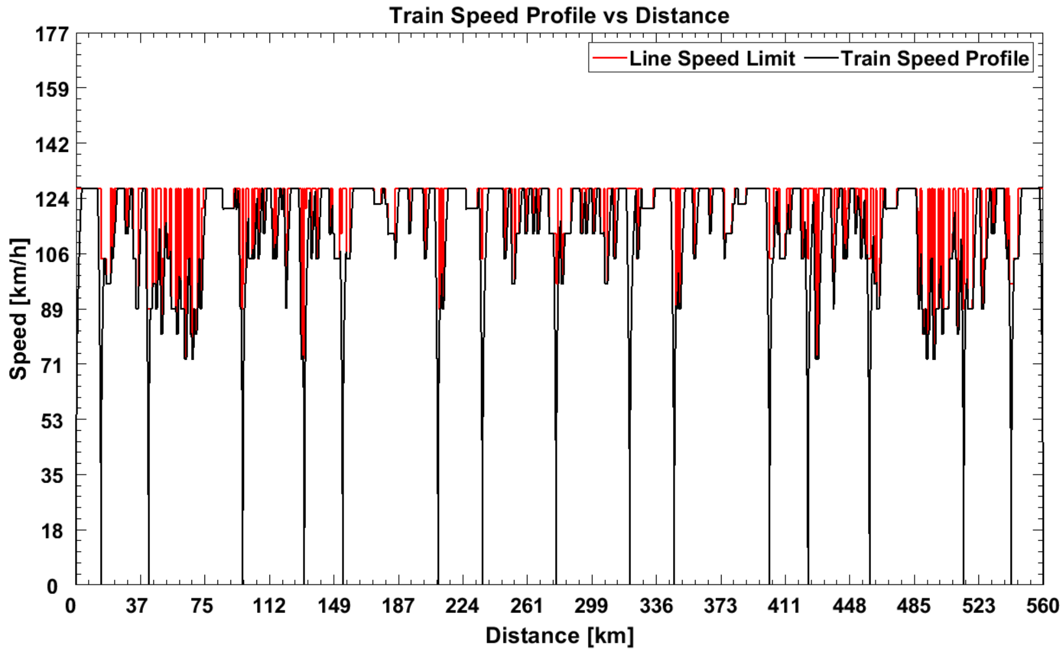
Tractive and Braking Effort of a Single Locomotive or Two Locomotives with Eight Traction Motors at Half Capability



Traction and Braking Power for a Two Locomotive Option with Eight Traction Motors at Full Capability



9.2 Speed Profile for Train Configuration with Two Locomotives and Eight Traction Motors at Full Capability



9.3 Well-to-Wheel Results

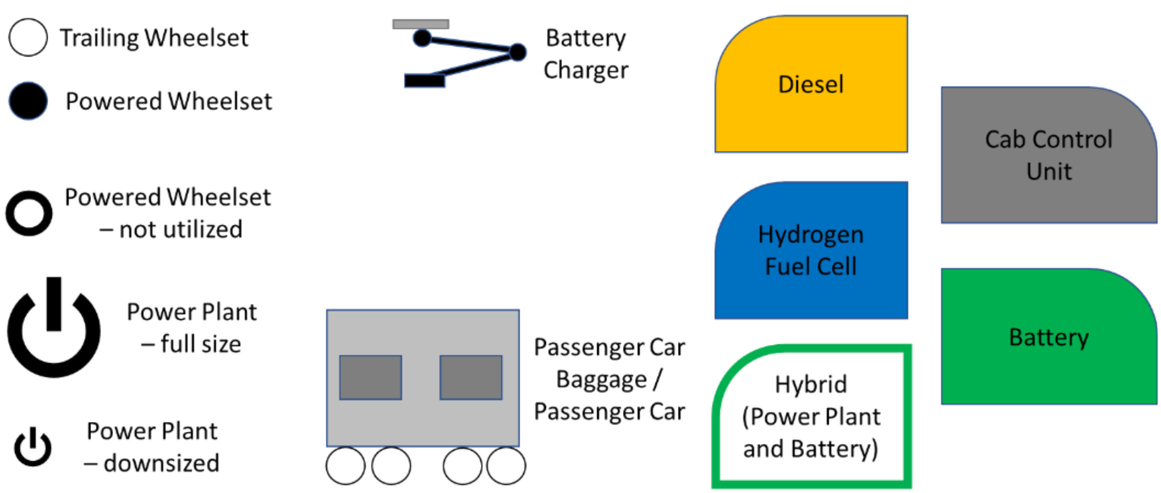
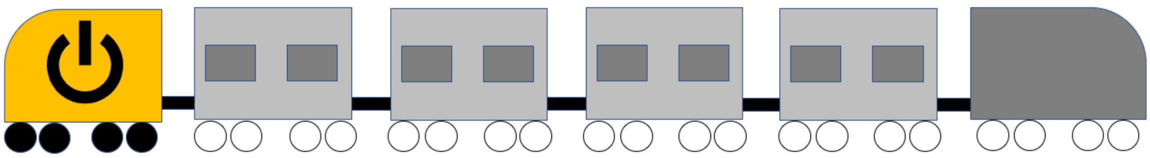
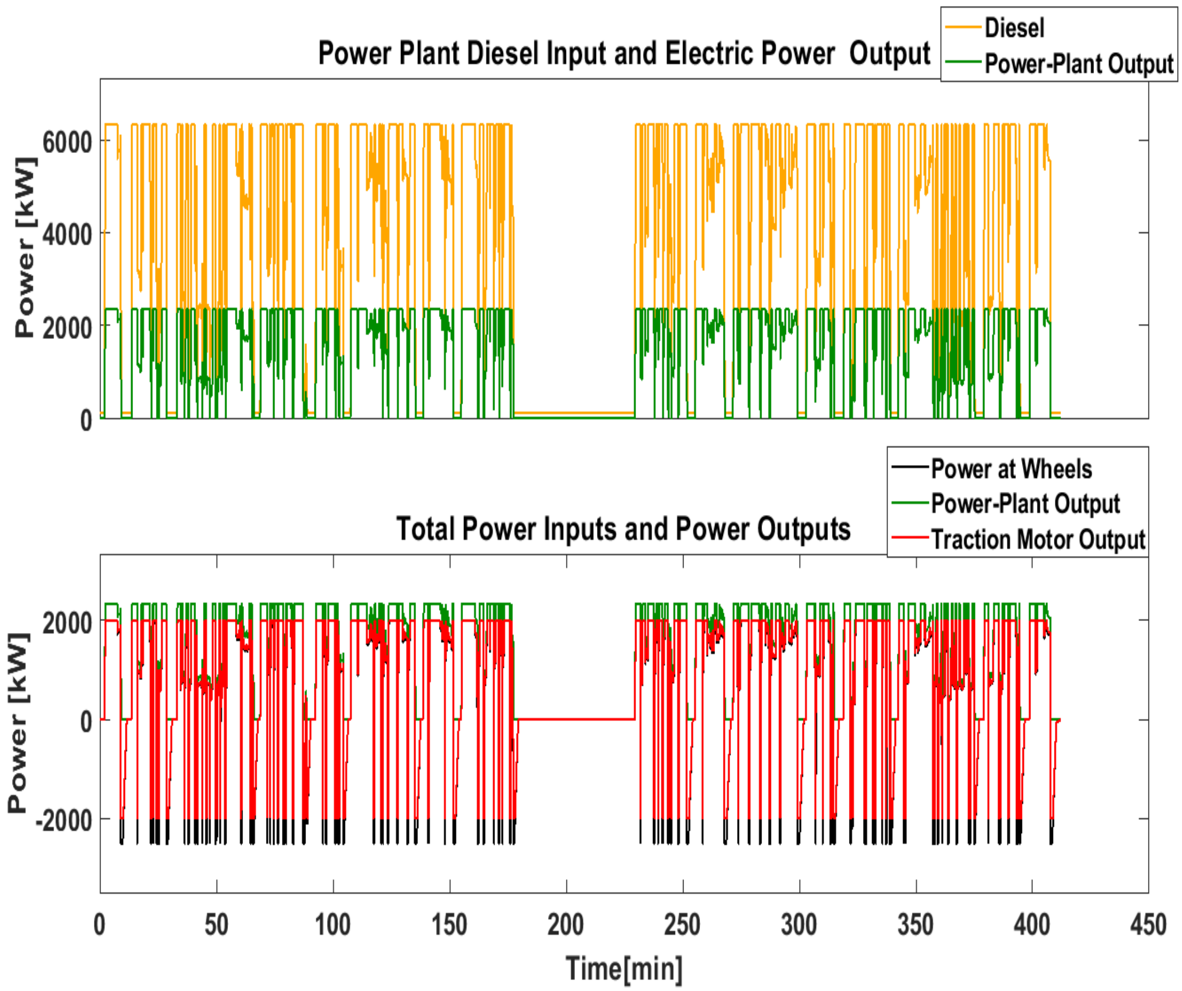


Figure 15: Legend for Appendix Graphs

All options with two locomotives (or converted CCUs), unless stated, illustrate four powered wheelsets, which would be equivalent to eight powered wheelsets operating at half capability.

9.3.1 Diesel-Electric Benchmark

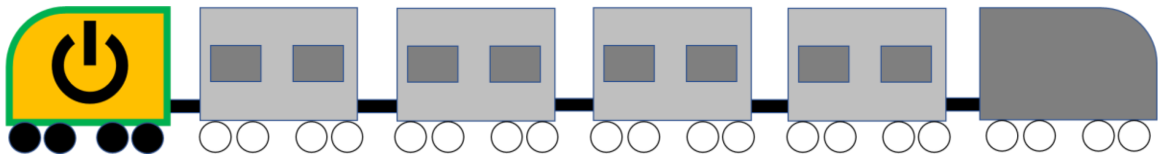


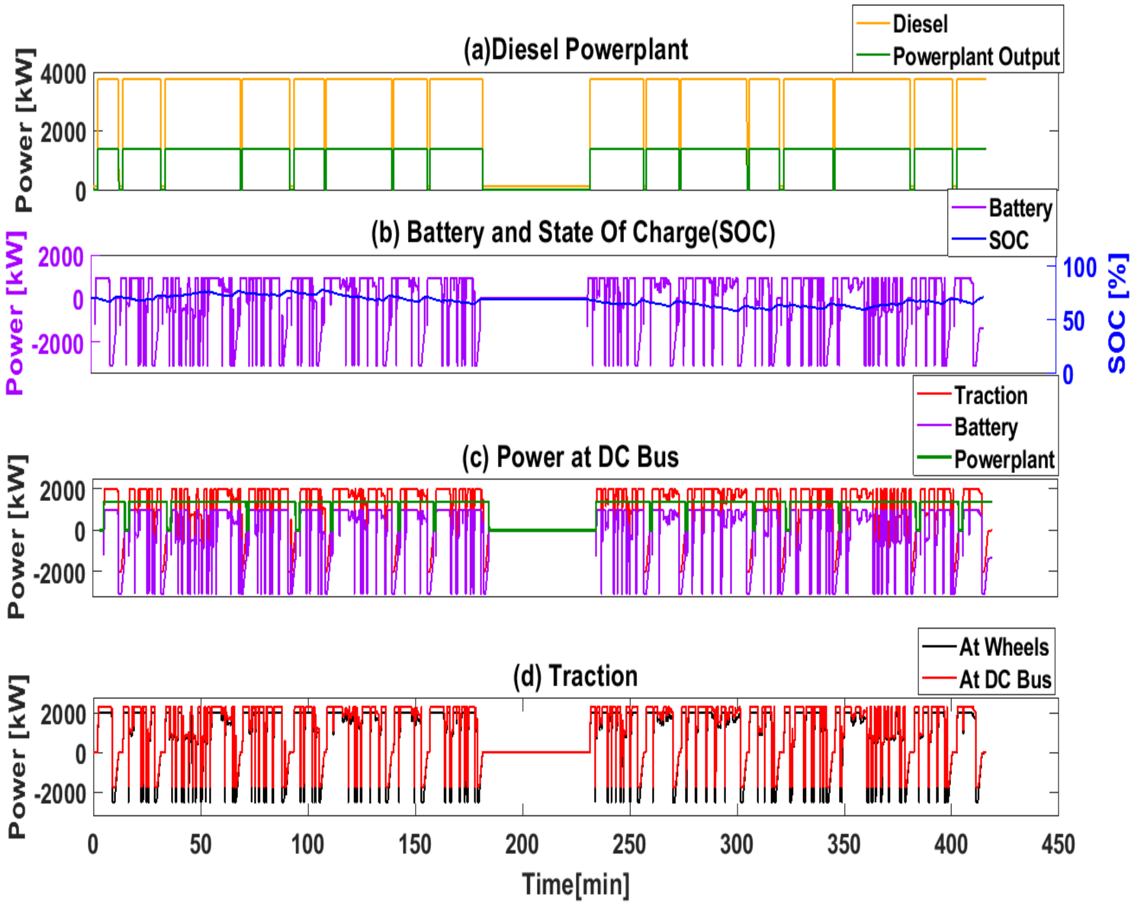


9.3.1 Diesel-Electric Benchmark (cont'd)

Round-trip, RGH-CLT-RGH	
DIESEL-ELECTRIC: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	**25981**
POINT-OF-USE-EMISSIONS	**Grams *(Based on SERC)***
GHGs	**6998297**
NOx: Total	**87660**
PM2.5: Total	**2494**
PM10: Total	**2571**
CO: Total	**12211**
VOC: Total	**3639**
SOx: Total	**48**
CH4	**605**
N2O	**189**
CO2 (w/ C in VOC & CO)	**6899535**
BC: Total	**209**
OC: Total	**2209**
DIESEL-ELECTRIC: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**5049**
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***
GHGs	**1527970**
NOx: Total	**2351**
PM2.5: Total	**133**
PM10: Total	**159**
CO: Total	**1132**
VOC: Total	**679**
SOx: Total	**885**
CH4	**9896**
N2O	**20**
CO2 (w/ C in VOC & CO)	**1202961**
BC: Total	**23**
OC: Total	**39**
DIESEL-ELECTRIC: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**31030**
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***
GHGs	**8526268**
NOx: Total	**90011**
PM2.5: Total	**2627**
PM10: Total	**2729**
CO: Total	**13344**
VOC: Total	**4318**
SOx: Total	**933**
CH4	**10501**
N2O	**209**
CO2 (w/ C in VOC & CO)	**8102496**
BC: Total	**233**
OC: Total	**2249**

9.3.2 Diesel Hybrid

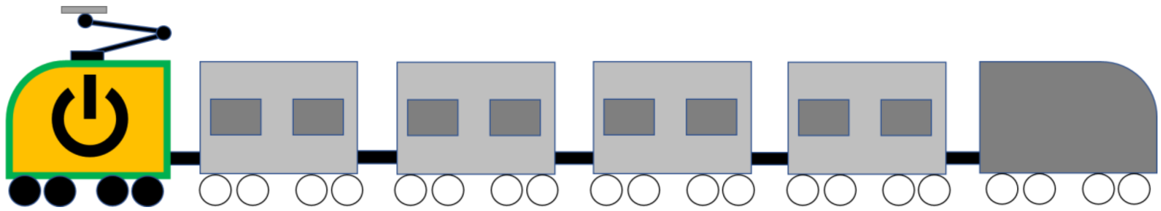


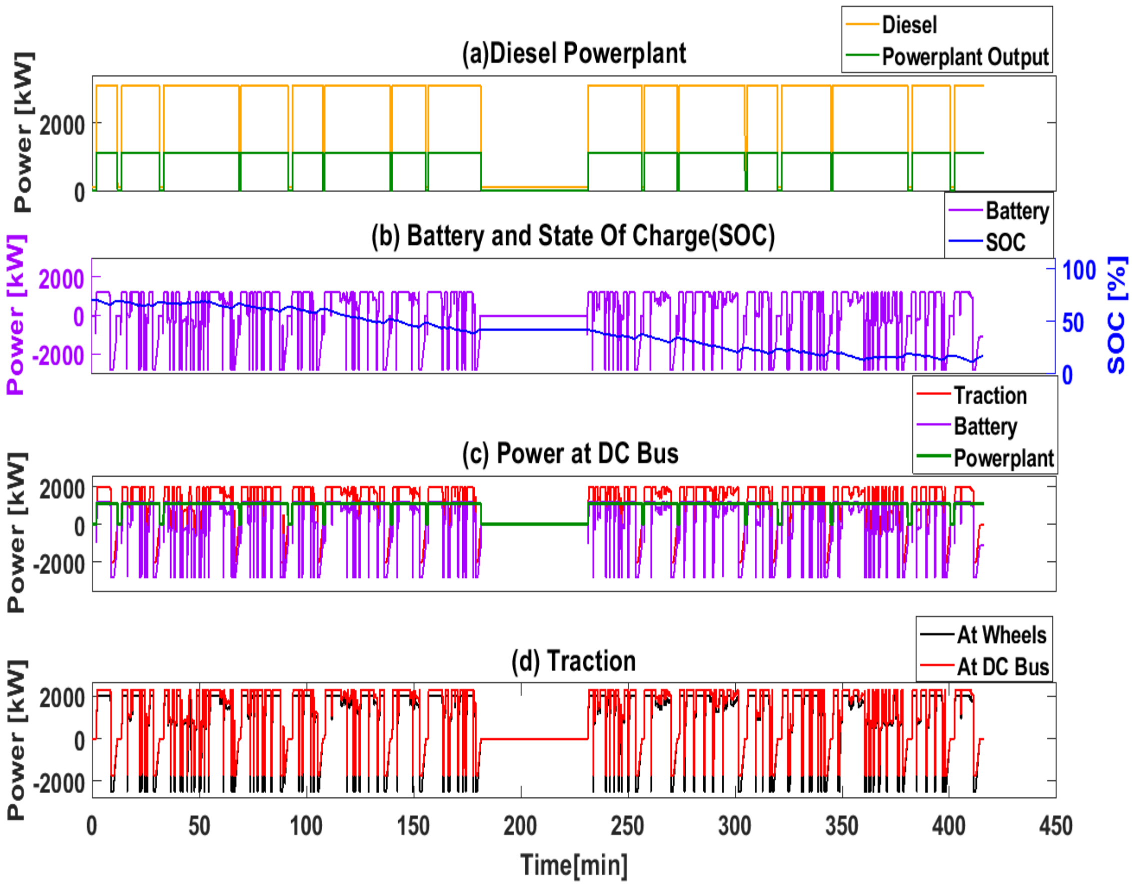


9.3.2 Diesel Hybrid (cont'd)

Round-trip, RGH-CLT-RGH		
DIESEL HYBRID: ENERGY CONSUMPTION, POINT-OF-USE (KwH)		**Reduction**
	21657	**16.64%**
POINT-OF-USE-EMISSIONS	**Grams *(Based on SERC)***	**% Reduc.**
GHGs	**5833575**	**16.64**
NOx: Total	**73071**	**16.64**
PM2.5: Total	**2079**	**16.64**
PM10: Total	**2143**	**16.64**
CO: Total	**10179**	**16.64**
VOC: Total	**3033**	**16.64**
SOx: Total	**40**	**16.64**
CH4	**504**	**16.64**
N2O	**158**	**16.64**
CO2 (w/ C in VOC & CO)	**5751250**	**16.64**
BC: Total	**175**	**16.64**
OC: Total	**1842**	**16.64**
DIESEL HYBRID: ENERGY CONSUMPTION, WELL-TO-PUMP (KwH)		**Reduction**
	4209	**16.64%**
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***	***In %***
GHGs	**1273671**	**16.64**
NOx: Total	**1960**	**16.64**
PM2.5: Total	**111**	**16.64**
PM10: Total	**132**	**16.64**
CO: Total	**944**	**16.64**
VOC: Total	**566**	**16.64**
SOx: Total	**738**	**16.64**
CH4	**8249**	**16.64**
N2O	**17**	**16.64**
CO2 (w/ C in VOC & CO)	**1002753**	**16.64**
BC: Total	**19**	**16.64**
OC: Total	**33**	**16.64**
DIESEL HYBRID: ENERGY CONSUMPTION, WELL-TO-WHEEL (KwH)		**Reduction**
	25866	**16.64%**
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	***In %***
GHGs	**7107247**	**16.64**
NOx: Total	**75030**	**16.64**
PM2.5: Total	**2190**	**16.64**
PM10: Total	**2275**	**16.64**
CO: Total	**11123**	**16.64**
VOC: Total	**3599**	**16.64**
SOx: Total	**778**	**16.64**
CH4	**8754**	**16.64**
N2O	**175**	**16.64**
CO2 (w/ C in VOC & CO)	**6754003**	**16.64**
BC: Total	**194**	**16.64**
OC: Total	**1874**	**16.64**

9.3.3 Diesel Hybrid Plugin





Round-trip, RGH-CLT-RGH

		Reduction
DIESEL HYBRID PLUG-IN: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	17999	30.72%
POINT-OF-USE-EMISSIONS	**Grams** *(Based on SERC)*	*In %*
GHGs	4848249	30.72
NOx: Total	60729	30.72
PM2.5: Total	1727	30.72
PM10: Total	1781	30.72
CO: Total	8460	30.72
VOC: Total	2521	30.72
SOx: Total	33	30.72
CH4	419	30.72
N2O	131	30.72
CO2 (w/ C in VOC & CO)	4779828	30.72
BC: Total	145	30.72
OC: Total	1531	30.72

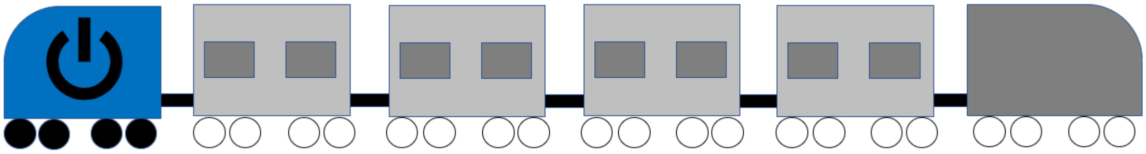
		Reduction
DIESEL HYBRID PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	3498	30.72%
WELL-TO-PUMP EMISSIONS	**Grams** *(Based on SERC)*	% Reduct.
GHGs	1058540	30.72
NOx: Total	1629	30.72
PM2.5: Total	92	30.72
PM10: Total	110	30.72
CO: Total	784	30.72
VOC: Total	470	30.72
SOx: Total	613	30.72
CH4	6856	30.72
N2O	14	30.72
CO2 (w/ C in VOC & CO)	833382	30.72
BC: Total	16	30.72
OC: Total	27	30.72

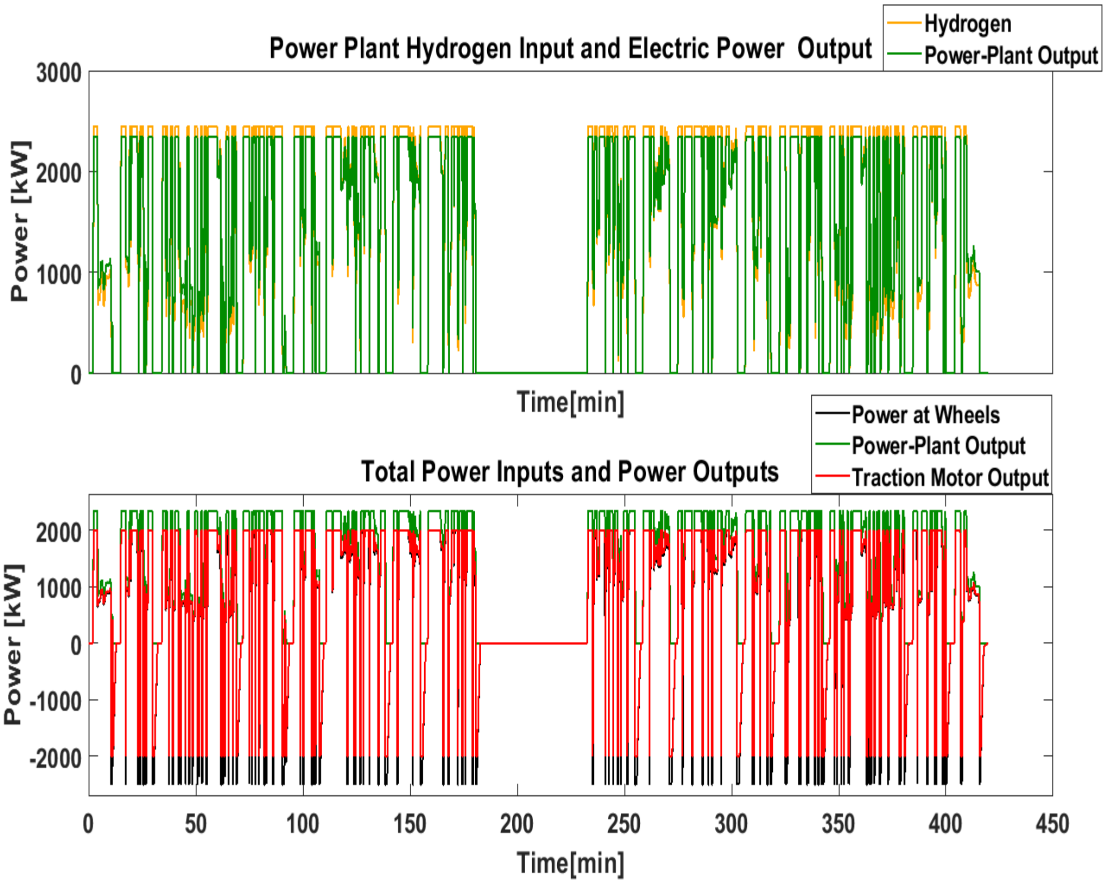
DIESEL HYBRID PLUG-IN: ENERGY REQUIREMENTS, WELL-TO-PUMP, PLUG ELECTRICITY (kWh)	2016
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	**Grams** *(Based on SERC)*
GHGs	879837
NOx: Total	903
PM2.5: Total	128
PM10: Total	197
CO: Total	358
VOC: Total	97
SOx: Total	1602
CH4	1667
N2O	13
CO2 (w/ C in VOC & CO)	826404
BC: Total	8
OC: Total	19

		Reduction
DIESEL HYBRID PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	21497	30.72%
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	*% Reduct.*
GHGs	5906789	30.72
NOx: Total	62357	30.72
PM2.5: Total	1820	30.72
PM10: Total	1891	30.72
CO: Total	9244	30.72
VOC: Total	2991	30.72
SOx: Total	646	30.72
CH4	7275	30.72
N2O	145	30.72
CO2 (w/ C in VOC & CO)	5613210	30.72
BC: Total	161	30.72
OC: Total	1558	30.72

		Reduction
DIESEL HYBRID PLUG-IN: ENERGY REQUIREMENTS, WELL-TO-WHEEL, PLUG ELECTRICITY (kWh)	25130	19.01%
WELL-TO-WHEEL EMISSIONS, INCL. PLUG	**Grams** *(Based on SERC)*	*% Reduct.*
GHGs	6786626	20.40
NOx: Total	63261	29.72
PM2.5: Total	1948	25.85
PM10: Total	2088	23.49
CO: Total	9602	28.04
VOC: Total	3088	28.49
SOx: Total	2249	-141.01
CH4	8942	14.85
N2O	158	24.56
CO2 (w/ C in VOC & CO)	6439614	20.52
BC: Total	170	27.10
OC: Total	1577	29.88

9.3.4 Hydrogen Fuel Cell





Round-trip, RGH-CLT-RGH		
HYDROGEN FUEL CELL: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	20432	Reduction 21.36%
POINT-OF-USE-EMISSIONS	ALL PRODUCTION METHODS	
	Grams (Based on SERC)	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

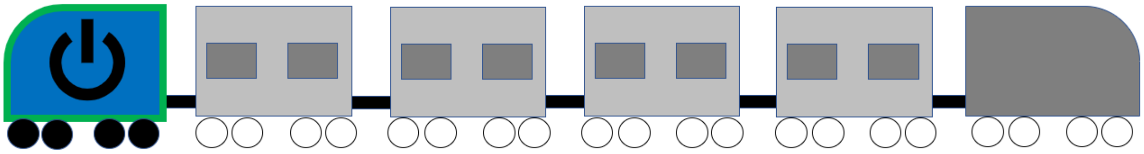
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	15739	Reduction -211.75%	27566	Reduction -446.00%	11600	Reduction -129.76%	23947	Reduction -374.32%
WELL-TO-PUMP EMISSIONS	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	8287239	-442.37	16568899	-984.37	0	100.00	10149754	-564.26
NOx: Total	5817	-147.43	17011	-623.57	0	100.00	6280	-167.14
PM2.5: Total	344	-158.48	2412	-1711.40	0	100.00	813	-510.75
PM10: Total	458	-188.90	3719	-2244.34	0	100.00	1155	-627.99
CO: Total	4038	-256.67	6735	-494.80	0	100.00	2933	-159.00
VOC: Total	1246	-83.60	1818	-167.80	0	100.00	1195	-76.03
SOx: Total	3549	-301.12	30172	-3309.69	0	100.00	8659	-878.57
CH4	25655	-159.23	31395	-217.23	0	100.00	22242	-124.75
N2O	170	-732.67	243	-1092.95	0	100.00	102	-403.05
CO2 (w/ C in VOC & CO)	7472653	-521.19	15562665	-1193.70	0	100.00	9455340	-686.01
BC: Total	30	-29.21	159	-586.81	0	100.00	67	-191.23
OC: Total	55	-39.23	358	-806.88	0	100.00	147	-271.17

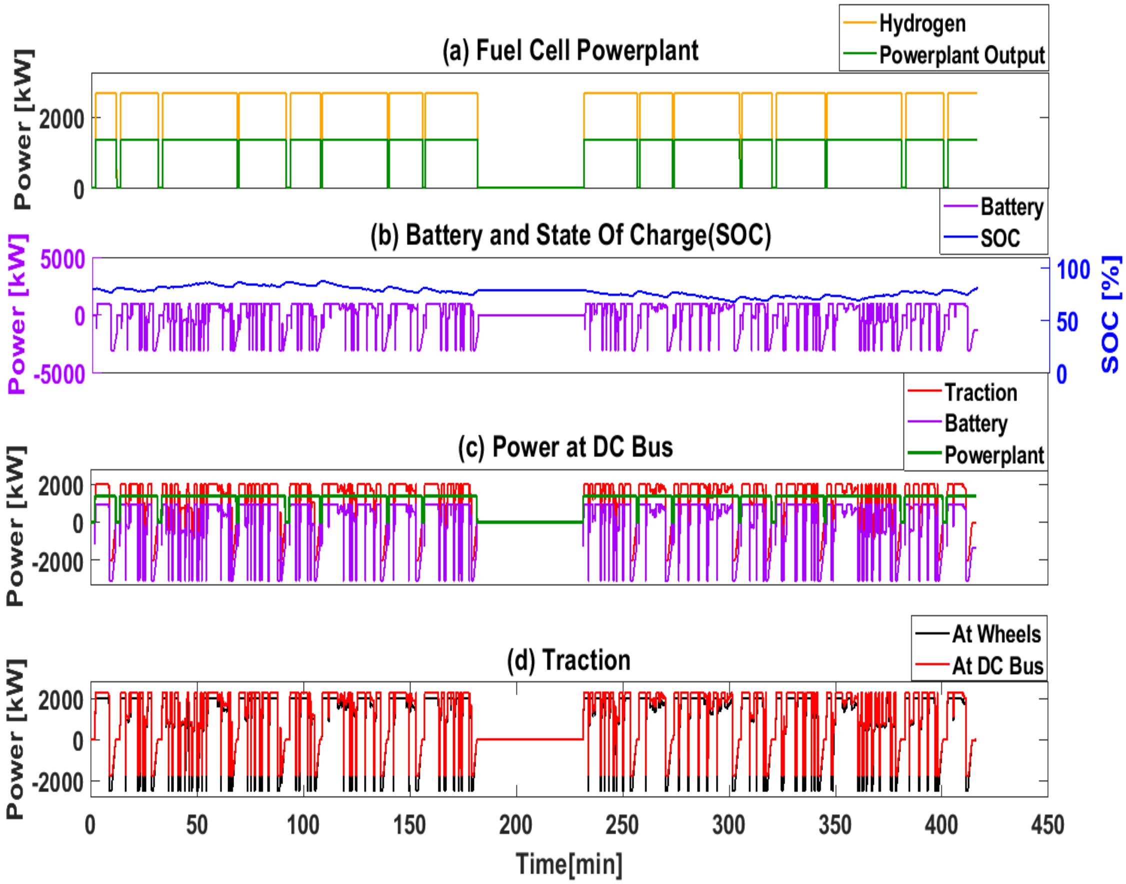
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	36171	Reduction -16.57%	47998	Reduction -54.69%	32032	Reduction -3.23%	44379	Reduction -43.02%
WELL-TO-WHEEL EMISSIONS	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	8287239	2.80	16568899	-94.33	0	100.00	10149754	-19.04
NOx: Total	5817	93.54	17011	81.10	0	100.00	6280	93.02
PM2.5: Total	344	86.89	2412	8.16	0	100.00	813	69.03
PM10: Total	458	83.21	3719	-36.26	0	100.00	1155	57.69
CO: Total	4038	69.74	6735	49.53	0	100.00	2933	78.02
VOC: Total	1246	71.14	1818	57.90	0	100.00	1195	72.33
SOx: Total	3549	-280.45	30172	-3133.97	0	100.00	8659	-828.13
CH4	25655	-144.30	31395	-198.96	0	100.00	22242	-111.80
N2O	170	18.99	243	-16.07	0	100.00	102	51.06
CO2 (w/ C in VOC & CO)	7472653	7.77	15562665	-92.07	0	100.00	9455340	-16.70
BC: Total	30	87.16	159	31.72	0	100.00	67	71.05
OC: Total	55	97.56	358	84.08	0	100.00	147	93.48

Round-trip, RGH-CLT-RGH										
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
HYDROGEN FUEL CELL: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	19799	Reduction -292.15%	29259	Reduction -479.53%	45064	Reduction -792.58%	13293	Reduction -163.29%	29098	-476.34%
WELL-TO-PUMP EMISSIONS	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	%Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	4802686	-214.32	16953528	-1009.55	20527189	-1243.43	51284	96.64	30809	97.98
NOx: Total	6219	-164.54	17432	-641.47	21497	-814.37	56	97.61	187	92.03
PM2.5: Total	798	-499.21	2472	-1756.22	3027	-2173.21	8	94.02	5	95.97
PM10: Total	1166	-634.99	3811	-2302.34	4665	-2840.68	12	92.27	6	96.11
CO: Total	2835	-150.41	6901	-509.52	8481	-649.04	22	98.04	45	96.07
VOC: Total	851	-25.41	1863	-174.43	2288	-237.15	6	99.12	11	98.33
SOx: Total	10931	-1135.30	30918	-3394.05	37799	-4171.68	100	88.75	2	99.73
CH4	9443	4.58	32171	-225.08	39368	-297.80	104	98.95	40	99.60
N2O	-504	2574.70	249	-1122.47	305	-1396.41	1	96.06	0	98.03
CO2 (w/ C in VOC & CO)	4645874	-286.20	15947294	-1225.67	19520955	-1522.74	51284	95.74	29516	97.55
BC: Total	115	-398.03	163	-603.81	200	-763.15	1	97.73	1	97.23
OC: Total	127	-221.63	367	-829.32	451	-1043.49	1	97.01	3	92.55

PRODUCTION METHOD	LIQUID DELIVERY, BIOMAS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
HYDROGEN FUEL CELL: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	40231	Reduction -29.65%	49691	Reduction -60.14%	65496	Reduction -111.08%	33725	Reduction -8.69%	49530	Reduction -59.62%
WELL-TO-WHEEL EMISSIONS	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	4802686	43.67	16953528	-98.84	20527189	-140.75	51284	99.40	30809	99.64
NOx: Total	6219	93.09	17432	80.63	21497	76.12	56	99.94	187	99.79
PM2.5: Total	798	69.62	2472	5.88	3027	-15.26	8	99.70	5	99.80
PM10: Total	1166	57.28	3811	-39.63	4665	-70.93	12	99.55	6	99.77
CO: Total	2835	78.75	6901	48.28	8481	36.44	22	99.83	45	99.67
VOC: Total	851	80.29	1863	56.86	2288	47.00	6	99.86	11	99.74
SOx: Total	10931	-1071.64	30918	-3213.98	37799	-3951.53	100	89.33	2	99.75
CH4	9443	10.08	32171	-206.36	39368	-274.89	104	99.01	40	99.62
N2O	-504	340.77	249	-18.94	305	-45.59	1	99.62	0	99.81
CO2 (w/ C in VOC & CO)	4645874	42.66	15947294	-96.82	19520955	-140.93	51284	99.37	29516	99.64
BC: Total	115	50.49	163	30.03	200	14.19	1	99.77	1	99.72
OC: Total	127	94.35	367	83.68	451	79.92	1	99.95	3	99.87

9.3.5 Hydrogen Fuel Cell Hybrid





Round-trip, RGH-CLT-RGH

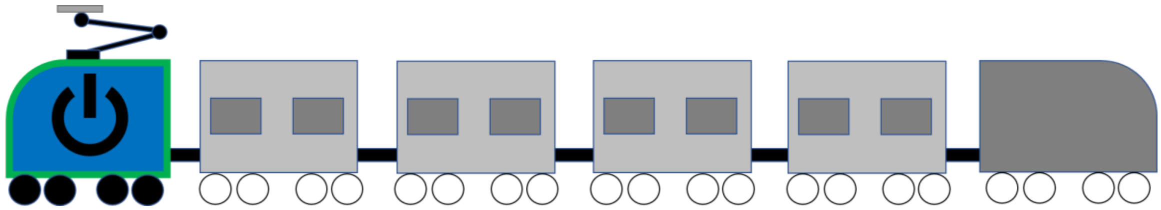
HYDROGEN FUEL CELL HYBRID: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	15410	Reduction 40.69%
POINT-OF-USE-EMISSIONS	**ALL PRODUCTION METHODS** Grams *(Based on SERC)*	*% Reduct.*
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

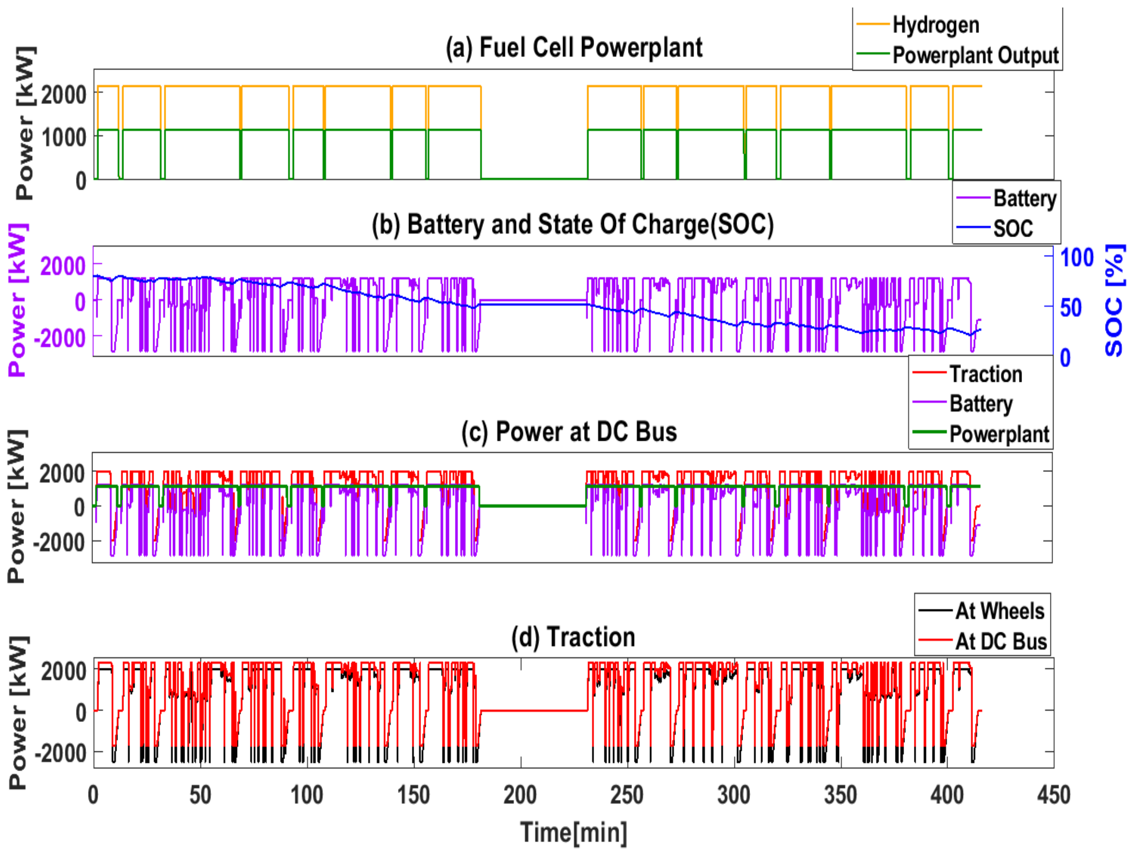
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	11871	Reduction -135.12%	20791	Reduction -311.80%	8749	Reduction -73.29%	18061	Reduction -257.74%
WELL-TO-PUMP EMISSIONS	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
	Grams *(Based on SECR)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6250311	-309.06	12496414	-717.84	0	100.00	7655037	-400.99
NOx: Total	4387	-86.61	12830	-445.72	0	100.00	4737	-101.48
PM2.5: Total	260	-94.95	1819	-1266.18	0	100.00	613	-360.63
PM10: Total	346	-117.89	2805	-1668.12	0	100.00	871	-449.06
CO: Total	3046	-169.00	5079	-348.61	0	100.00	2212	-95.34
VOC: Total	940	-38.47	1371	-101.98	0	100.00	901	-32.76
SOx: Total	2677	-202.53	22756	-2471.62	0	100.00	6531	-638.04
CH4	19349	-95.52	23678	-139.26	0	100.00	16775	-69.51
N2O	128	-528.00	183	-799.74	0	100.00	77	-279.41
CO2 (w/ C in VOC & CO)	5635943	-368.51	11737503	-875.72	0	100.00	7131303	-492.81
BC: Total	23	2.55	120	-418.00	0	100.00	51	-119.65
OC: Total	41	-5.01	270	-583.98	0	100.00	111	-179.94

PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	27281	Reduction 12.08%	36201	Reduction -16.66%	24159	Reduction 22.14%	33471	Reduction -7.87%
WELL-TO-WHEEL EMISSIONS	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct	Grams *(Based on SERC)*	% Reduct.
GHGs	6250311	26.69	12496414	-46.56	0	100.00	7655037	10.22
NOx: Total	4387	95.13	12830	85.75	0	100.00	4737	94.74
PM2.5: Total	260	90.12	1819	30.73	0	100.00	613	76.64
PM10: Total	346	87.34	2805	-2.77	0	100.00	871	68.09
CO: Total	3046	77.17	5079	61.93	0	100.00	2212	83.42
VOC: Total	940	78.23	1371	68.25	0	100.00	901	79.13
SOx: Total	2677	-186.94	22756	-2339.09	0	100.00	6531	-600.01
CH4	19349	-84.25	23678	-125.48	0	100.00	16775	-59.74
N2O	128	38.90	183	12.46	0	100.00	77	63.09
CO2 (w/ C in VOC & CO)	5635943	30.44	11737503	-44.86	0	100.00	7131303	11.99
BC: Total	23	90.31	120	48.50	0	100.00	51	78.16
OC: Total	41	98.16	270	87.99	0	100.00	111	95.08

Round-trip, RGH-CLT-RGH										
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
HYDROGEN FUEL CELL HYBRID: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**14932**	**Reduction**	**22068**	**Reduction**	**33988**	**Reduction**	**10025**	**Reduction**	**21946**	**Reduction**
		-195.76%		**-337.09%**		**-573.19%**		**-98.57%**		**-334.68%**
WELL-TO-PUMP EMISSIONS	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
	Grams *(Based on SERC)*	**% Reduct**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3622230	-137.06	12786505	-736.83	15481792	-913.23	38679	97.47	23236	98.48
NOx: Total	4691	-99.52	13148	-459.23	16213	-589.63	42	98.20	141	93.99
PM2.5: Total	602	-351.93	1865	-1299.98	2283	-1614.47	6	95.49	4	96.96
PM10: Total	879	-454.33	2874	-1711.86	3518	-2117.89	9	94.17	5	97.07
CO: Total	2138	-88.86	5205	-359.71	6396	-464.94	17	98.52	34	97.03
VOC: Total	642	5.41	1405	-106.98	1726	-154.28	5	99.33	9	98.74
SOx: Total	8244	-831.68	23319	-2535.24	28509	-3121.74	75	91.52	2	99.80
CH4	7122	28.03	24264	-145.18	29692	-200.03	78	99.21	30	99.70
N2O	-380	1966.44	188	-822.00	230	-1028.60	1	97.03	0	98.51
CO2 (w/ C in VOC & CO)	3503961	-191.28	12027594	-899.83	14722881	-1123.89	38679	96.78	22262	98.15
BC: Total	87	-275.62	123	-430.82	151	-551.00	0	98.29	0	97.91
OC: Total	96	-142.58	277	-600.90	341	-762.43	1	97.74	2	94.38
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**				**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
HYDROGEN FUEL CELL HYBRID: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**30342.2431**	**Reduction**	**37477.5**	**Reduction**	**49398**	**Reduction**	**25435**	**Reduction**	**37356**	**Reduction**
	2.215704236			**-20.78%**		**-59.20%**		**18.03%**		**-20.39%**
WELL-TO-WHEEL EMISSIONS	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**Liquid Delivery, Electrolysis**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
	Grams *(Based on SERC)*	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3622230	57.52	12786505	-49.97	15481792	-81.58	38679	99.55	23236	99.73
NOx: Total	4691	94.79	13148	85.39	16213	81.99	42	99.95	141	99.84
PM2.5: Total	602	77.09	1865	29.02	2283	13.07	6	99.77	4	99.85
PM10: Total	879	67.78	2874	-5.31	3518	-28.91	9	99.66	5	99.83
CO: Total	2138	83.97	5205	60.99	6396	52.06	17	99.87	34	99.75
VOC: Total	642	85.13	1405	67.46	1726	60.03	5	99.90	9	99.80
SOx: Total	8244	-783.66	23319	-2399.43	28509	-2955.70	75	91.95	2	99.81
CH4	7122	32.18	24264	-131.06	29692	-182.74	78	99.26	30	99.72
N2O	-380	281.59	188	10.30	230	-9.81	1	99.71	0	99.86
CO2 (w/ C in VOC & CO)	3503961	56.75	12027594	-48.44	14722881	-81.71	38679	99.52	22262	99.73
BC: Total	87	62.66	123	47.23	151	35.28	0	99.83	0	99.79
OC: Total	96	95.74	277	87.69	341	84.86	1	99.96	2	99.90

9.3.6 Hydrogen Fuel Cell Hybrid Plugin





Round-trip, RGH-CLT-RGH

HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	12317	Reduction 52.59%
	ALL PRODUCTION METHODS	
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	9488	Reduction -87.93%	16618	Reduction -229.15%	6993	Reduction -38.51%	14436	Reduction -185.93%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL_TO_PUMP EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*
GHGs	4995787	-226.96	9988211	-553.69	0	100.00	6118565	-300.44
NOx: Total	3507	-49.16	10255	-336.19	0	100.00	3786	-61.04
PM2.5: Total	208	-55.82	1454	-991.97	0	100.00	490	-268.18
PM10: Total	276	-74.16	2242	-1313.23	0	100.00	696	-338.86
CO: Total	2434	-115.01	4060	-258.57	0	100.00	1768	-56.14
VOC: Total	751	-10.68	1096	-61.44	0	100.00	720	-6.12
SOx: Total	2140	-141.81	18188	-1955.46	0	100.00	5220	-489.91
CH4	15465	-56.27	18926	-91.24	0	100.00	13408	-35.48
N2O	102	-401.96	146	-619.15	0	100.00	62	-203.26
CO2 (w/ C in VOC & CO)	4504731	-274.47	9381624	-679.88	0	100.00	5699952	-373.83
BC: Total	18	22.11	96	-314.03	0	100.00	41	-75.56
OC: Total	33	16.07	216	-446.69	0	100.00	88	-123.75

PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	21805	Reduction 29.73%	28935	Reduction 6.75%	19310	Reduction 37.77%	26753	Reduction 13.78%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	4995787	41.41	9988211	-17.15	0	100.00	6118565	28.24
NOx: Total	3507	96.10	10255	88.61	0	100.00	3786	95.79
PM2.5: Total	208	92.10	1454	44.63	0	100.00	490	81.33
PM10: Total	276	89.88	2242	17.86	0	100.00	696	74.49
CO: Total	2434	81.76	4060	69.57	0	100.00	1768	86.75
VOC: Total	751	82.60	1096	74.62	0	100.00	720	83.32
SOx: Total	2140	-129.35	18188	-1849.53	0	100.00	5220	-459.51
CH4	15465	-47.27	18926	-80.22	0	100.00	13408	-27.68
N2O	102	51.16	146	30.03	0	100.00	62	70.50
CO2 (w/ C in VOC & CO)	4504731	44.40	9381624	-15.79	0	100.00	5699952	29.65
BC: Total	18	92.26	96	58.84	0	100.00	41	82.55
OC: Total	33	98.53	216	90.40	0	100.00	88	96.07

Round-trip, RGH-CLT-RGH										
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	11935.13551	Reduction -136.40%	17638	Reduction -249.36%	27166	Reduction -438.07%	8013	Reduction -58.72%	17541	Reduction -247.43%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	2895198	-89.48	10220077	-568.87	12374383	-709.86	30915	97.977	18573	98.78
NOx: Total	3749	-59.47	10509	-346.98	12959	-451.21	34	98.561	113	95.19
PM2.5: Total	481	-261.22	1490	-1018.98	1825	-1270.35	5	96.398	3	97.57
PM10: Total	703	-343.07	2297	-1348.20	2812	-1672.73	7	95.338	4	97.66
CO: Total	1709	-50.95	4160	-267.44	5113	-351.55	13	98.817	27	97.63
VOC: Total	513	24.40	1123	-65.43	1379	-103.24	4	99.467	7	98.99
SOx: Total	6590	-644.68	18638	-2006.31	22787	-2475.09	60	93.220	1	99.84
CH4	5692	42.48	19394	-95.97	23732	-139.81	62	99.369	24	99.76
N2O	-304	1591.82	150	-636.94	184	-802.08	0	97.628	0	98.81
CO2 (w/ C in VOC & CO)	2800667	-132.81	9613490	-699.15	11767796	-878.24	30915	97.430	17793	98.52
BC: Total	69	-200.23	98	-324.27	120	-420.33	0	98.634	0	98.33
OC: Total	77	-93.89	221	-460.22	272	-589.33	1	98.197	2	95.51
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	24252	Reduction 21.84%	29955	Reduction 3.46%	39483	Reduction -27.24%	20330	Reduction 34.48%	29858	Reduction 3.78%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	2895198	66.04	10220077	-19.87	12374383	-45.13	30915	99.64	18573	99.78
NOx: Total	3749	95.83	10509	88.33	12959	85.60	34	99.96	113	99.87
PM2.5: Total	481	81.68	1490	43.26	1825	30.52	5	99.82	3	99.88
PM10: Total	703	74.25	2297	15.82	2812	-3.04	7	99.73	4	99.86
CO: Total	1709	87.19	4160	68.82	5113	61.69	13	99.90	27	99.80
VOC: Total	513	88.12	1123	73.99	1379	68.05	4	99.92	7	99.84
SOx: Total	6590	-606.30	18638	-1897.76	22787	-2342.38	60	93.57	1	99.85
CH4	5692	45.79	19394	-84.68	23732	-125.99	62	99.41	24	99.77
N2O	-304	245.14	150	28.30	184	12.23	0	99.77	0	99.88
CO2 (w/ C in VOC & CO)	2800667	65.43	9613490	-18.65	11767796	-45.24	30915	99.62	17793	99.78
BC: Total	69	70.15	98	57.82	120	48.27	0	99.86	0	99.83
OC: Total	77	96.60	221	90.16	272	87.90	1	99.97	2	99.92

Round-trip, RGH-CLT-RGH

HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP, INCL. PLUG ELECTRICITY (kWh)	PLUG-IN ELECTRICITY 100% RENEWABLE	
		Reduction
	1513	62.56%

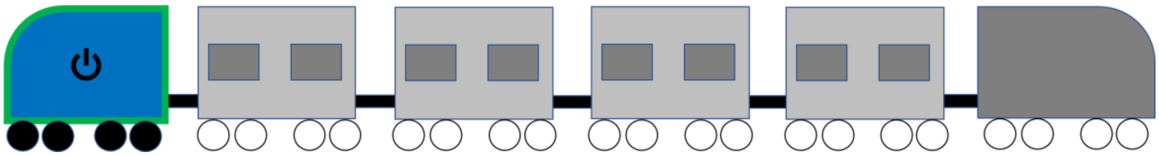
PLUG-IN ELECTRICITY 100% RENEWABLE

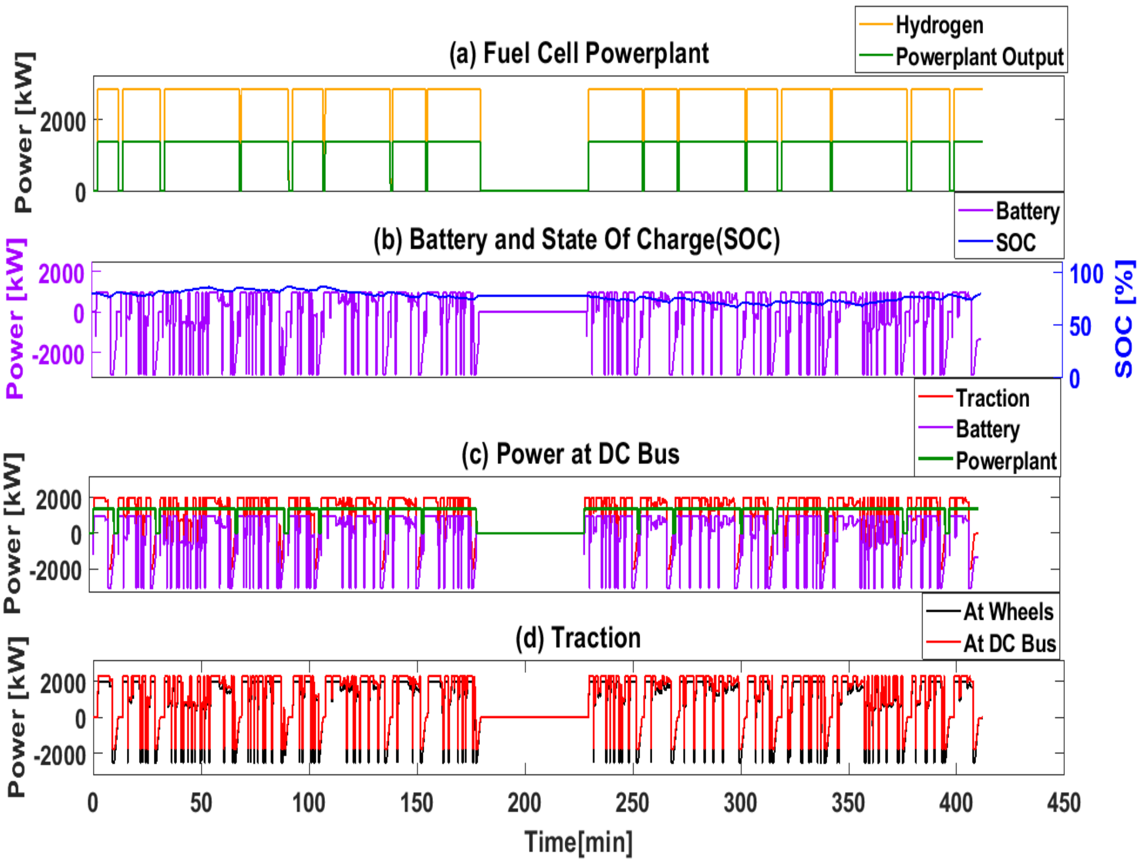
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	Grams
GHGs	660482
NOx: Total	678
PM2.5: Total	96
PM10: Total	148
CO: Total	268
VOC: Total	72
SOx: Total	1203
CH4	1251
N2O	10
CO2 (w/ C in VOC & CO)	620371
BC: TOTAL	6
OC: TOTAL	14

HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION & COMPARISON, WELL-TO-WHEEL, INCL. PLUG ELECTRICITY (kWh)	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
		Reduction		Reduction		Reduction		Reduction
	23318	24.85%	30448	1.87%	19310	37.77%	28266.40416	8.91%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	% Reduct.	In Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5656269	33.66	10648693	-24.89	0	100.00	6779047	20.49
NOx: Total	4185	95.35	10933	87.85	0	100.00	4464	95.04
PM2.5: Total	304	88.44	1550	40.97	0	100.00	587	77.67
PM10: Total	425	84.45	2390	12.42	0	100.00	844	69.06
CO: Total	2703	79.74	4328	67.56	0	100.00	2036	84.74
VOC: Total	824	80.92	1168	72.94	0	100.00	793	81.64
SOx: Total	3342	-258.26	19391	-1978.44	0	100.00	6423	-588.42
CH4	16717	-59.19	20177	-92.14	0	100.00	14660	-39.60
N2O	112	46.54	156	25.41	0	100.00	71	65.87
CO2 (w/ C in VOC & CO)	5125102	36.75	10001995	-23.44	0	100.00	6320323	22.00
BC: Total	24	89.54	102	56.12	0	100.00	47	79.83
OC: Total	47	97.89	230	89.77	0	100.00	103	95.44

HYDROGEN FUEL CELL HYBRID PLUG-IN: ENERGY CONSUMPTION & COMPARISON, WELL-TO-WHEEL, INCL. PLUG ELECTRICITY (kWh)	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
		Reduction		Reduction		Reduction		Reduction		Reduction
	25765	16.97%	31469	-1.41%	40996	-32.12%	20331	34.48%	29859	3.77%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3555680	58.30	10880559	-27.61	13034865	-52.88	30915	99.64	18573	99.78
NOx: Total	4427	95.08	11187	87.57	13637	84.85	34	99.96	113	99.87
PM2.5: Total	577	78.02	1586	39.60	1921	26.86	5	99.82	3	99.88
PM10: Total	851	68.81	2446	10.39	2960	-8.47	7	99.73	4	99.86
CO: Total	1978	85.18	4429	66.81	5381	59.67	13	99.90	27	99.80
VOC: Total	586	86.44	1195	72.32	1452	66.37	4	99.92	7	99.84
SOx: Total	7792	-735.21	19841	-2026.68	23989	-2471.30	60	93.57	1	99.85
CH4	6944	33.88	20645	-96.60	24984	-137.91	62	99.41	24	99.77
N2O	-294	240.52	160	23.67	193	7.61	0	99.77	0	99.88
CO2 (w/ C in VOC & CO)	3421038	57.78	10233860	-26.31	12388166	-52.89	30915	99.62	17793	99.78
BC: Total	76	67.43	104	55.10	127	45.55	0	99.86	0	99.83
OC: Total	91	95.96	235	89.53	286	87.26	1	99.97	2	99.92

9.3.7 Hydrogen Fuel Cell Hybrid Downsized





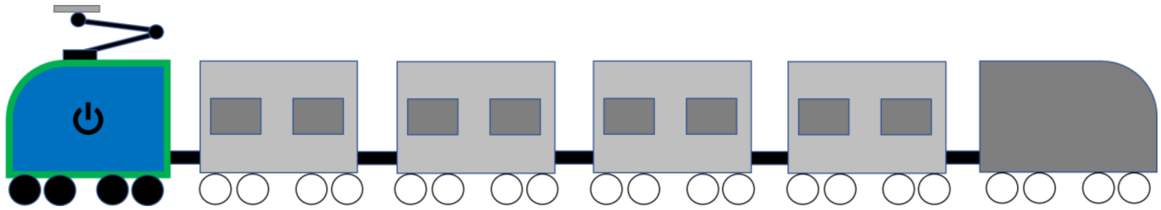
Round-trip, RGH-CLT		
HYDROGEN FUEL CELL HYBRID - DOWNSIZED: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	16325	Reduction 37.17%
POINT-OF-USE-EMISSIONS	ALL PRODUCTION METHODS	
	Grams *(Based on SERC)*	*% Reduct.*
GHGs	0	100
NOx: Total	0	100
PM2.5: Total	0	100
PM10: Total	0	100
CO: Total	0	100
VOC: Total	0	100
SOx: Total	0	100
CH4	0	100
N2O	0	100
CO2 (w/ C in VOC & CO)	0	100
BC: Total	0	100
OC: Total	0	100

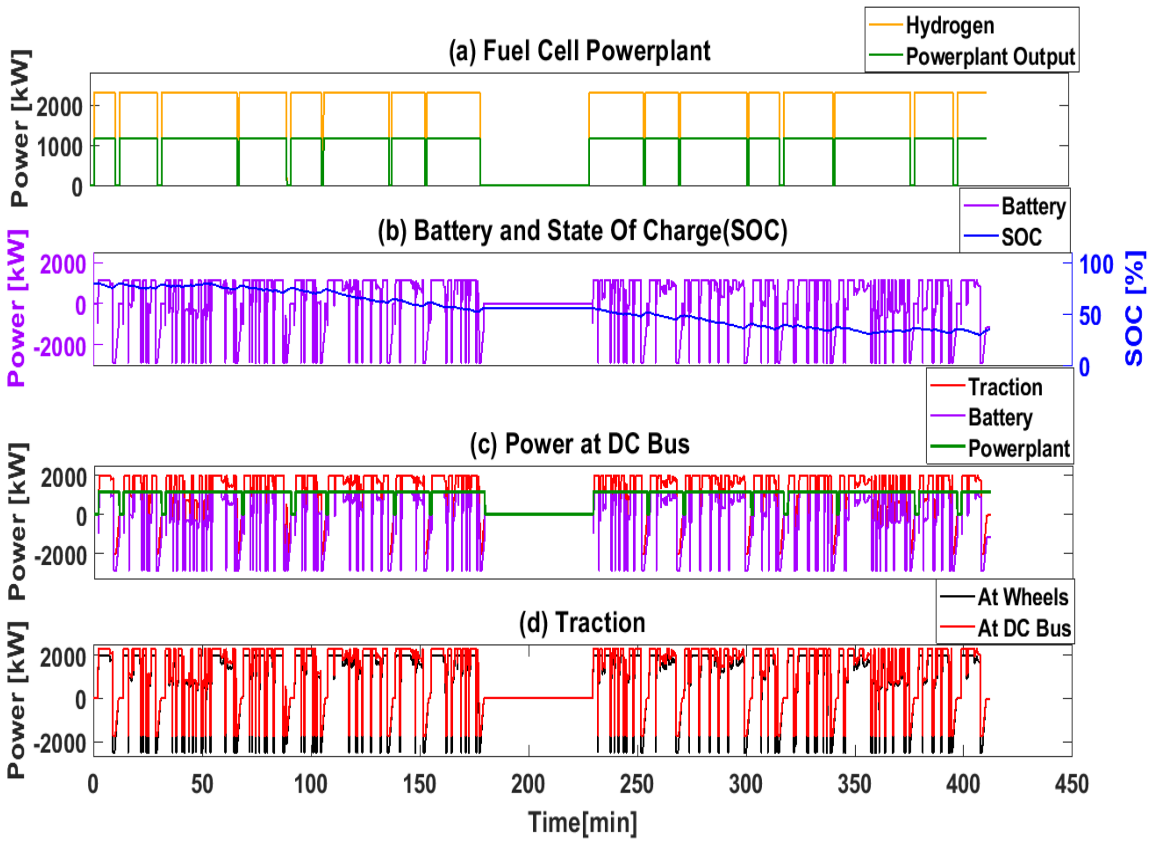
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC		LIQUID DELIVERY, BIOMASS	
HYDROGEN FUEL CELL HYBRID DOWNSIZED: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12576	Reduction -149.08%	22025.36585	Reduction -336.25%	9268	Reduction -83.58%	19134	Reduction -278.98%	15819	Reduction -213.32%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC		LIQUID DELIVERY, BIOMASS	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*
GHGs	6621436	-333.35	13238414	-766.41	0	100.00	8109570	-430.74	3837307	-151.14
NOx: Total	4648	-97.69	13592	-478.13	0	100.00	5018	-113.44	4969	-111.37
PM2.5: Total	275	-106.52	1928	-1347.29	0	100.00	650	-387.99	638	-378.77
PM10: Total	366	-130.83	2971	-1773.11	0	100.00	923	-481.66	932	-487.25
CO: Total	3227	-184.97	5381	-375.24	0	100.00	2343	-106.94	2265	-100.07
VOC: Total	996	-46.69	1452	-113.97	0	100.00	955	-40.65	680	-0.20
SOx: Total	2836	-220.49	24107	-2624.31	0	100.00	6919	-681.87	8734	-887.00
CH4	20498	-107.12	25084	-153.47	0	100.00	17771	-79.57	7545	23.76
N2O	136	-565.29	194	-853.16	0	100.00	82	-301.94	-403	2077.26
CO2 (w/ C in VOC & CO)	5970588	-396.32	12434441	-933.65	0	100.00	7554739	-528.01	3712015	-208.57
BC: Total	24	-3.23	127	-448.76	0	100.00	54	-132.69	92	-297.92
OC: Total	44	-11.24	286	-624.59	0	100.00	117	-196.57	101	-156.98

PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC		LIQUID DELIVERY, BIOMASS	
HYDROGEN FUEL CELL HYBRID DOWNSIZED: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	28901	Reduction 6.86%	38350	Reduction -23.59%	25593	Reduction 17.52%	35459	Reduction -14.27%	32144	Reduction -3.59%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC		LIQUID DELIVERY, BIOMASS	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*
GHGs	6621436	22.34	13238414	-55.27	0	100.00	8109570	4.89	3837307	54.99
NOx: Total	4648	94.84	13592	84.90	0	100.00	5018	94.43	4969	94.48
PM2.5: Total	275	89.53	1928	26.62	0	100.00	650	75.26	638	75.72
PM10: Total	366	86.58	2971	-8.87	0	100.00	923	66.19	932	65.87
CO: Total	3227	75.82	5381	59.67	0	100.00	2343	82.44	2265	83.02
VOC: Total	996	76.94	1452	66.36	0	100.00	955	77.89	680	84.25
SOx: Total	2836	-203.97	24107	-2483.91	0	100.00	6919	-641.57	8734	-836.13
CH4	20498	-95.19	25084	-138.87	0	100.00	17771	-69.23	7545	28.15
N2O	136	35.27	194	7.26	0	100.00	82	60.89	-403	292.37
CO2 (w/ C in VOC & CO)	5970588	26.31	12434441	-53.46	0	100.00	7554739	6.76	3712015	54.19
BC: Total	24	89.74	127	45.45	0	100.00	54	76.87	92	60.44
OC: Total	44	98.05	286	87.28	0	100.00	117	94.79	101	95.49

Round-trip, RGH-CLT-RGH								
PRODUCTION METHOD	GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
HYDROGEN FUEL CELL HYBRID DOWNSIZED: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	23378	Reduction -363.04%	36006	Reduction -613.17%	10621	Reduction -110.36%	23249	Reduction -360.49%
PRODUCTION METHOD	GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams	*% Reduct.*
GHGs	13545730	-786.52	16401055	-973.39	40975	97.32	24616	98.389
NOx: Total	13928	-492.43	17176	-630.58	45	98.09	150	93.629
PM2.5: Total	1975	-1383.10	2419	-1716.27	6	95.23	4	96.778
PM10: Total	3045	-1819.45	3727	-2249.58	10	93.82	5	96.895
CO: Total	5514	-387.00	6776	-498.48	18	98.43	36	96.856
VOC: Total	1488	-119.27	1828	-169.38	5	99.29	9	98.664
SOx: Total	24703	-2691.71	30201	-3313.03	80	91.01	2	99.787
CH4	25705	-159.74	31455	-217.84	83	99.16	32	99.681
N2O	199	-876.74	244	-1095.62	1	96.86	0	98.426
CO2 (w/ C in VOC & CO)	12741757	-959.20	15597082	-1196.56	40975	96.59	23583	98.040
BC: Total	130	-462.34	159	-589.65	0	98.19	1	97.784
OC: Total	293	-642.52	361	-813.64	1	97.61	2	94.047
PRODUCTION METHOD	GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
HYDROGEN FUEL CELL HYBRID DOWNSIZED: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	39703	Reduction -27.95%	52331.13184	Reduction -68.65%	26946	Reduction 13.16%	39574	Reduction -27.54%
PRODUCTION METHOD	GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams	*% Reduct.*
GHGs	13545730	-58.87	16401055	-92.36	40975	99.52	24616	99.71
NOx: Total	13928	84.53	17176	80.92	45	99.95	150	99.83
PM2.5: Total	1975	24.80	2419	7.91	6	99.76	4	99.84
PM10: Total	3045	-11.57	3727	-36.57	10	99.64	5	99.82
CO: Total	5514	58.68	6776	49.22	18	99.87	36	99.73
VOC: Total	1488	65.53	1828	57.65	5	99.89	9	99.79
SOx: Total	24703	-2547.84	30201	-3137.14	80	91.48	2	99.80
CH4	25705	-144.78	31455	-199.53	83	99.21	32	99.70
N2O	199	4.97	244	-16.33	1	99.69	0	99.85
CO2 (w/ C in VOC & CO)	12741757	-57.26	15597082	-92.50	40975	99.49	23583	99.71
BC: Total	130	44.10	159	31.44	0	99.82	1	99.78
OC: Total	293	86.96	361	83.96	1	99.96	2	99.90

9.3.8 Hydrogen Fuel Cell Hybrid Downsized Plugin





Round-trip, RGH-CLT-RGH		
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	12721	Reduction 51.04%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	9799	Reduction -94.10%	17163	Reduction -239.94%	7222	Reduction -43.05%	14910	Reduction -195.31%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*
GHGs	5159650	-237.68	10315827	-575.13	0	100.00	6319255	-313.57
NOx: Total	3622	-54.05	10591	-350.50	0	100.00	3910	-66.32
PM2.5: Total	214	-60.93	1502	-1027.78	0	100.00	506	-280.26
PM10: Total	285	-79.87	2315	-1359.59	0	100.00	719	-353.25
CO: Total	2514	-122.06	4193	-270.33	0	100.00	1826	-61.26
VOC: Total	776	-14.31	1132	-66.73	0	100.00	744	-9.60
SOx: Total	2210	-149.74	18785	-2022.88	0	100.00	5391	-509.26
CH4	15973	-61.40	19546	-97.51	0	100.00	13848	-39.93
N2O	106	-418.42	151	-642.73	0	100.00	64	-213.20
CO2 (w/ C in VOC & CO)	4652487	-286.75	9689343	-705.46	0	100.00	5886912	-389.37
BC: Total	19	19.56	99	-327.61	0	100.00	42	-81.32
OC: Total	34	13.32	223	-464.63	0	100.00	91	-131.09

PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	22520	Reduction 27.42%	29884	Reduction 3.69%	19943	Reduction 35.73%	27631	Reduction 10.95%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*
GHGs	5159650	39.49	10315827	-20.99	0	100.00	6319255	25.88
NOx: Total	3622	95.98	10591	88.23	0	100.00	3910	95.66
PM2.5: Total	214	91.84	1502	42.82	0	100.00	506	80.72
PM10: Total	285	89.55	2315	15.16	0	100.00	719	73.66
CO: Total	2514	81.16	4193	68.58	0	100.00	1826	86.32
VOC: Total	776	82.03	1132	73.79	0	100.00	744	82.77
SOx: Total	2210	-136.87	18785	-1913.47	0	100.00	5391	-477.86
CH4	15973	-52.10	19546	-86.13	0	100.00	13848	-31.87
N2O	106	49.56	151	27.74	0	100.00	64	69.53
CO2 (w/ C in VOC & CO)	4652487	42.58	9689343	-19.58	0	100.00	5886912	27.34
BC: Total	19	92.00	99	57.49	0	100.00	42	81.97
OC: Total	34	98.48	223	90.09	0	100.00	91	95.94

Round-trip RGH-CLT-RGH										
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS, 100%		LIQUID DELIVERY, ELECTROLYSIS, 100%	
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12327	Reduction -144.15%	18217	Reduction -260.82%	28057	Reduction -455.72%	8276	Reduction -63.92%	18116	Reduction -258.83%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS, 100%		LIQUID DELIVERY, ELECTROLYSIS, 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams	*% Reduct.*
GHGs	2990161	-95.69	10555297	-590.81	12780265	-736.42	31929	97.91	19182	98.74
NOx: Total	3872	-64.70	10853	-361.64	13384	-469.29	35	98.51	117	95.04
PM2.5: Total	497	-273.07	1539	-1055.68	1885	-1315.30	5	96.28	3	97.49
PM10: Total	726	-357.60	2373	-1395.70	2904	-1730.87	8	95.19	4	97.58
CO: Total	1765	-55.90	4297	-279.49	5280	-366.36	14	98.78	28	97.55
VOC: Total	530	21.92	1160	-70.86	1425	-109.91	4	99.45	7	98.96
SOx: Total	6806	-669.10	19250	-2075.40	23534	-2559.55	62	93.00	1	99.83
CH4	5879	40.59	20030	-102.40	24511	-147.67	64	99.35	25	99.75
N2O	-314	1640.75	155	-661.11	190	-831.67	0	97.55	0	98.77
CO2 (w/ C in VOC & CO)	2892530	-140.45	9928814	-725.36	12153782	-910.32	31929	97.35	18377	98.47
BC: Total	72	-210.07	101	-338.19	124	-437.40	0	98.59	0	98.27
OC: Total	79	-100.25	228	-478.60	281	-611.94	1	98.14	2	95.36

PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS, 100%		LIQUID DELIVERY, ELECTROLYSIS, 100%	
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	25048	Reduction 19.28%	30938	Reduction 0.30%	40778	Reduction -31.42%	20997	Reduction 32.33%	30837	Reduction 0.62%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS, 100%		LIQUID DELIVERY, ELECTROLYSIS, 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams	*% Reduct.*
GHGs	2990161	64.93	10555297	-23.80	12780265	-49.89	31929	99.63	19182	99.78
NOx: Total	3872	95.70	10853	87.94	13384	85.13	35	99.96	117	99.87
PM2.5: Total	497	81.08	1539	41.40	1885	28.24	5	99.81	3	99.87
PM10: Total	726	73.40	2373	13.06	2904	-6.42	8	99.72	4	99.86
CO: Total	1765	86.77	4297	67.80	5280	60.43	14	99.90	28	99.79
VOC: Total	530	87.73	1160	73.14	1425	67.00	4	99.91	7	99.84
SOx: Total	6806	-629.46	19250	-1963.29	23534	-2422.49	62	93.36	1	99.84
CH4	5879	44.01	20030	-90.74	24511	-133.41	64	99.39	25	99.77
N2O	-314	249.90	155	25.95	190	9.36	0	99.76	0	99.88
CO2 (w/ C in VOC & CO)	2892530	64.30	9928814	-22.54	12153782	-50.00	31929	99.61	18377	99.77
BC: Total	72	69.18	101	56.44	124	46.58	0	99.86	0	99.83
OC: Total	79	96.48	228	89.84	281	87.50	1	99.97	2	99.92

Round-trip RGH-CLT-RGH

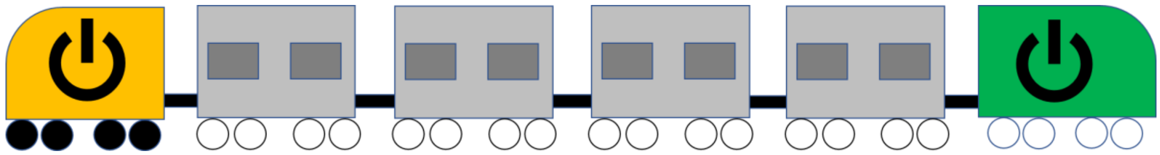
ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP, PLUG		
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	1513	Reduction 62.56%
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	Grams *(Based on SERC)*	
GHGs	660482	
NOx: Total	678	
PM2.5: Total	96	
PM10: Total	148	
CO: Total	268	
VOC: Total	72	
SOx: Total	1203	
CH4	1251	
N2O	10	
CO2 (w/ C in VOC & CO)	620371	
BC: Total	6	
OC: Total	14	

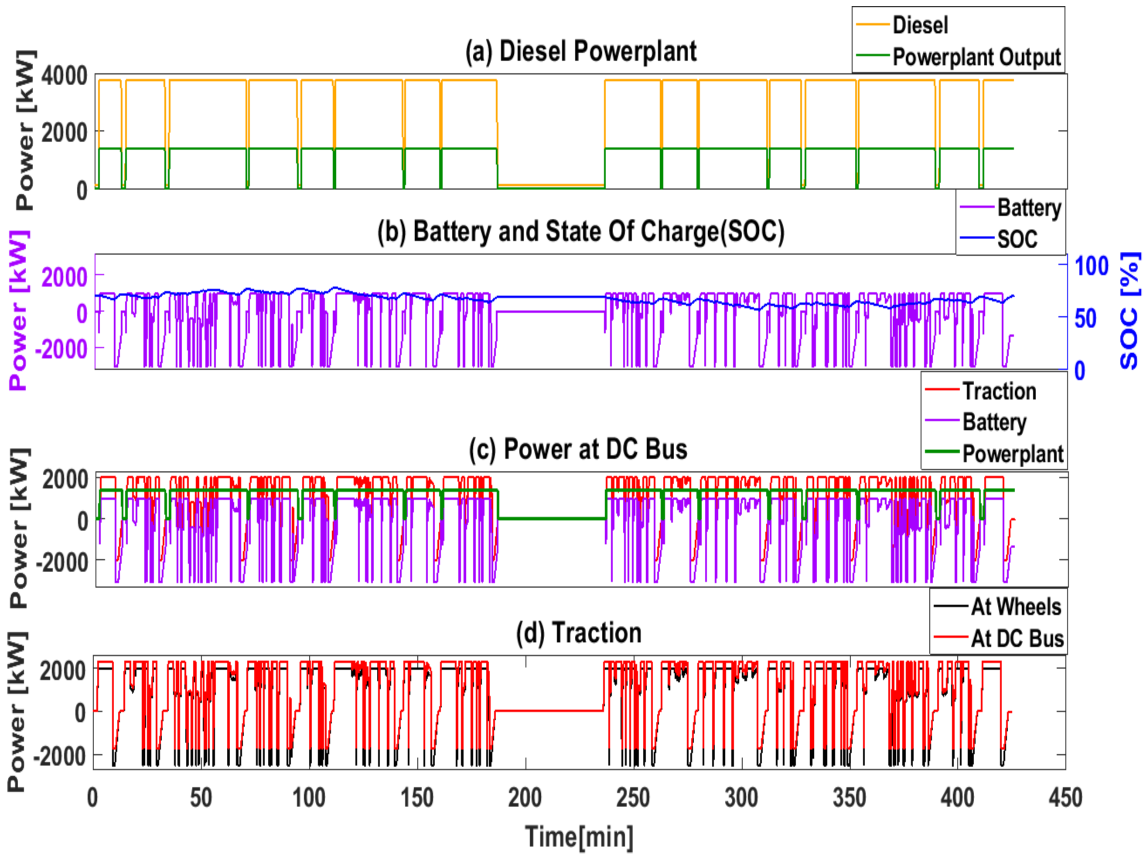
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	24034	Reduction 22.55%	31397	Reduction -1.18%	19943	Reduction 35.73%	29144	Reduction 6.08%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*
GHGs	5820132	31.74	10976308	-28.74	0	100.00	6979737	18.14
NOx: Total	4300	95.22	11269	87.48	0	100.00	4588	94.90
PM2.5: Total	310	88.18	1598	39.16	0	100.00	603	77.06
PM10: Total	434	84.11	2464	9.73	0	100.00	867	68.22
CO: Total	2783	79.15	4461	66.57	0	100.00	2094	84.31
VOC: Total	848	80.35	1204	72.11	0	100.00	816	81.09
SOx: Total	3413	-265.78	19988	-2042.39	0	100.00	6594	-606.77
CH4	17224	-64.02	20798	-98.05	0	100.00	15099	-43.79
N2O	115	44.93	161	23.11	0	100.00	73	64.90
CO2 (w/ C in VOC & CO)	5272858	34.92	10309714	-27.24	0	100.00	6507282	19.69
BC: Total	25	89.28	105	54.77	0	100.00	48	79.25
OC: Total	48	97.84	237	89.45	0	100	106	95.31

Round-trip RGH-CLT-RGH

PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS, 100%		LIQUID DELIVERY, ELECTROLYSIS, 100%	
HYDROGEN FUEL CELL HYBRID DOWNSIZED - PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	26561	Reduction 14.40%	32451	Reduction -4.58%	42291	Reduction -36.29%	20997	Reduction 32.33%	30837	Reduction 0.62%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS, 100%		LIQUID DELIVERY, ELECTROLYSIS, 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams *(Based on SERC)*	*% Reduct.*	Grams	*% Reduct.*	Grams	*% Reduct.*
GHGs	3650643	57.18	11215779	-31.54	13440747	-57.64	31929	99.63	19182	99.78
NOx: Total	4550	94.94	11531	87.19	14062	84.38	35	99.96	117	99.87
PM2.5: Total	593	77.42	1635	37.74	1981	24.58	5	99.81	3	99.87
PM10: Total	874	67.97	2521	7.63	3053	-11.85	8	99.72	4	99.86
CO: Total	2034	84.76	4565	65.79	5549	58.42	14	99.90	28	99.79
VOC: Total	602	86.05	1232	71.46	1497	65.32	4	99.91	7	99.84
SOx: Total	8008	-758.38	20452	-2092.20	24737	-2551.41	62	93.36	1	99.84
CH4	7131	32.10	21281	-102.65	25762	-145.32	64	99.39	25	99.77
N2O	-304	245.28	165	21.32	199	4.73	0	99.76	0	99.88
CO2 (w/ C in VOC & CO)	3512900	56.64	10549185	-30.20	12774152	-57.66	31929	99.61	18377	99.77
BC: Total	78	66.45	108	53.72	131	43.85	0	99.86	0	99.83
OC: Total	93	95.85	243	89.21	295	86.86	1	99.97	2	99.92

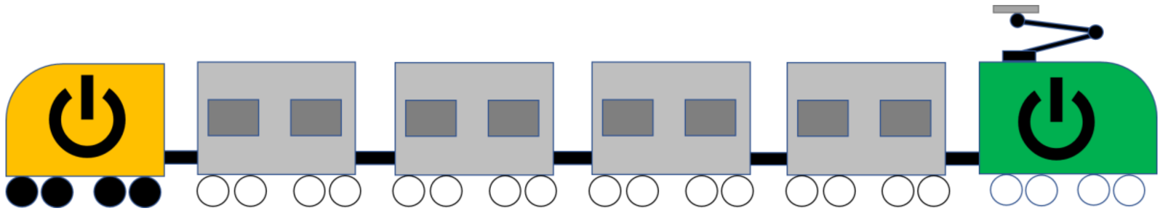
9.3.9 Diesel and Battery

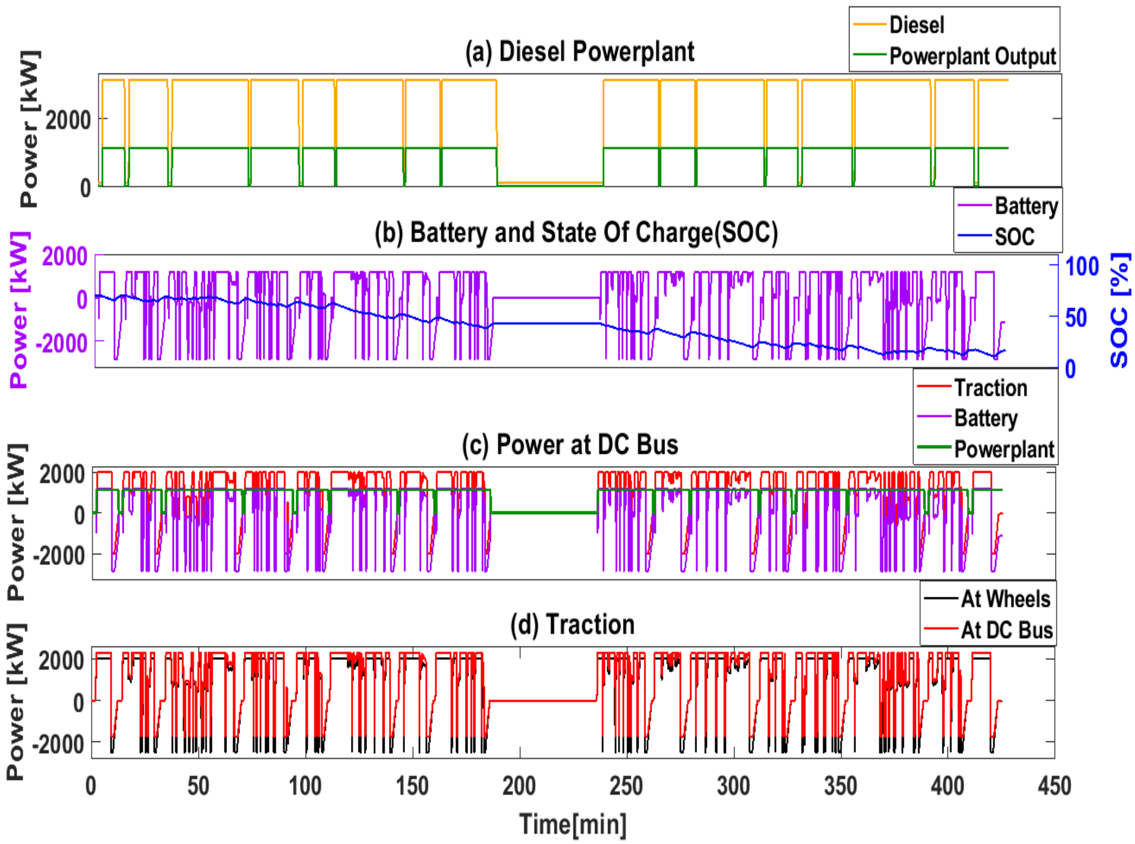




Round-trip, RGH-CLT-RGH		
DIESEL AND BATTERY (TWO LOCOMOTIVES): ENERGY CONSUMPTION & COMPARISON, POINT-OF-USE (kWh)	**22224**	**Reduction** **14.46%**
POINT-OF-USE-EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	**5986304**	**14.46**
NOx: Total	**74984**	**14.46**
PM2.5: Total	**2133**	**14.46**
PM10: Total	**2199**	**14.46**
CO: Total	**10445**	**14.46**
VOC: Total	**3113**	**14.46**
SOx: Total	**41**	**14.46**
CH4	**517**	**14.46**
N2O	**162**	**14.46**
CO2 (w/ C in VOC & CO)	**5901823**	**14.46**
BC: Total	**179**	**14.46**
OC: Total	**1890**	**14.46**
DIESEL AND BATTERY (TWO LOCOMOTIVES): ENERGY CONSUMPTION & COMPARISON, POINT-OF-USE (kWh)	**4318.7**	**Reduction** **14.46%**
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	**1307017**	**14.46**
NOx: Total	**2011**	**14.46**
PM2.5: Total	**114**	**14.46**
PM10: Total	**136**	**14.46**
CO: Total	**969**	**14.46**
VOC: Total	**581**	**14.46**
SOx: Total	**757**	**14.46**
CH4	**8465**	**14.46**
N2O	**17**	**14.46**
CO2 (w/ C in VOC & CO)	**1029006**	**14.46**
BC: Total	**20**	**14.46**
OC: Total	**34**	**14.46**
DIESEL AND BATTERY (TWO LOCOMOTIVES): ENERGY CONSUMPTION & COMPARISON, POINT-OF-USE (kWh)	**26543**	**Reduction** **14.46%**
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct**
GHGs	**7293321**	**14.46**
NOx: Total	**76995**	**14.46**
PM2.5: Total	**2247**	**14.46**
PM10: Total	**2335**	**14.46**
CO: Total	**11414**	**14.46**
VOC: Total	**3693**	**14.46**
SOx: Total	**798**	**14.46**
CH4	**8983**	**14.46**
N2O	**179**	**14.46**
CO2 (w/ C in VOC & CO)	**6930829**	**14.46**
BC: Total	**199**	**14.46**
OC: Total	**1924**	**14.46**

9.3.10 Diesel and Battery Plugin





Round-trip, RGH-CLT-RGH

DIESEL AND BATTERY PLUG-IN (TWO LOCOS): ENERGY CONSUMPTION & COMPARISON, POINT-OF-USE (kWh)	18631	Reduction 28.29%
POINT-OF-USE-EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	5018486	28.29
NOx: Total	62861	28.29
PM2.5: Total	1788	28.29
PM10: Total	1843	28.29
CO: Total	8757	28.29
VOC: Total	2609	28.29
SOx: Total	34	28.29
CH4	434	28.29
N2O	136	28.29
CO2 (w/ C in VOC & CO)	4947663	28.29
BC: Total	150	28.29
OC: Total	1584	28.29

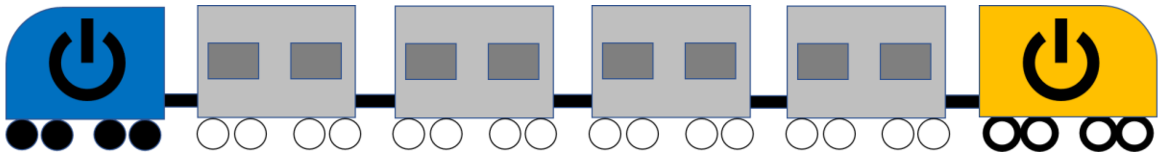
DIESEL AND BATTERY PLUG-IN (TWO LOCOS): ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP (kWh)	3620.478558 28.28990416	Reduction
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***	***In %***
GHGs	1095708.99	28.289904
NOx: Total	1685.917196	28.289904
PM2.5: Total	95.5044533	28.289904
PM10: Total	113.7585194	28.289904
CO: Total	811.9207839	28.289904
VOC: Total	486.7219087	28.289904
SOx: Total	634.5514945	28.289904
CH4	7096.699977	28.289904
N2O	14.60734648	28.289904
CO2 (w/ C in VOC & CO)	862644.4917	28.289904
BC: Total	16.57978906	28.289904
OC: Total	28.31379905	28.289904

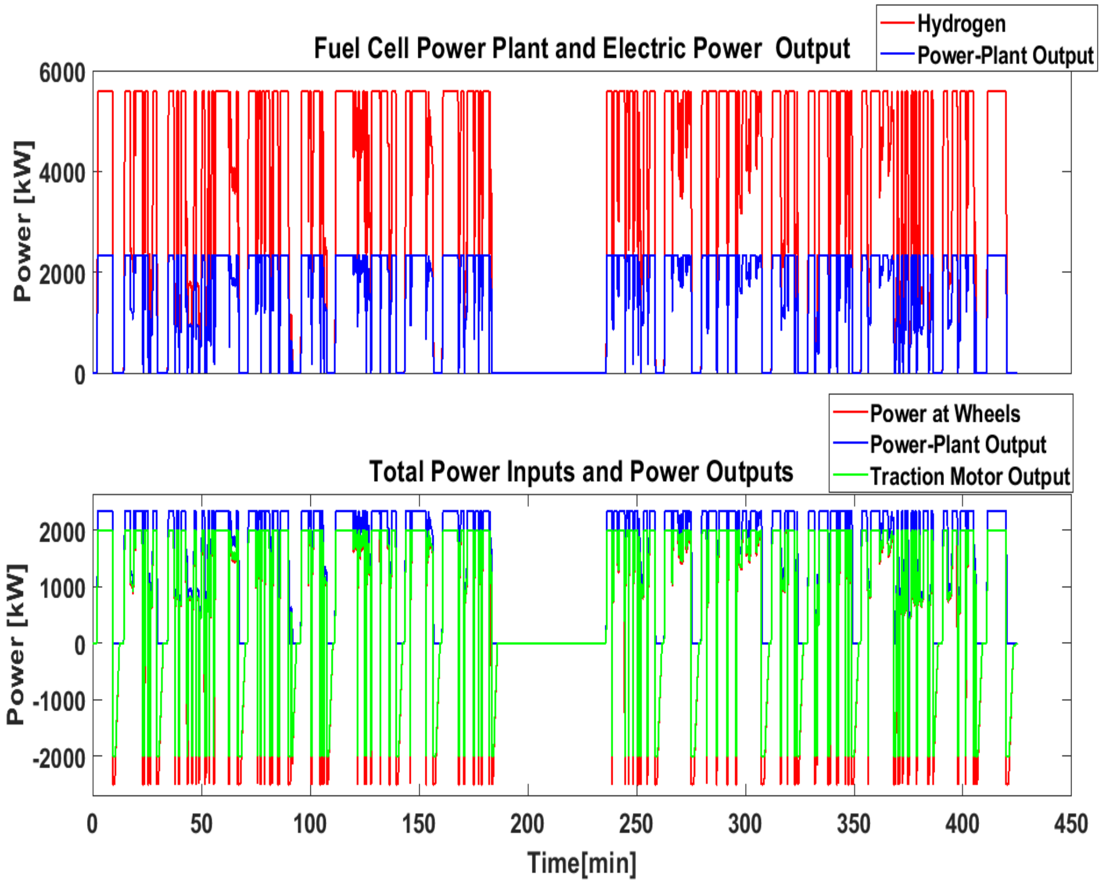
ENERGY REQUIREMENT (kWh), ELECTRICITY	2003	
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	**Grams *(Based on SERC)***	
GHGs	874398.0965	
NOx: Total	897.7459797	
PM2.5: Total	127.3132372	
PM10: Total	196.2633263	
CO: Total	355.4046506	
VOC: Total	95.92490097	
SOx: Total	1592.269817	
CH4	1656.801675	
N2O	12.82418601	
CO2 (w/ C in VOC & CO)	821295.637	
BC: Total	8.380184129	
OC: Total	18.8966217	

DIESEL AND BATTERY PLUG-IN (TWO LOCOS): ENERGY CONSUMPTION & COMPARISON, WELL-TO-WHEEL (kWh)	22251	Reduction 28.29%
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	6114195	28.29
NOx: Total	64547	28.29
PM2.5: Total	1884	28.29
PM10: Total	1957	28.29
CO: Total	9569	28.29
VOC: Total	3096	28.29
SOx: Total	669	28.29
CH4	7531	28.29
N2O	150	28.29
CO2 (w/ C in VOC & CO)	5810307	28.29
BC: Total	167	28.29
OC: Total	1613	28.29

DIESEL AND BATTERY PLUG-IN (TWO LOCOS): ENERGY CONSUMPTION & COMPARISON, WELL-TO-WHEEL (kWh) INCL. PLUG	24255	Reduction 21.83%
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	6988593	18.03
NOx: Total	65445	27.29
PM2.5: Total	2011	23.44
PM10: Total	2153	21.10
CO: Total	9924	25.63
VOC: Total	3192	26.07
SOx: Total	2261	-142.38
CH4	9187	12.51
N2O	163	22.16
CO2 (w/ C in VOC & CO)	6631603	18.15
BC: Total	175	24.69
OC: Total	1631	27.45

9.3.11 Fuel Cell and Diesel





Round-trip, RGH-CLT-RGH

HYDROGEN FUEL CELL & DIESEL (TWO LOCOS): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	21064	Reduction 18.93%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

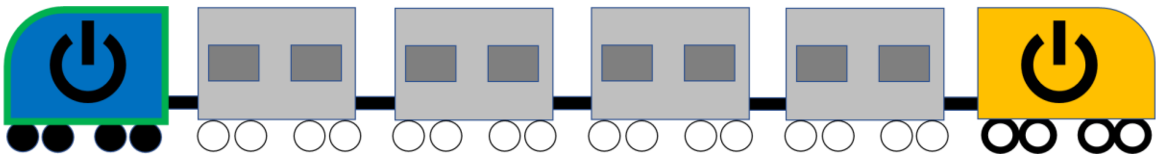
HYDROGEN FUEL CELL & DIESEL (TWO LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	16226	Reduction -221.39%	28419	Reduction -462.89%	11959	Reduction -136.87%	24688	Reduction -388.99%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	In Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	8543579	-459.15	17081406	-1017.91	0	100.00	10463705	-584.81
NOx: Total	5997	-155.08	17538	-645.95	0	100.00	6475	-175.40
PM2.5: Total	355	-166.48	2487	-1767.43	0	100.00	839	-529.64
PM10: Total	472	-197.84	3834	-2316.85	0	100.00	1191	-650.51
CO: Total	4163	-267.70	6943	-513.20	0	100.00	3023	-167.02
VOC: Total	1285	-89.28	1874	-176.09	0	100.00	1232	-81.48
SOx: Total	3659	-313.53	31105	-3415.16	0	100.00	8927	-908.84
CH4	26448	-167.25	32366	-227.05	0	100.00	22930	-131.70
N2O	175	-758.42	251	-1129.85	0	100.00	106	-418.62
CO2 (w/ C in VOC & CO)	7703796	-540.40	16044047	-1233.71	0	100.00	9747811	-710.32
BC: Total	31	-33.20	164	-608.06	0	100.00	69	-200.24
OC: Total	57	-43.54	369	-834.93	0	100.00	151	-282.66

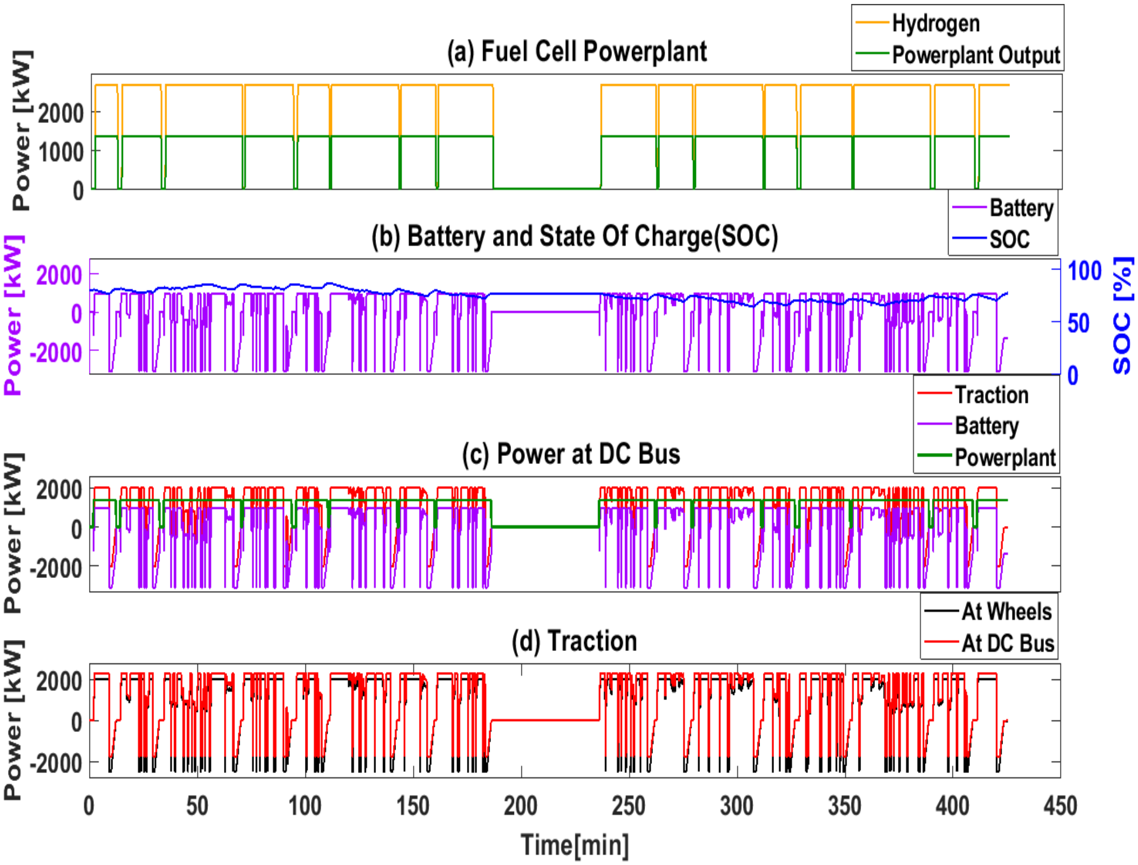
HYDROGEN FUEL CELL & DIESEL (TWO LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	37290	Reduction -20.18%	49483	Reduction -59.47%	33023	Reduction -6.42%	45752	Reduction -47.45%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	8543579	-0.20	17081406	-100.34	0	100.00	10463705	-22.72
NOx: Total	5997	93.34	17538	80.52	0	100.00	6475	92.81
PM2.5: Total	355	86.49	2487	5.32	0	100.00	839	68.08
PM10: Total	472	82.69	3834	-40.48	0	100.00	1191	56.38
CO: Total	4163	68.80	6943	47.97	0	100.00	3023	77.34
VOC: Total	1285	70.25	1874	56.60	0	100.00	1232	71.47
SOx: Total	3659	-292.22	31105	-3234.00	0	100.00	8927	-856.84
CH4	26448	-151.86	32366	-208.21	0	100.00	22930	-118.35
N2O	175	16.48	251	-19.66	0	100.00	106	49.54
CO2 (w/ C in VOC & CO)	7703796	4.92	16044047	-98.01	0	100.00	9747811	-20.31
BC: Total	31	86.76	164	29.61	0	100.00	69	70.15
OC: Total	57	97.48	369	83.58	0	100.00	151	93.28

Round-trip, RGH-CLT-RGH										
HYDROGEN FUEL CELL & DIESEL (TWO LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	20411	Reduction -304.28%	30164	Reduction -497.46%	46458	Reduction -820.19%	13704	Reduction -171.43%	29998	Reduction -494.17%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	In Grams	% Reduct.	In Grams	*in %*
GHGs	4951242	-224.04	17477933	-1043.87	21162133	-1284.98	52870	96.54	31762	97.92
NOx: Total	6412	-172.72	17971	-664.41	22162	-842.66	58	97.54	193	91.78
PM2.5: Total	823	-517.75	2549	-1813.63	3121	-2243.52	8	93.84	6	95.84
PM10: Total	1202	-657.72	3929	-2376.65	4809	-2931.64	13	92.03	6	95.99
CO: Total	2923	-158.15	7115	-528.37	8743	-672.21	23	97.98	46	95.94
VOC: Total	878	-29.29	1920	-182.92	2359	-247.58	6	99.09	12	98.28
SOx: Total	11269	-1173.51	31875	-3502.12	38969	-4303.81	103	88.40	2	99.72
CH4	9735	1.63	33166	-235.14	40586	-310.11	107	98.92	41	99.59
N2O	-520	2651.24	257	-1160.28	314	-1442.69	1	95.94	0	97.97
CO2 (w/ C in VOC & CO)	4789580	-298.15	16440574	-1266.68	20124775	-1572.94	52870	95.60	30429	97.47
BC: Total	119	-413.43	168	-625.58	206	-789.85	1	97.66	1	97.14
OC: Total	131	-231.58	378	-858.06	465	-1078.86	1	96.92	3	92.32

HYDROGEN FUEL CELL & DIESEL (TWO LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	41475	Reduction -33.66%	51228	Reduction -65.09%	67522	Reduction -117.61%	34768	Reduction -12.05%	51062	Reduction -64.56%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASSEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		Gaseous Delivery, Electrolysis 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	4951242	41.93	17477933	-104.99	21162133	-148.20	52870	99.38	31762	99.63
NOx: Total	6412	92.88	17971	80.03	22162	75.38	58	99.94	193	99.79
PM2.5: Total	823	68.68	2549	2.97	3121	-18.82	8	99.69	6	99.79
PM10: Total	1202	55.96	3929	-43.95	4809	-76.21	13	99.54	6	99.77
CO: Total	2923	78.10	7115	46.68	8743	34.48	23	99.83	46	99.66
VOC: Total	878	79.68	1920	55.52	2359	45.36	6	99.86	12	99.73
SOx: Total	11269	-1107.88	31875	-3316.48	38969	-4076.85	103	89.00	2	99.74
CH4	9735	7.30	33166	-215.83	40586	-286.48	107	98.98	41	99.61
N2O	-520	348.22	257	-22.62	314	-50.09	1	99.61	0	99.80
CO2 (w/ C in VOC & CO)	4789580	40.89	16440574	-102.91	20124775	-148.38	52870	99.35	30429	99.62
BC: Total	119	48.96	168	27.87	206	11.54	1	99.77	1	99.72
OC: Total	131	94.18	378	83.18	465	79.30	1	99.95	3	99.87

9.3.12 Fuel Cell Hybrid and Diesel





Round-trip, RGH-CLT-RGH

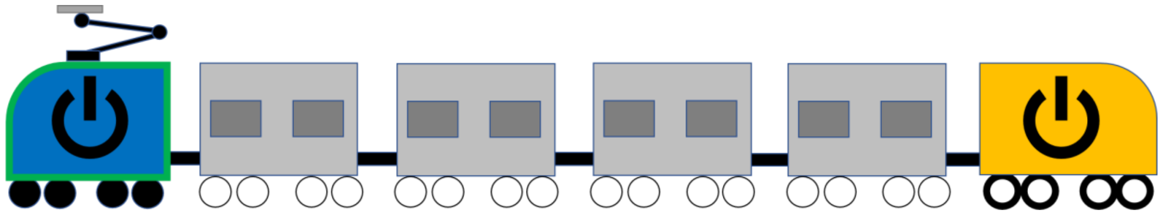
HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	15992	Reduction 38.45%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

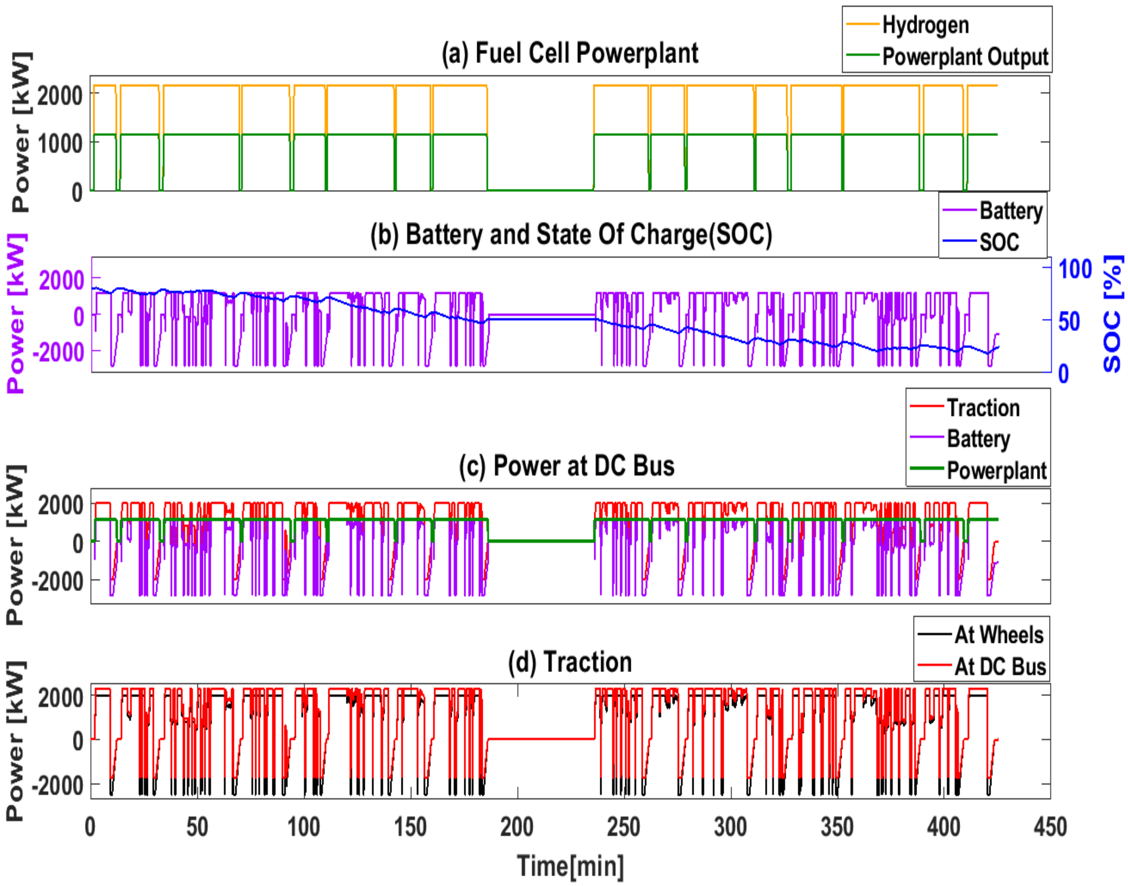
HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12319	Reduction -144.00%	21576	Reduction -327.35%	9079	Reduction -79.83%	18743	Reduction -271.25%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6486371	-324.51	12968375	-748.73	0	100.00	7944150	-419.92
NOx: Total	4553	-93.66	13315	-466.34	0	100.00	4916	-109.09
PM2.5: Total	269	-102.31	1888	-1317.77	0	100.00	637	-378.03
PM10: Total	359	-126.12	2911	-1734.90	0	100.00	904	-469.80
CO: Total	3161	-179.16	5271	-365.55	0	100.00	2295	-102.72
VOC: Total	975	-43.70	1423	-109.61	0	100.00	935	-37.78
SOx: Total	2778	-213.95	23615	-2568.74	0	100.00	6777	-665.92
CH4	20080	-102.90	24572	-148.30	0	100.00	17409	-75.91
N2O	133	-551.72	190	-833.72	0	100.00	80	-293.74
CO2 (w/ C in VOC & CO)	5848799	-386.20	12180802	-912.57	0	100.00	7400636	-515.20
BC: Total	23	-1.13	124	-437.57	0	100.00	53	-127.94
OC: Total	43	-8.97	280	-609.81	0	100.00	115	-190.52

HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	28311	Reduction 8.76%	37568	Reduction -21.07%	25071	Reduction 19.20%	34735	Reduction -11.94%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6486371	23.92	12968375	-52.10	0	100.00	7944150	6.83
NOx: Total	4553	94.94	13315	85.21	0	100.00	4916	94.54
PM2.5: Total	269	89.74	1888	28.11	0	100.00	637	75.76
PM10: Total	359	86.86	2911	-6.65	0	100.00	904	66.88
CO: Total	3161	76.31	5271	60.50	0	100.00	2295	82.80
VOC: Total	975	77.41	1423	67.05	0	100.00	935	78.34
SOx: Total	2778	-197.77	23615	-2431.20	0	100.00	6777	-626.45
CH4	20080	-91.21	24572	-133.99	0	100.00	17409	-65.78
N2O	133	36.59	190	9.16	0	100.00	80	61.69
CO2 (w/ C in VOC & CO)	5848799	27.81	12180802	-50.33	0	100.00	7400636	8.66
BC: Total	23	89.95	124	46.56	0	100.00	53	77.34
OC: Total	43	98.09	280	87.54	0	100.00	115	94.90

Round-trip RGH-CLT-RGH										
HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**15496**	**Reduction** -206.93%	**22901**	**Reduction** -353.60%	**35272**	**Reduction** -598.62%	**10404**	**Reduction** -106.07%	**22775**	**Reduction** -351.10%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3759033	-146.01	13269422	-768.43	16066504	-951.49	40140	97.37	24114	98.42
NOx: Total	4868	-107.06	13644	-480.35	16826	-615.68	44	98.13	147	93.76
PM2.5: Total	625	-369.00	1935	-1352.85	2370	-1679.22	6	95.32	4	96.84
PM10: Total	913	-475.27	2983	-1780.29	3651	-2201.65	10	93.95	5	96.96
CO: Total	2219	-95.99	5401	-377.07	6638	-486.27	17	98.46	35	96.92
VOC: Total	666	1.84	1458	-114.79	1791	-163.88	5	99.31	9	98.69
SOx: Total	8556	-866.86	24200	-2634.77	29585	-3243.42	78	91.20	2	99.79
CH4	7391	25.32	25180	-154.44	30813	-211.36	81	99.18	31	99.69
N2O	-395	2036.93	195	-856.82	239	-1071.23	1	96.92	0	98.46
CO2 (w/ C in VOC & CO)	3636297	-202.28	12481848	-937.59	15278931	-1170.11	40140	96.66	23102	98.08
BC: Total	90	-289.80	127	-450.87	156	-575.58	0	98.23	1	97.83
OC: Total	99	-151.74	287	-627.37	353	-795.00	1	97.66	2	94.17
HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**31488**	**Reduction** -1.48%	**38893**	**Reduction** -25.34%	**51264**	**Reduction** -65.21%	**26396**	**Reduction** 14.93%	**38767**	**Reduction** -24.93%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3759033	55.91	13269422	-55.63	16066504	-88.44	40140	99.53	24114	99.72
NOx: Total	4868	94.59	13644	84.84	16826	81.31	44	99.95	147	99.84
PM2.5: Total	625	76.22	1935	26.34	2370	9.79	6	99.76	4	99.84
PM10: Total	913	66.56	2983	-9.29	3651	-33.78	10	99.65	5	99.82
CO: Total	2219	83.37	5401	59.52	6638	50.25	17	99.87	35	99.74
VOC: Total	666	84.57	1458	66.23	1791	58.52	5	99.89	9	99.79
SOx: Total	8556	-817.03	24200	-2493.83	29585	-3071.11	78	91.65	2	99.80
CH4	7391	29.62	25180	-139.78	30813	-193.42	81	99.23	31	99.71
N2O	-395	288.45	195	6.91	239	-13.95	1	99.70	0	99.85
CO2 (w/ C in VOC & CO)	3636297	55.12	12481848	-54.05	15278931	-88.57	40140	99.50	23102	99.71
BC: Total	90	61.25	127	45.24	156	32.84	0	99.82	1	99.78
OC: Total	99	95.58	287	87.23	353	84.29	1	99.96	2	99.90

9.3.13 Fuel Cell Hybrid Plugin and Diesel





Round-trip, RGH-CLT-RGH

H2 FUEL CELL HYBRID PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	12911	Reduction
	50.30599284	
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	In Grams *(Based on SERC)*	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	9946	Reduction	17419	Reduction	7330	Reduction	15132	Reduction
		-96.99%		-245.02%		-45.18%		-199.72%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5236714	-242.72	10469903	-585.22	0	100.00	6413639	-319.75
NOx: Total	3676	-56.35	10749	-357.23	0	100.00	3969	-68.80
PM2.5: Total	218	-63.33	1524	-1044.63	0	100.00	514	-285.93
PM10: Total	290	-82.56	2350	-1381.39	0	100.00	730	-360.02
CO: Total	2552	-125.38	4256	-275.86	0	100.00	1853	-63.67
VOC: Total	787	-16.02	1149	-69.22	0	100.00	755	-11.23
SOx: Total	2243	-153.47	19066	-2054.58	0	100.00	5472	-518.36
CH4	16211	-63.81	19838	-100.46	0	100.00	14055	-42.02
N2O	107	-426.16	154	-653.83	0	100.00	65	-217.88
CO2 (w/ C in VOC & CO)	4721976	-292.53	9834063	-717.49	0	100.00	5974838	-396.68
BC: Total	19	18.35	100	-334.00	0	100.00	43	-84.03
OC: Total	35	12.02	226	-473.06	0	100.00	93	-134.55

HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	22857	Reduction	30330.26484	Reduction	20241	Reduction	28043	Reduction
		26.34%	2.254306711	2.25%		34.77%		9.62%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5236714	38.58	10469903	-22.80	0	100.00	6413639	24.78
NOx: Total	3676	95.92	10749	88.06	0	100.00	3969	95.59
PM2.5: Total	218	91.72	1524	41.96	0	100.00	514	80.43
PM10: Total	290	89.39	2350	13.90	0	100.00	730	73.26
CO: Total	2552	80.88	4256	68.11	0	100.00	1853	86.11
VOC: Total	787	81.76	1149	73.40	0	100.00	755	82.51
SOx: Total	2243	-140.41	19066	-1943.55	0	100.00	5472	-486.49
CH4	16211	-54.37	19838	-88.91	0	100.00	14055	-33.84
N2O	107	48.81	154	26.66	0	100.00	65	69.07
CO2 (w/ C in VOC & CO)	4721976	41.72	9834063	-21.37	0	100.00	5974838	26.26
BC: Total	19	91.88	100	56.86	0	100.00	43	81.71
OC: Total	35	98.46	226	89.94	0	100.00	93	95.88

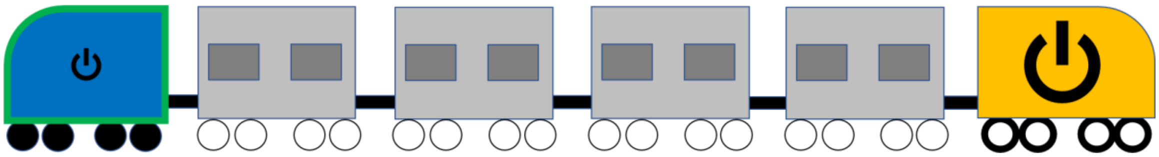
Round-trip, RGH-CLT-RGH										
HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12511	Reduction -147.80%	18489	Reduction -266.21%	28476	Reduction -464.02%	8399.687897	Reduction -66.37%	18387	Reduction -264.19%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3034822	-98.62	10712950	-601.12	12971150	-748.91	32406	97.88	19468	98.73
NOx: Total	3930	-67.16	11015	-368.54	13584	-477.79	35	98.49	118	94.96
PM2.5: Total	504	-278.64	1562	-1072.95	1913	-1336.44	5	96.22	3	97.45
PM10: Total	737	-364.44	2408	-1418.04	2948	-1758.22	8	95.11	4	97.54
CO: Total	1792	-58.23	4361	-285.16	5359	-373.32	14	98.76	28	97.51
VOC: Total	538	20.75	1177	-73.41	1446	-113.04	4	99.44	7	98.94
SOx: Total	6907	-680.59	19537	-2107.89	23885	-2599.28	63	92.89	1	99.83
CH4	5967	39.70	20329	-105.42	24877	-151.37	65	99.34	25	99.75
N2O	-319	1663.76	157	-672.48	193	-845.58	1	97.51	0	98.76
CO2 (w/ C in VOC & CO)	2935732	-144.04	10077110	-737.69	12335310	-925.41	32406	97.31	18651	98.45
BC: Total	73	-214.71	103	-344.74	126	-445.43	0	98.57	0	98.25
OC: Total	80	-103.24	232	-487.24	285	-622.57	1	98.11	2	95.29
HYDROGEN FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	25422	Reduction 18.07%	31400	Reduction -1.19%	41387	Reduction -33.38%	21311	Reduction 31.32%	31298	Reduction -0.86%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3034822	64.41	10712950	-25.65	12971150	-52.13	32406	99.62	19468	99.77
NOx: Total	3930	95.63	11015	87.76	13584	84.91	35	99.96	118	99.87
PM2.5: Total	504	80.80	1562	40.53	1913	27.17	5	99.81	3	99.87
PM10: Total	737	73.00	2408	11.76	2948	-8.01	8	99.72	4	99.86
CO: Total	1792	86.57	4361	67.32	5359	59.84	14	99.89	28	99.79
VOC: Total	538	87.54	1177	72.74	1446	66.51	4	99.91	7	99.83
SOx: Total	6907	-640.36	19537	-1994.10	23885	-2460.17	63	93.26	1	99.84
CH4	5967	43.18	20329	-93.59	24877	-136.89	65	99.38	25	99.76
N2O	-319	252.14	157	24.84	193	8.00	1	99.76	0	99.88
CO2 (w/ C in VOC & CO)	2935732	63.77	10077110	-24.37	12335310	-52.24	32406	99.60	18651	99.77
BC: Total	73	68.71	103	55.79	126	45.78	0	99.86	0	99.83
OC: Total	80	96.43	232	89.69	285	87.31	1	99.97	2	99.92

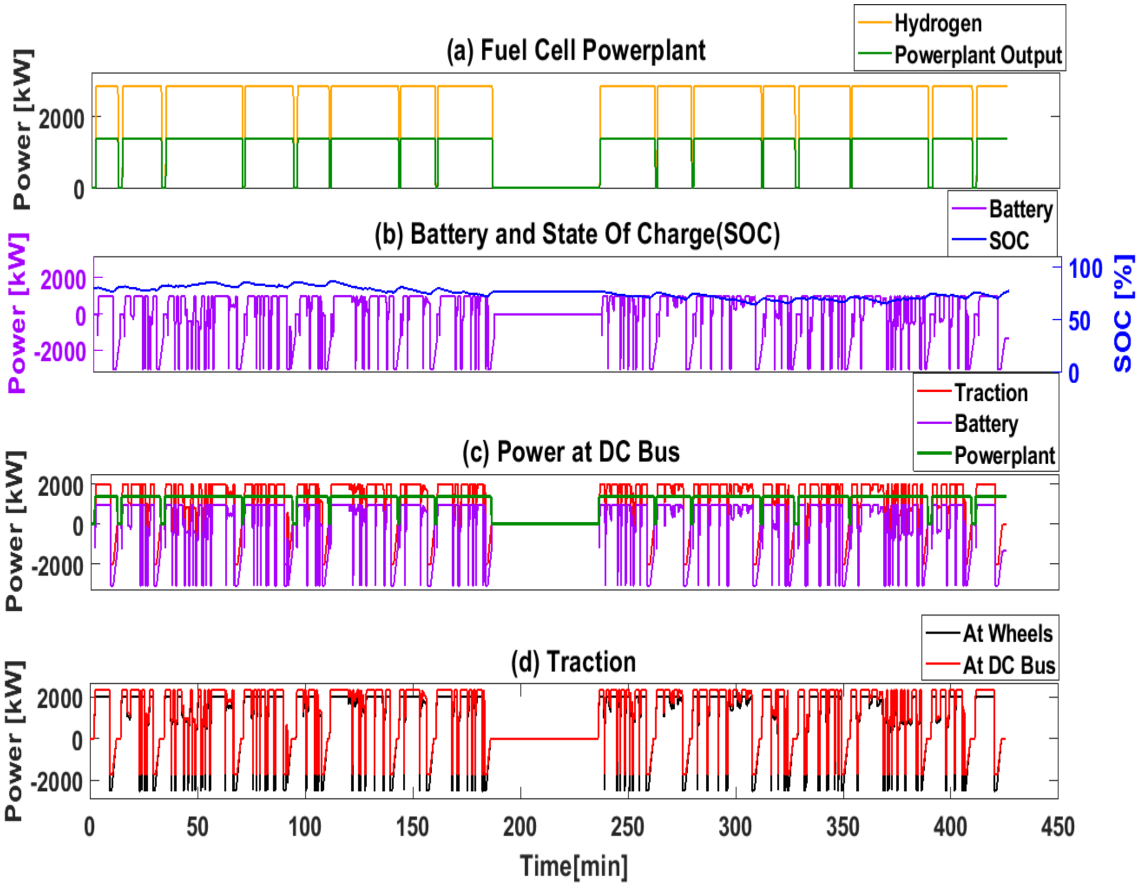
Round-trip, RGH-CLT-RGH	
ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP, PLUG-IN	
Energy Requirements (in kWh), Electricity	**1490**
Energy Requirements (in kWh), Electricity - 100%	61.58%
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	**Grams** *(Based on SERC)*
GHGs	**650209**
NOx: Total	**668**
PM2.5: Total	**95**
PM10: Total	**146**
CO: Total	**264**
VOC: Total	**71**
SOx: Total	**1184**
CH4	**1232**
N2O	**10**
CO2 (w/ C in VOC & CO)	**610722**
BC: Total	**6**
OC: Total	**14**

H2 FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL, INCL. PLUG ELECTRICITY (kWh)	**24347**	**Reduction** **21.54%**	**31820**	**Reduction** **-2.55%**	**20242**	**Reduction** **34.77%**	**29533**	**Reduction** **4.82%**
PRODUCTION METHOD	**ONSITE SMR**		**ONSITE ELECTROLYSIS**		**ONSITE ELECTROLYSIS, 100% RENEW**		**LIQUID DELIVERY, SMR SERC**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**
GHGs	**5886923**	**30.96**	**11120112**	**-30.42**	**0**	**100.00**	**7063848**	**17.15**
NOx: Total	**4343**	**95.17**	**11417**	**87.32**	**0**	**100.00**	**4636**	**94.85**
PM2.5: Total	**312**	**88.11**	**1619**	**38.36**	**0**	**100.00**	**609**	**76.83**
PM10: Total	**436**	**84.04**	**2496**	**8.55**	**0**	**100.00**	**876**	**67.91**
CO: Total	**2816**	**78.90**	**4520**	**66.13**	**0**	**100.00**	**2117**	**84.13**
VOC: Total	**859**	**80.11**	**1220**	**71.75**	**0**	**100.00**	**826**	**80.86**
SOx: Total	**3427**	**-267.32**	**20250**	**-2070.46**	**0**	**100.00**	**6656**	**-613.40**
CH4	**17443**	**-66.10**	**21070**	**-100.64**	**0**	**100.00**	**15287**	**-45.57**
N2O	**117**	**44.25**	**163**	**22.10**	**0**	**100.00**	**74**	**64.52**
CO2 (w/ C in VOC & CO)	**5332698**	**34.18**	**10444784**	**-28.91**	**0**	**100.00**	**6585560**	**18.72**
BC: Total	**25**	**89.20**	**107**	**54.18**	**0**	**100.00**	**49**	**79.03**
OC: Total	**49**	**97.83**	**240**	**89.31**	**0**	**100.00**	**107**	**95.26**

	Round-trip, RGH-CLT-RGH									
H2 FUEL CELL HYBRID & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL, INCL. PLUG ELECTRICITY (kWh)	**26911**	**Reduction** **13.27%**	**32890**	**Reduction** **-5.99%**	**42877**	**Reduction** **-38.18%**	**21311**	**Reduction** **31.32%**	**31299**	**Reduction** **-0.87%**
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	**3685031**	**56.78**	**11363159**	**-33.27**	**13621359**	**-59.76**	**32406**	**99.62**	**19468**	**99.77**
NOx: Total	**4598**	**94.89**	**11683**	**87.02**	**14252**	**84.17**	**35**	**99.96**	**118**	**99.87**
PM2.5: Total	**599**	**77.20**	**1657**	**36.92**	**2008**	**23.56**	**5**	**99.81**	**3**	**99.87**
PM10: Total	**883**	**67.66**	**2554**	**6.42**	**3094**	**-13.36**	**8**	**99.72**	**4**	**99.86**
CO: Total	**2056**	**84.59**	**4625**	**65.34**	**5623**	**57.86**	**14**	**99.89**	**28**	**99.79**
VOC: Total	**609**	**85.89**	**1248**	**71.09**	**1517**	**64.86**	**4**	**99.91**	**7**	**99.83**
SOx: Total	**8091**	**-767.27**	**20721**	**-2121.01**	**25070**	**-2587.08**	**63**	**93.26**	**1**	**99.84**
CH4	**7199**	**31.45**	**21561**	**-105.32**	**26109**	**-148.62**	**65**	**99.38**	**25**	**99.76**
N2O	**-309**	**247.59**	**167**	**20.29**	**202**	**3.45**	**1**	**99.76**	**0**	**99.88**
CO2 (w/ C in VOC & CO)	**3546454**	**56.23**	**10687832**	**-31.91**	**12946031**	**-59.78**	**32406**	**99.60**	**18651**	**99.77**
BC: Total	**79**	**66.04**	**109**	**53.11**	**132**	**43.10**	**0**	**99.86**	**0**	**99.83**
OC: Total	**94**	**95.81**	**246**	**89.06**	**299**	**86.69**	**1**	**99.97**	**2**	**99.92**

9.3.14 Fuel Cell Hybrid Downsized and Diesel





Round-trip, RGH-CLT-RGH

H2 FUEL CELL HYBRID DOWNSIZED & DIESEL (2 LOCOS): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	16942	Reduction 34.79%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

H2 FUEL CELL HYBRID DOWNSIZED & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	13051	Reduction -158.50%	22858	Reduction -352.74%	9619	Reduction -90.51%	19857	Reduction -293.30%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6871692	-349.73	13738758	-799.15	0	100.00	8416070	-450.80
NOx: Total	4824	-105.17	14106	-499.98	0	100.00	5208	-121.51
PM2.5: Total	285	-114.33	2000	-1402.00	0	100.00	674	-406.43
PM10: Total	380	-139.56	3084	-1843.90	0	100.00	958	-503.64
CO: Total	3348	-195.74	5584	-393.21	0	100.00	2432	-114.76
VOC: Total	1033	-52.24	1507	-122.06	0	100.00	991	-45.96
SOx: Total	2943	-232.60	25018	-2727.28	0	100.00	7180	-711.42
CH4	21273	-114.95	26032	-163.05	0	100.00	18443	-86.36
N2O	141	-590.44	201	-889.18	0	100.00	85	-317.13
CO2 (w/ C in VOC & CO)	6196245	-415.08	12904399	-972.72	0	100.00	7840269	-551.75
BC: Total	25	-7.14	132	-469.50	0	100.00	56	-141.49
OC: Total	46	-15.45	297	-651.98	0	100.00	122	-207.77

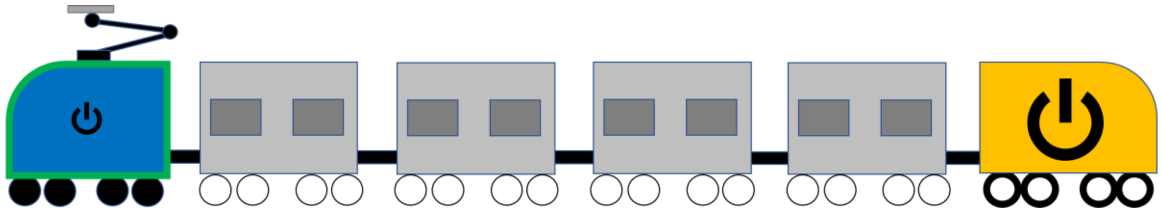
H2 FUEL CELL HYBRID DOWNSIZED & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	29993	Reduction 3.34%	39800	Reduction -28.26%	26561	Reduction 14.40%	36799	Reduction -18.59%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6871691.9	19.405627	13738757.5	-61.13449	0	100	8416069.525	1.2924536
NOx: Total	4823.506428	94.641196	14105.60518	84.329	0	100	5207.698596	94.214368
PM2.5: Total	285.4474292	89.132782	2000.376831	23.844014	0	100	674.4692193	74.322404
PM10: Total	380.0228174	86.075964	3083.737553	-12.98814	0	100	957.6008215	64.913506
CO: Total	3348.494953	74.905442	5584.2051	58.150404	0	100	2431.612626	81.776814
VOC: Total	1033.287994	76.068002	1507.195588	65.091822	0	100	990.7001949	77.054379
SOx: Total	2943.167191	-215.4636	25018.13417	-2581.57	0	100	7180.101337	-669.5996
CH4	21272.54969	-102.5704	26032.07456	-147.8935	0	100	18442.80552	-75.62379
N2O	140.6421937	32.825114	201.4967582	3.7591683	0	100	84.96892756	59.416319
CO2 (w/ C in VOC & CO)	6196245.228	23.526706	12904398.63	-59.2645	0	100	7840268.594	3.2363725
BC: Total	24.77047645	89.349457	131.6715099	43.3853	0	100	55.83286115	75.993587
OC: Total	45.58283902	97.972949	296.9083581	86.796601	0	100	121.5204439	94.596033

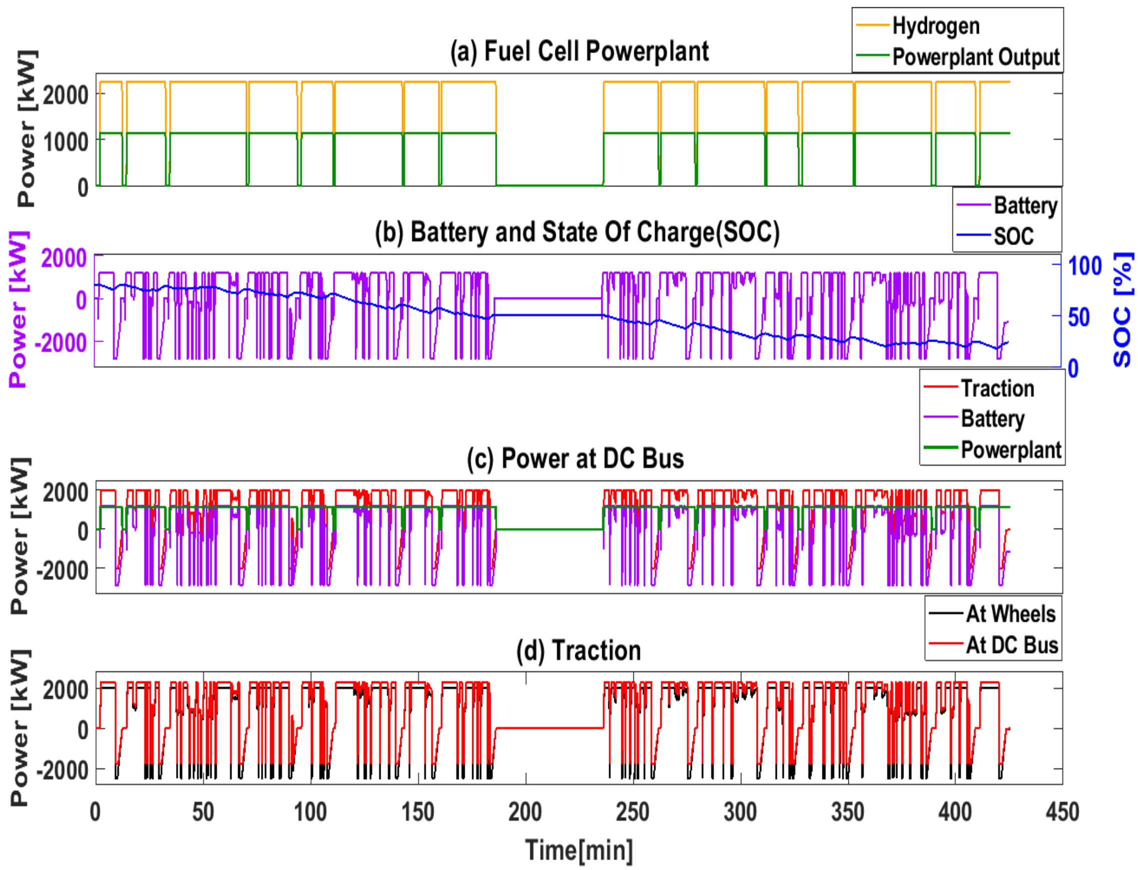
Round-trip RGH-CLT-RGH

H2 FUEL CELL HYBRID DOWNSIZED & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	16416.74643 -225.1632184	Reduction	24261	Reduction -380.54%	37367	Reduction -640.12%	11022	Reduction -118.31%	24128	Reduction -377.89%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3982337	-160.63	14057688	-820.02	17020930	-1013.96	42524	97.21696	25547	98.33
NOx: Total	5157	-119.36	14455	-514.82	17825	-658.19	47	98.02082	155	93.39
PM2.5: Total	662	-396.86	2050	-1439.16	2510	-1784.92	7	95.04528	4	96.66
PM10: Total	967	-509.44	3160	-1891.99	3868	-2338.38	10	93.58755	5	96.78
CO: Total	2351	-107.64	5722	-405.41	7032	-521.10	18	98.37303	37	96.74
VOC: Total	706	-3.99	1544	-127.55	1897	-179.56	5	99.26748	9	98.61
SOx: Total	9064	-924.30	25637	-2797.23	31343	-3442.03	83	90.6735	2	99.78
CH4	7830	20.88	26676	-169.55	32644	-229.86	86	99.13227	33	99.67
N2O	-418	2151.99	206	-913.66	253	-1140.80	1	96.73692	0	98.37
CO2 (w/ C in VOC & CO)	3852310	-220.24	13223329	-999.23	16186571	-1245.56	42524	96.46505	24475	97.97
BC: Total	95	-312.96	135	-483.59	165	-615.72	0	98.12136	1	97.70
OC: Total	105	-166.69	304	-670.58	374	-848.17	1	97.51941	2	93.82

H2 FUEL CELL HYBRID DOWNSIZED & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	33359	Reduction -7.51%	41203	Reduction -32.79%	54309	Reduction -75.02%	27964	Reduction 9.88%	41070	Reduction -32.36%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3982337.179	53.293312	14057687.78	-64.87505	17020929.8	-99.62932	42524.03729	99.50126	25546.5725	99.700378
NOx: Total	5157.084006	94.270599	14454.58744	83.941289	17825.17226	80.196647	46.53096911	99.94831	155.4372048	99.827313
PM2.5: Total	661.7274051	74.807495	2049.867515	21.959863	2510.358977	4.4285754	6.598757824	99.74878	4.452989152	99.830471
PM10: Total	966.8007774	64.576419	3160.031318	-15.78355	3868.171592	-41.72981	10.172502	99.62728	5.112342786	99.812684
CO: Total	2350.903385	82.381672	5722.362133	57.115016	7032.254459	47.298317	18.42093776	99.86195	36.94154624	99.72315
VOC: Total	705.8099709	83.652725	1544.484632	64.228169	1897.4751	56.052552	4.971872561	99.88485	9.413987074	99.781963
SOx: Total	9063.857735	-871.5102	25637.09983	-2647.914	31342.87137	-3259.488	82.52875462	91.15415	1.957700375	99.790164
CH4	7830.011883	25.437789	26676.12579	-154.0266	32643.74882	-210.8539	85.87349795	99.18226	32.78839138	99.687769
N2O	-417.990763	299.64479	206.4819251	1.3781047	252.751822	-20.72177	0.664688917	99.68252	0.332720728	99.841083
CO2 (w/ C in VOC & CO)	3852310.324	52.455261	13223328.91	-63.20069	16186570.93	-99.77266	42524.03729	99.47517	24474.74976	99.697936
BC: Total	95.47885567	58.947028	134.9291526	41.984614	165.4777928	28.849638	0.434352364	99.81324	0.531783088	99.77135
OC: Total	105.3004285	95.317331	304.2540729	86.46994	374.372901	83.351783	0.979428636	99.95645	2.43928134	99.891526

9.3.15 Fuel Cell Hybrid Downsized Plugin and Diesel





Round-trip, RGH-CLT-RGH

H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	13340	Reduction 48.65%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	10276	Reduction -103.54%	17998	Reduction -256.48%	7574	Reduction -50.01%	15635	Reduction -209.68%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5410717	-254.11	10817792	-607.98	0	100.00	6626748	-333.70
NOx: Total	3798	-61.55	11107	-372.42	0	100.00	4101	-74.41
PM2.5: Total	225	-68.76	1575	-1082.66	0	100.00	531	-298.76
PM10: Total	299	-88.62	2428	-1430.61	0	100.00	754	-375.30
CO: Total	2637	-132.87	4397	-288.35	0	100.00	1915	-69.10
VOC: Total	814	-19.87	1187	-74.85	0	100.00	780	-14.93
SOx: Total	2317	-161.89	19699	-2126.18	0	100.00	5654	-538.90
CH4	16750	-69.25	20497	-107.12	0	100.00	14522	-46.74
N2O	111	-443.65	159	-678.88	0	100.00	67	-228.44
CO2 (w/ C in VOC & CO)	4878876	-305.57	10160824	-744.65	0	100.00	6173367	-413.18
BC: Total	20	15.64	104	-348.42	0	100.00	44	-90.14
OC: Total	36	9.10	234	-492.10	0	100.00	96	-142.34

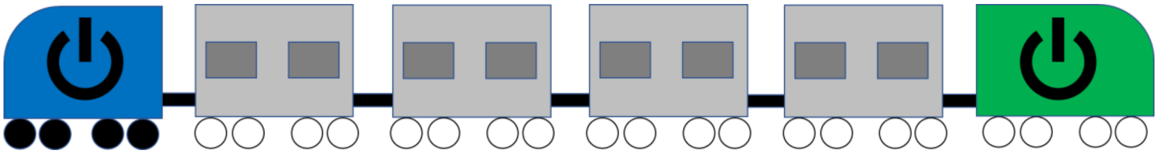
H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	23616	Reduction 23.89%	31338	Reduction -0.99%	20914	Reduction 32.60%	28975	Reduction 6.62%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5410717	36.54	10817792	-26.88	0	100.00	6626748	22.28
NOx: Total	3798	95.78	11107	87.66	0	100.00	4101	95.44
PM2.5: Total	225	91.44	1575	40.04	0	100.00	531	79.78
PM10: Total	299	89.04	2428	11.03	0	100.00	754	72.37
CO: Total	2637	80.24	4397	67.05	0	100.00	1915	85.65
VOC: Total	814	81.16	1187	72.51	0	100.00	780	81.93
SOx: Total	2317	-148.39	19699	-2011.45	0	100.00	5654	-505.98
CH4	16750	-59.50	20497	-95.19	0	100.00	14522	-38.28
N2O	111	47.11	159	24.22	0	100.00	67	68.04
CO2 (w/ C in VOC & CO)	4878876	39.79	10160824	-25.40	0	100.00	6173367	23.81
BC: Total	20	91.61	104	55.42	0	100.00	44	81.10
OC: Total	36	98.40	234	89.60	0	100.00	96	95.74

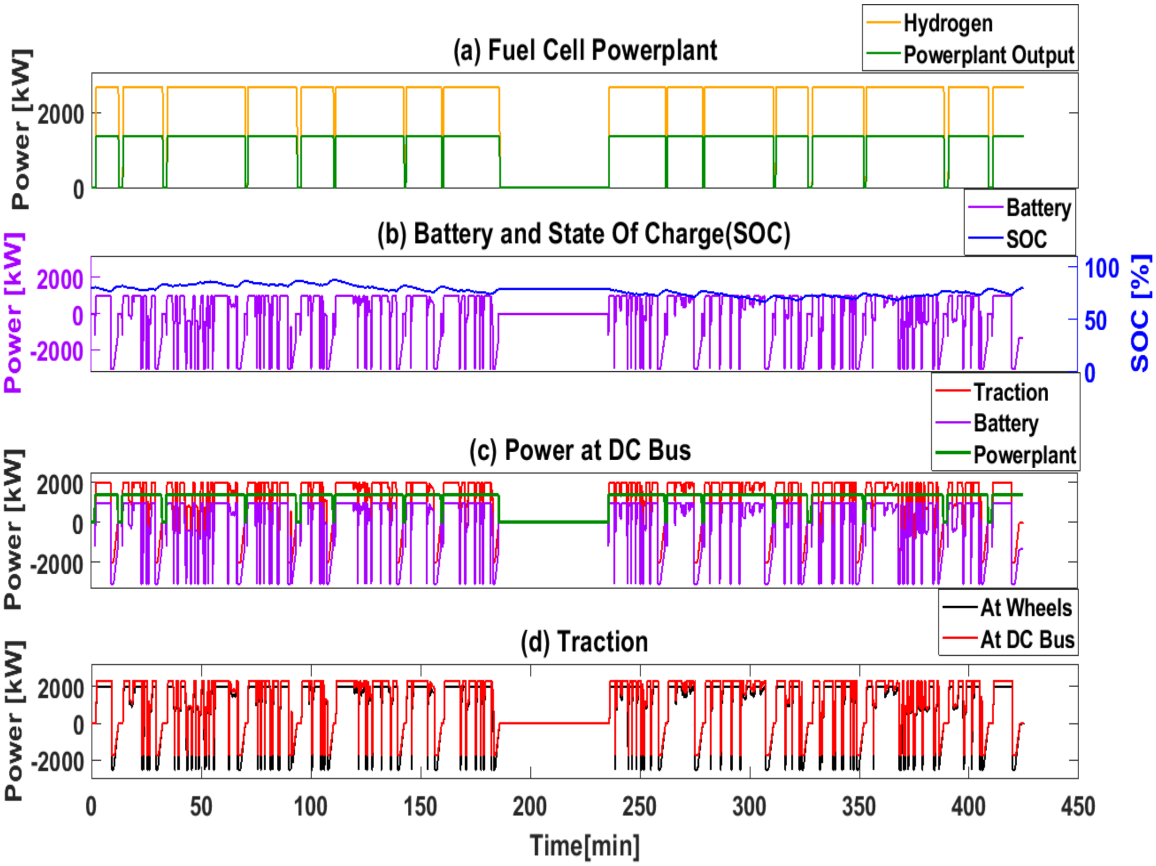
Round-trip RGH-CLT-RGH										
H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**12926**	**Reduction** **-156.03%**	**19103**	**Reduction** **-278.37%**	**29422**	**Reduction** **-482.76%**	**8679**	**Reduction** **-71.90%**	**18998**	**Reduction** **-276.29%**
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-PUMP EMISSIONS	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	**3135662**	**-105.22**	**11068915**	**-624.42**	**13402149**	**-777.12**	**33483**	**97.81**	**20115**	**98.68**
NOx: Total	**4061**	**-72.72**	**11381**	**-384.11**	**14035**	**-496.99**	**37**	**98.44**	**122**	**94.79**
PM2.5: Total	**521**	**-291.23**	**1614**	**-1111.92**	**1977**	**-1384.17**	**5**	**96.10**	**4**	**97.37**
PM10: Total	**761**	**-379.87**	**2488**	**-1468.48**	**3046**	**-1819.96**	**8**	**94.95**	**4**	**97.46**
CO: Total	**1851**	**-63.49**	**4506**	**-297.95**	**5537**	**-389.05**	**15**	**98.72**	**29**	**97.43**
VOC: Total	**556**	**18.12**	**1216**	**-79.17**	**1494**	**-120.12**	**4**	**99.42**	**7**	**98.91**
SOx: Total	**7137**	**-706.52**	**20186**	**-2181.25**	**24679**	**-2688.97**	**65**	**92.66**	**2**	**99.83**
CH4	**6165**	**37.70**	**21005**	**-112.25**	**25703**	**-159.73**	**68**	**99.32**	**26**	**99.74**
N2O	**-329**	**1715.72**	**163**	**-698.15**	**199**	**-877.00**	**1**	**97.43**	**0**	**98.71**
CO2 (w/ C in VOC & CO)	**3033279**	**-152.15**	**10411947**	**-765.53**	**12745181**	**-959.48**	**33483**	**97.22**	**19271**	**98.40**
BC: Total	**75**	**-225.16**	**106**	**-359.51**	**130**	**-463.55**	**0**	**98.52**	**0**	**98.19**
OC: Total	**83**	**-109.99**	**240**	**-506.75**	**295**	**-646.58**	**1**	**98.05**	**2**	**95.14**
H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**26266**	**Reduction** **15.35%**	**32443**	**Reduction** **-4.56%**	**42762**	**Reduction** **-37.81%**	**22019**	**Reduction** **29.04%**	**32338**	**Reduction** **-4.22%**
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	**3135662**	**63.22**	**11068915**	**-29.82**	**13402149**	**-57.19**	**33483**	**99.61**	**20115**	**99.76**
NOx: Total	**4061**	**95.49**	**11381**	**87.36**	**14035**	**84.41**	**37**	**99.96**	**122**	**99.86**
PM2.5: Total	**521**	**80.16**	**1614**	**38.55**	**1977**	**24.75**	**5**	**99.80**	**4**	**99.87**
PM10: Total	**761**	**72.11**	**2488**	**8.83**	**3046**	**-11.60**	**8**	**99.71**	**4**	**99.85**
CO: Total	**1851**	**86.13**	**4506**	**66.23**	**5537**	**58.50**	**15**	**99.89**	**29**	**99.78**
VOC: Total	**556**	**87.13**	**1216**	**71.83**	**1494**	**65.40**	**4**	**99.91**	**7**	**99.83**
SOx: Total	**7137**	**-664.96**	**20186**	**-2063.69**	**24679**	**-2545.23**	**65**	**93.03**	**2**	**99.83**
CH4	**6165**	**41.29**	**21005**	**-100.02**	**25703**	**-144.76**	**68**	**99.36**	**26**	**99.75**
N2O	**-329**	**257.20**	**163**	**22.35**	**199**	**4.94**	**1**	**99.75**	**0**	**99.87**
CO2 (w/ C in VOC & CO)	**3033279**	**62.56**	**10411947**	**-28.50**	**12745181**	**-57.30**	**33483**	**99.59**	**19271**	**99.76**
BC: Total	**75**	**67.68**	**106**	**54.32**	**130**	**43.98**	**0**	**99.85**	**0**	**99.82**
OC: Total	**83**	**96.31**	**240**	**89.35**	**295**	**86.89**	**1**	**99.97**	**2**	**99.91**

Round trip, RGH-CLT-RGH								
FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP, PLUG (kWh)	1490							
Energy Requirements (in kWh), Electricity - 100% Renewable		61.58%						
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	Grams (Based on SERC)							
GHGs	650209							
NOx: Total	668							
PM2.5: Total	95							
PM10: Total	146							
CO: Total	264							
VOC: Total	71							
SOx: Total	1184							
CH4	1232							
N2O	10							
CO2 (w/ C in VOC & CO)	610722							
BC: Total	6							
OC: Total	14							
H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL, INCL. PLUG ELECTRICITY (kWh)	25106	Reduction 19.09%	32828	Reduction -5.79%	20914	Reduction 32.60%	30465	Reduction 1.82%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	6060926	28.91	11468001	-34.50	0	100.00	7276957	14.65
NOx: Total	4466	95.04	11774	86.92	0	100.00	4768	94.70
PM2.5: Total	319	87.84	1670	36.43	0	100.00	626	76.18
PM10: Total	445	83.69	2574	5.69	0	100.00	900	67.03
CO: Total	2901	78.26	4661	65.07	0	100.00	2179	83.67
VOC: Total	885	79.50	1258	70.86	0	100.00	851	80.28
SOx: Total	3501	-275.30	20883	-2138.36	0	100.00	6838	-632.89
CH4	17982	-71.23	21729	-106.92	0	100.00	15754	-50.02
N2O	120	42.55	168	19.67	0	100.00	76	63.49
CO2 (w/ C in VOC & CO)	5489597	32.25	10771545	-32.94	0	100.00	6784089	16.27
BC: Total	26	88.93	110	52.74	0	100.00	50	78.42
OC: Total	50	97.78	248	88.98	0	100.00	110	95.12

Round trip, RGH-CLT-RGH										
H2 FUEL CELL HYBRID DOWNSIZED PLUG-IN & DIESEL (2 LOCOS): ENERGY CONSUMPTION, WELL-TO-WHEEL, INCL. PLUG ELECTRICITY (kWh)	27756	Reduction 10.55%	33933	Reduction -9.36%	44252	Reduction -42.61%	22019	Reduction 29.04%	32339	Reduction -4.22%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3785871	55.60	11719124	-37.45	14052358	-64.81	33483	99.61	20115.17395	99.76
NOx: Total	4728	94.75	12049	86.61	14703	83.67	37	99.96	122	99.86
PM2.5: Total	616	76.56	1709	34.95	2071	21.14	5	99.80	4	99.87
PM10: Total	907	66.76	2634	3.49	3192	-16.94	8	99.71	4	99.85
CO: Total	2115	84.15	4770	64.25	5801	56.52	15	99.89	29	99.78
VOC: Total	627	85.48	1287	70.18	1565	63.74	4	99.91	7	99.83
SOx: Total	8321	-791.87	21370	-2190.60	25863	-2672.14	65	93.03	2	99.83
CH4	7397	29.56	22237	-111.75	26935	-156.50	68	99.36	26	99.75
N2O	-320	252.64	172	17.79	209	0.39	1	99.75	0	99.87
CO2 (w/ C in VOC & CO)	3644001	55.03	11022669	-36.04	13355903	-64.84	33483	99.59	19271	99.76
BC: Total	81	65.00	112	51.64	137	41.30	0	99.85	0	99.82
OC: Total	97	95.69	254	88.72	309	86.27	1	99.97	2	99.91

9.3.16 Fuel Cell and Battery





Round-trip, RGH-CLT-RGH		
HYDROGEN FUEL CELL AND BATTERY (2 LOCOMOTIVES): ENERGY COONSUMPTION, POINT-OF-USE (kWh)	15816	Reduction 39.12%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams (Based on SERC)	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

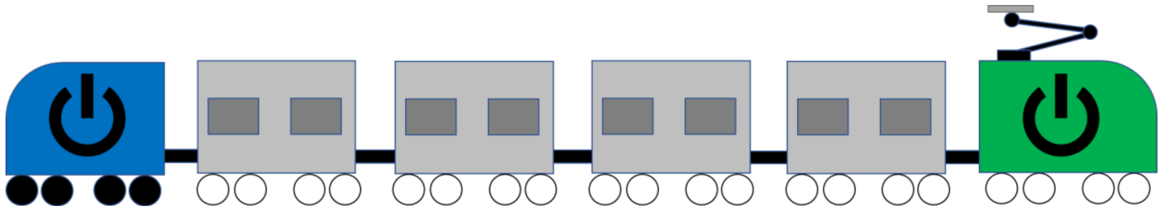
HYDROGEN FUEL CELL AND BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12184	Reduction -141.32%	21339	Reduction -322.65%	8979	Reduction -77.85%	18537	Reduction -267.16%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	6414985	-319.84	12825652	-739.39	0	100.00	7856720	-414.19
NOx: Total	4503	-91.53	13168	-460.10	0	100.00	4862	-106.79
PM2.5: Total	266	-100.09	1867	-1302.17	0	100.00	630	-372.77
PM10: Total	355	-123.63	2879	-1714.70	0	100.00	894	-463.52
CO: Total	3126	-176.09	5213	-360.43	0	100.00	2270	-100.49
VOC: Total	965	-42.12	1407	-107.30	0	100.00	925	-36.26
SOx: Total	2748	-210.50	23355	-2539.37	0	100.00	6703	-657.49
CH4	19859	-100.67	24302	-145.56	0	100.00	17217	-73.97
N2O	131	-544.55	188	-823.44	0	100.00	79	-289.40
CO2 (w/ C in VOC & CO)	5784430	-380.85	12046746	-901.42	0	100.00	7319188	-508.43
BC: Total	23	-0.02	123	-431.65	0	100.00	52	-125.44
OC: Total	43	-7.77	277	-602.00	0	100.00	113	-187.32

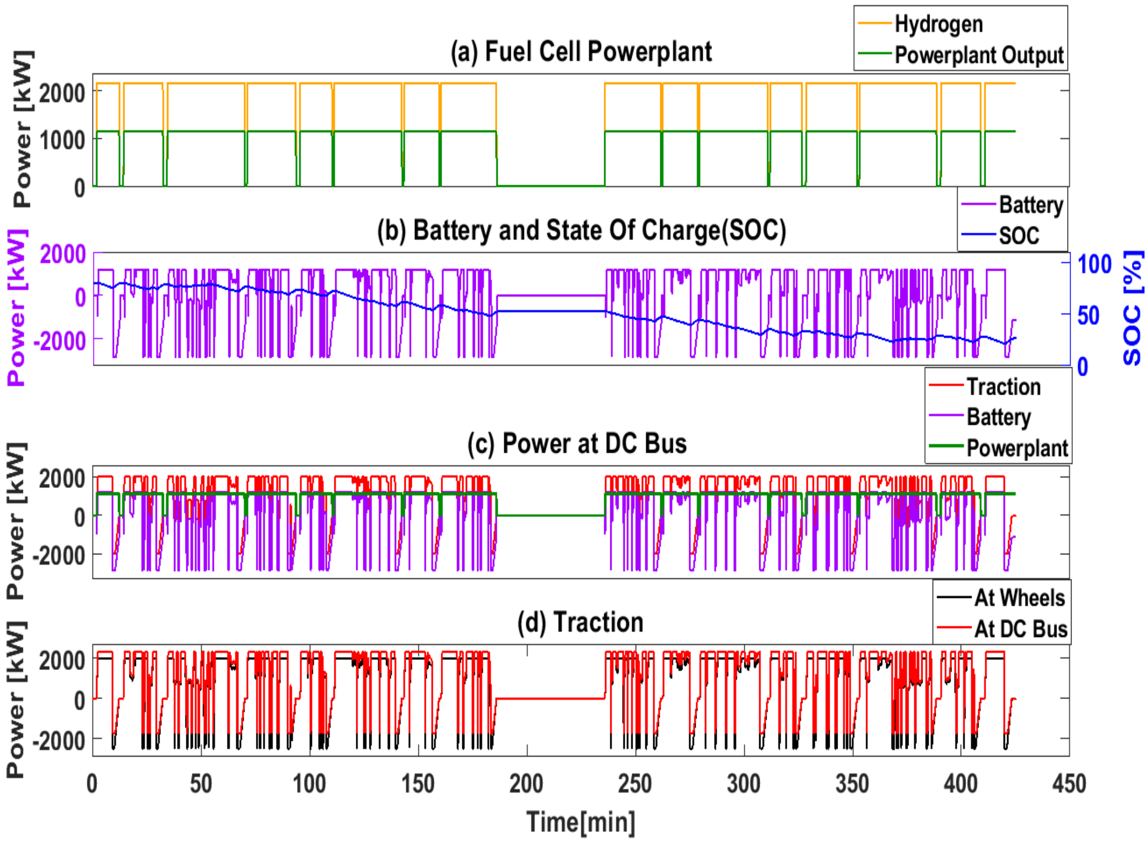
HYDROGEN FUEL CELL AND BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	28000	Reduction 9.77%	37155	Reduction -19.74%	24795	Reduction 20.09%	34353	Reduction -10.71%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	6414985	24.76	12825652	-50.43	0	100.00	7856720	7.85
NOx: Total	4503	95.00	13168	85.37	0	100.00	4862	94.60
PM2.5: Total	266	89.86	1867	28.91	0	100.00	630	76.03
PM10: Total	355	87.00	2879	-5.48	0	100.00	894	67.25
CO: Total	3126	76.57	5213	60.93	0	100.00	2270	82.99
VOC: Total	965	77.66	1407	67.41	0	100.00	925	78.58
SOx: Total	2748	-194.50	23355	-2403.35	0	100.00	6703	-618.45
CH4	19859	-89.11	24302	-131.42	0	100.00	17217	-63.95
N2O	131	37.29	188	10.16	0	100.00	79	62.11
CO2 (w/ C in VOC & CO)	5784430	28.61	12046746	-48.68	0	100.00	7319188	9.67
BC: Total	23	90.06	123	47.15	0	100.00	52	77.59
OC: Total	43	98.11	277	87.67	0	100.00	113	94.96

Round-trip, RGH-CLT-RGH										
HYDROGEN FUEL CELL AND BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	15326	Reduction	22649	Reduction	34883	Reduction	10290	Reduction	22524	Reduction
		-203.55%		-348.60%		-590.93%		-103.80%		-346.13%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3717663	-143.31	13123385	-758.88	15889684	-939.92	39698	97.40	23849	98.44
NOx: Total	4814	-104.78	13494	-473.96	16640	-607.80	43	98.15	145	93.83
PM2.5: Total	618	-363.84	1914	-1336.86	2344	-1659.64	6	95.37	4	96.88
PM10: Total	903	-468.94	2950	-1759.60	3611	-2176.32	9	94.01	5	96.99
CO: Total	2195	-93.84	5342	-371.82	6565	-479.82	17	98.48	34	96.95
VOC: Total	659	2.92	1442	-112.43	1771	-160.98	5	99.32	9	98.71
SOx: Total	8461	-856.22	23933	-2604.67	29260	-3206.62	77	91.29	2	99.79
CH4	7310	26.14	24903	-151.64	30474	-207.93	80	99.19	31	99.69
N2O	-390	2015.61	193	-846.29	236	-1058.34	1	96.95	0	98.48
CO2 (w/ C in VOC & CO)	3596278	-198.95	12344479	-926.17	15110778	-1156.13	39698	96.70	22848	98.10
BC: Total	89	-285.51	126	-444.80	154	-568.15	0	98.25	0	97.85
OC: Total	98	-148.97	284	-619.37	349	-785.15	1	97.68	2	94.23

HYDROGEN FUEL CELL AND BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	31142	Reduction	38465	Reduction	50699	Reduction	26106	Reduction	38340	Reduction
		-0.36%		-23.96%		-63.39%		15.87%		-23.56%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3717663	56.40	13123385.08	-53.92	15889684	-86.36	39698	99.53	23849	99.72
NOx: Total	4814	94.65	13494	85.01	16640	81.51	43	99.95	145	99.84
PM2.5: Total	618	76.48	1914	27.15	2344	10.78	6	99.77	4	99.84
PM10: Total	903	66.93	2950	-8.09	3611	-32.31	9	99.65	5	99.83
CO: Total	2195	83.55	5342	59.97	6565	50.80	17	99.87	34	99.74
VOC: Total	659	84.74	1442	66.61	1771	58.97	5	99.89	9	99.80
SOx: Total	8461	-806.94	23933	-2465.28	29260	-3036.21	77	91.74	2	99.80
CH4	7310	30.39	24903	-137.14	30474	-190.19	80	99.24	31	99.71
N2O	-390	286.38	193	7.93	236	-12.70	1	99.70	0	99.85
CO2 (w/ C in VOC & CO)	3596278	55.62	12344479	-52.35	15110778	-86.50	39698	99.51	22848	99.72
BC: Total	89	61.68	126	45.84	154	33.58	0	99.83	0	99.79
OC: Total	98	95.63	284	87.37	349	84.46	1	99.96	2	99.90

9.3.17 Fuel Cell and Battery Plugin





Round-trip, RGH-CLT-RGH

H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	12769	Reduction 50.85%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	9836	Reduction -94.83%	17228	Reduction -241.23%	7249	Reduction -43.59%	14966	Reduction -196.43%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5179119	-238.95	10354751	-577.68	0	100	6343100	-315.13
NOx: Total	3635	-54.63	10631	-352.20	0	100	3925	-66.95
PM2.5: Total	215	-61.54	1508	-1032.04	0	100	508	-281.69
PM10: Total	286	-80.55	2324	-1365.10	0	100	722	-354.96
CO: Total	2524	-122.90	4209	-271.72	0	100	1833	-61.87
VOC: Total	779	-14.74	1136	-67.36	0	100	747	-10.01
SOx: Total	2218	-150.68	18856	-2030.89	0	100	5412	-511.56
CH4	16033	-62.01	19620	-98.26	0	100	13900	-40.46
N2O	106	-420.38	152	-645.54	0	100	64	-214.38
CO2 (w/ C in VOC & CO)	4670042	-288.21	9725904	-708.50	0	100	5909125	-391.21
BC: Total	19	19.25	99	-329.23	0	100	42	-82.01
OC: Total	34	12.99	224	-466.76	0	100	92	-131.97

H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	22605	Reduction 27.15%	29997	Reduction 3.33%	20018	Reduction 35.49%	27735	Reduction 10.62%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5179119	39.26	10354751	-21.45	0	100.00	6343100	25.61
NOx: Total	3635	95.96	10631	88.19	0	100.00	3925	95.64
PM2.5: Total	215	91.81	1508	42.60	0	100.00	508	80.65
PM10: Total	286	89.51	2324	14.84	0	100.00	722	73.56
CO: Total	2524	81.09	4209	68.46	0	100.00	1833	86.27
VOC: Total	779	81.96	1136	73.69	0	100.00	747	82.71
SOx: Total	2218	-137.76	18856	-1921.07	0	100.00	5412	-480.04
CH4	16033	-52.68	19620	-86.83	0	100.00	13900	-32.37
N2O	106	49.37	152	27.46	0	100.00	64	69.41
CO2 (w/ C in VOC & CO)	4670042	42.36	9725904	-20.04	0	100.00	5909125	27.07
BC: Total	19	91.97	99	57.33	0	100.00	42	81.91
OC: Total	34	98.47	224	90.05	0	100.00	92	95.93

Round-trip, RGH-CLT-RGH										
H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12373	Reduction -145.07%	18286	Reduction -262.18%	28163	Reduction -457.82%	11481	Reduction -127.40%	18185	Reduction -260.18%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3001444	-96.43	10595125	-593.41	12828489	-739.58	32050	97.90	19254	98.74
NOx: Total	3887	-65.33	10894	-363.39	13435	-471.44	35	98.51	117	95.02
PM2.5: Total	499	-274.48	1545	-1060.04	1892	-1320.64	5	96.27	3	97.48
PM10: Total	729	-359.33	2382	-1401.34	2915	-1737.78	8	95.17	4	97.57
CO: Total	1772	-56.49	4313	-280.92	5300	-368.12	14	98.77	28	97.54
VOC: Total	532	21.62	1164	-71.50	1430	-110.70	4	99.45	7	98.95
SOx: Total	6831	-672.00	19322	-2083.61	23623	-2569.59	62	92.97	1	99.83
CH4	5901	40.37	20106	-103.16	24603	-148.61	65	99.35	25	99.75
N2O	-315	1646.56	156	-663.98	190	-835.18	1	97.54	0	98.77
CO2 (w/ C in VOC & CO)	2903444	-141.36	9966278	-728.48	12199641	-914.13	32050	97.34	18446	98.47
BC: Total	72	-211.24	102	-339.84	125	-439.43	0	98.58	0	98.27
OC: Total	79	-101.00	229	-480.78	282	-614.63	1	98.13	2	95.34
H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	25142	Reduction 18.97%	31055	Reduction -0.08%	40932	Reduction -31.91%	24250	Reduction 21.85%	30954	Reduction 0.24%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3001444	64.80	10595125	-24.26	12828489	-50.46	32050	99.62	19254	99.77
NOx: Total	3887	95.68	10894	87.90	13435	85.07	35	99.96	117	99.87
PM2.5: Total	499	81.01	1545	41.18	1892	27.97	5	99.81	3	99.87
PM10: Total	729	73.30	2382	12.74	2915	-6.82	8	99.72	4	99.86
CO: Total	1772	86.72	4313	67.68	5300	60.28	14	99.90	28	99.79
VOC: Total	532	87.68	1164	73.04	1430	66.88	4	99.91	7	99.84
SOx: Total	6831	-632.22	19322	-1971.07	23623	-2432.01	62	93.33	1	99.84
CH4	5901	43.80	20106	-91.46	24603	-134.29	65	99.38	25	99.76
N2O	-315	250.47	156	25.67	190	9.01	1	99.76	0	99.88
CO2 (w/ C in VOC & CO)	2903444	64.17	9966278	-23.00	12199641	-50.57	32050	99.60	18446	99.77
BC: Total	72	69.06	102	56.27	125	46.37	0	99.86	0	99.83
OC: Total	79	96.47	229	89.80	282	87.45	1	99.97	2	99.92

Round-trip, RGH-CLT-RGH

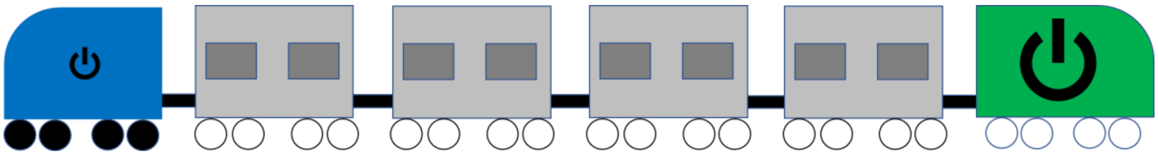
H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION , WELL-TO-PUMP, PLUG (kWh)	1504	
WELL-TO-PUMP EMISSIONS	**Grams**	
GHGs	656252	
NOx: Total	674	
PM2.5: Total	96	
PM10: Total	147	
CO: Total	267	
VOC: Total	72	
SOx: Total	1195	
CH4	1243	
N2O	10	
CO2 (w/ C in VOC & CO)	616397	
BC: Total	6	
OC: Total	14	

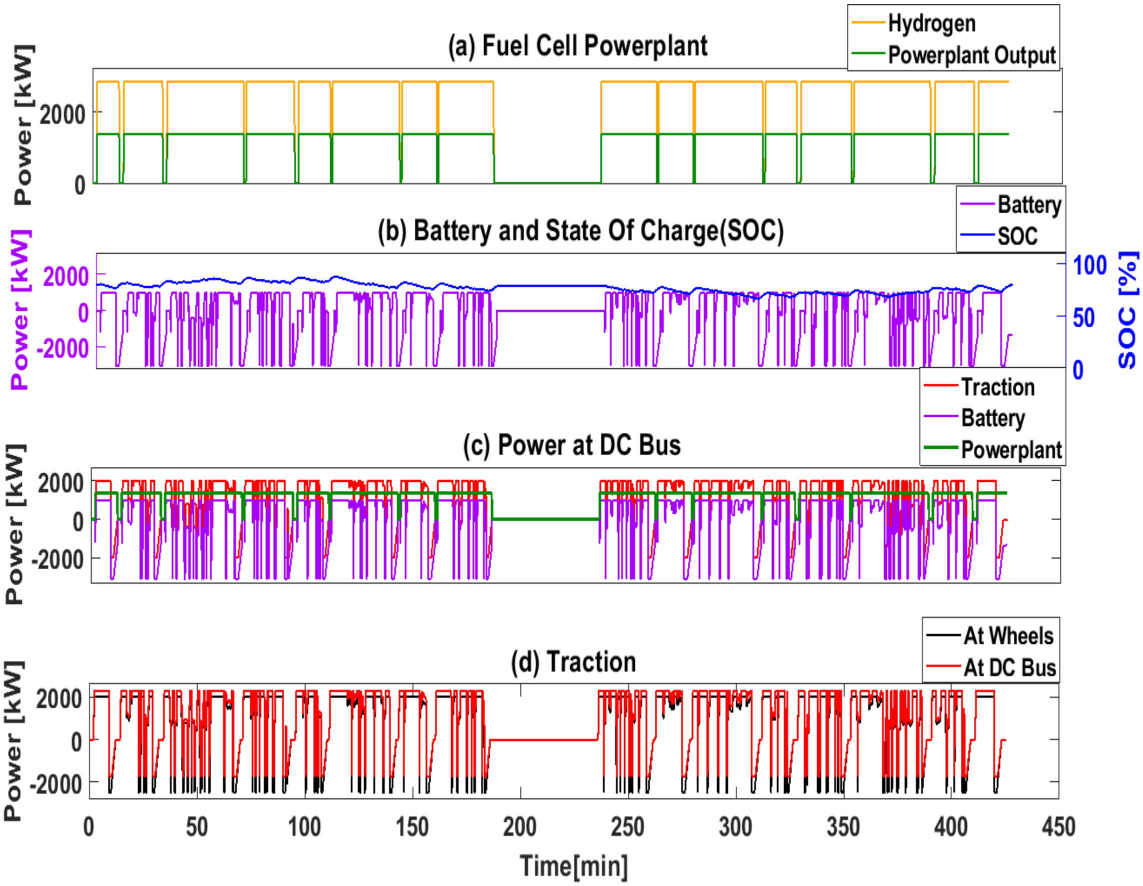
H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	24109	Reduction 22.30%	31500	Reduction -1.52%	20018	Reduction 35.49%	29238	Reduction 5.77%
PRODUCTION METHOD	**ONSITE SMR**		**ONSITE ELECTROLYSIS**		**ONSITE ELECTROLYSIS, 100% RENEW**		**LIQUID DELIVERY, SMR SERC**	
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	5835371	31.56	11011003	-29.14	0	100.00	6999351.287	17.91
NOx: Total	4309	95.21	11305	87.44	0	100.00	4599	94.89
PM2.5: Total	311	88.17	1603	38.96	0	100.00	604	77.01
PM10: Total	434	84.11	2471	9.45	0	100.00	869	68.16
CO: Total	2790	79.09	4475	66.46	0	100.00	2099	84.27
VOC: Total	851	80.30	1208	72.02	0	100.00	819	81.04
SOx: Total	3413	-265.85	20051	-2049.16	0	100.00	6607	-608.13
CH4	17276	-64.52	20864	-98.68	0	100.00	15144	-44.21
N2O	116	44.77	161	22.87	0	100.00	74	64.82
CO2 (w/ C in VOC & CO)	5286440	34.76	10342301	-27.64	0	100.00	6525522	19.46
BC: Total	25	89.27	106	54.63	0	100.00	48	79.20
OC: Total	49	97.84	238	89.42	0	100.00	106	95.30

Round-trip, RGH-CLT-RGH

H2 FUEL CELL AND BATTERY PLUG-IN (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	26646	Reduction 14.13%	32558	Reduction -492.54%	42436	Reduction -36.76%	24250	Reduction 21.85%	30954	Reduction 0.24%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3657696	57.10	11251377	-31.96	13484740	-58.16	32050	99.62	19254	99.77
NOx: Total	4561	94.93	11568	87.15	14108	84.33	35	99.96	117	99.87
PM2.5: Total	594	77.37	1641	37.54	1988	24.33	5	99.81	3	99.87
PM10: Total	876	67.90	2529	7.34	3063	-12.22	8	99.72	4	99.86
CO: Total	2039	84.72	4580	65.68	5567	58.28	14	99.90	28	99.79
VOC: Total	604	86.01	1236	71.37	1502	65.21	4	99.91	7	99.84
SOx: Total	8026	-760.31	20517	-2099.16	24818	-2560.10	62	93.33	1	99.84
CH4	7145	31.96	21349	-103.30	25847	-146.13	65	99.38	25	99.76
N2O	-305	245.87	165	21.07	200	4.42	1	99.76	0	99.88
CO2 (w/ C in VOC & CO)	3519842	56.56	10582676	-30.61	12816039	-58.17	32050	99.60	18446	99.77
BC: Total	78	66.35	108	53.57	131	43.67	0	99.86	0	99.83
OC: Total	94	95.84	243	89.17	296	86.82	1	99.97	2	99.92

9.3.18 Fuel Cell Downsized and Battery





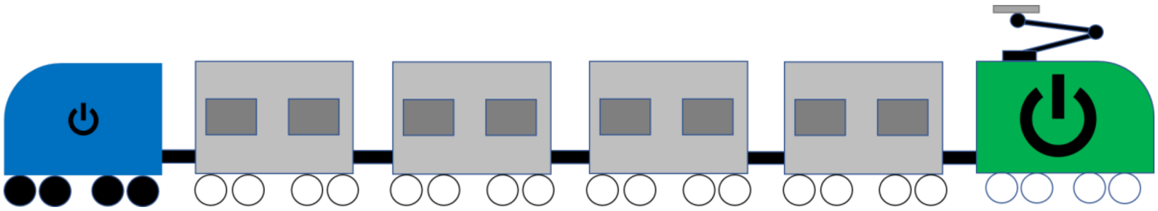
Round-trip, RGH-CLT-RGH

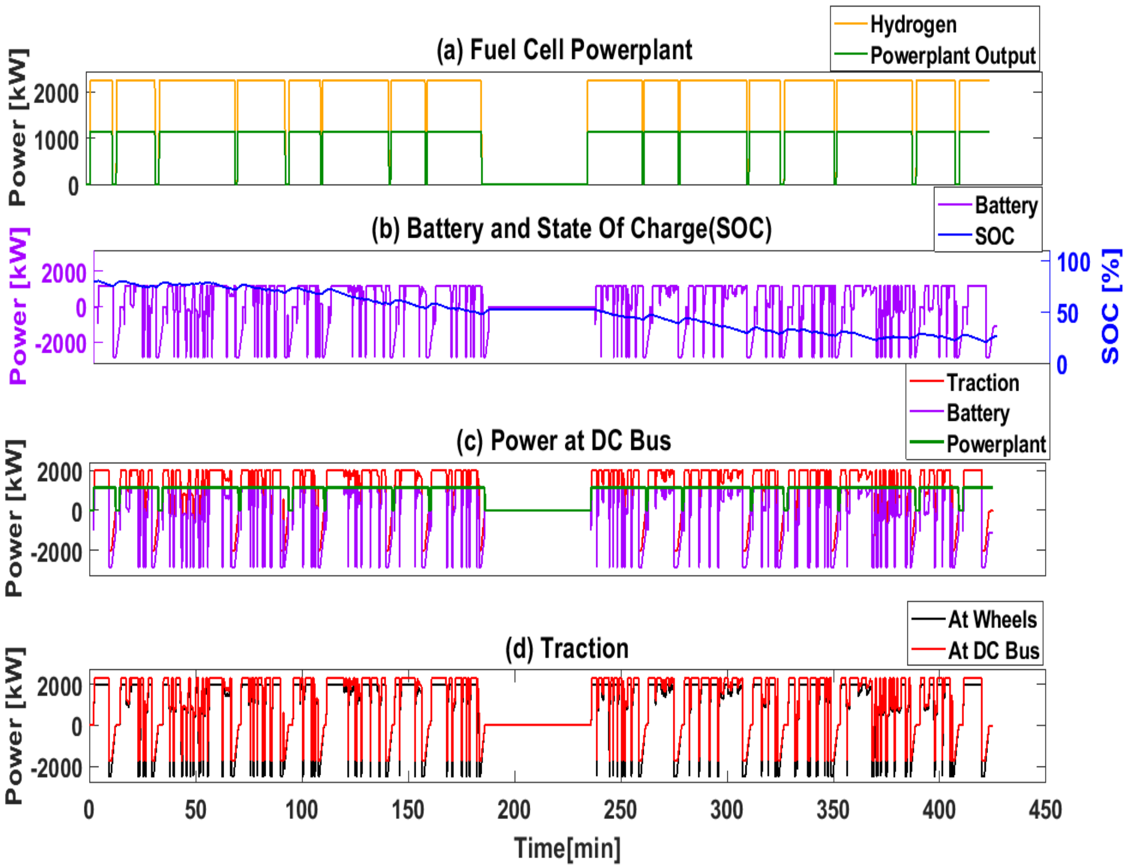
H2 FUEL CELL (DOWNSIZED) & BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, POINT-OF-USE (kWh)	16755	Reduction 35.51%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

H2 FUEL CELL (DOWNSIZED) & BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12907	Reduction -155.65%	22606	Reduction -347.74%	9512	Reduction -88.41%	19638	Reduction -288.96%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6795845	-344.76	13587114	-789.23	0	100.00	8323176	-444.72
NOx: Total	4770	-102.90	13950	-493.36	0	100.00	5150	-119.06
PM2.5: Total	282	-111.96	1978	-1385.42	0	100.00	667	-400.84
PM10: Total	376	-136.91	3050	-1822.44	0	100.00	947	-496.98
CO: Total	3312	-192.48	5523	-387.76	0	100.00	2405	-112.39
VOC: Total	1022	-50.56	1491	-119.61	0	100.00	980	-44.35
SOx: Total	2911	-228.93	24742	-2696.07	0	100.00	7101	-702.46
CH4	21038	-112.58	25745	-160.14	0	100.00	18239	-84.30
N2O	139	-582.82	199	-878.27	0	100.00	84	-312.52
CO2 (w/ C in VOC & CO)	6127853	-409.40	12761964	-960.88	0	100.00	7753730	-544.55
BC: Total	24	-5.95	130	-463.21	0	100.00	55	-138.82
OC: Total	45	-14.17	294	-643.68	0	100.00	120	-204.38

H2 FUEL CELL (DOWNSIZED) & BATTERY (2 LOCOMOTIVES): ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	29662	Reduction 4.41%	39361	Reduction -26.85%	26267	Reduction 15.35%	36393	Reduction -17.28%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6795845	20.30	13587114	-59.36	0	100.00	8323176	2.38
NOx: Total	4770	94.70	13950	84.50	0	100.00	5150	94.28
PM2.5: Total	282	89.25	1978	24.68	0	100.00	667	74.61
PM10: Total	376	86.23	3050	-11.74	0	100.00	947	65.30
CO: Total	3312	75.18	5523	58.61	0	100.00	2405	81.98
VOC: Total	1022	76.33	1491	65.48	0	100.00	980	77.31
SOx: Total	2911	-211.98	24742	-2551.97	0	100.00	7101	-661.11
CH4	21038	-100.33	25745	-145.16	0	100.00	18239	-73.69
N2O	139	33.57	199	4.82	0	100.00	84	59.86
CO2 (w/ C in VOC & CO)	6127853	24.37	12761964	-57.51	0	100.00	7753730	4.30
BC: Total	24	89.47	130	44.01	0	100.00	55	76.26
OC: Total	45	98.00	294	86.94	0	100.00	120	94.66

9.3.19 Fuel Cell Downsized + Battery Plugin





Round-trip, RGH-CLT=RGH		
H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON, POINT-OF-USE (kWh)	13193	Reduction 49.22%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams (Based on SERC)	% Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON,	10163	Reduction -101.30%	17800	Reduction -252.56%	7490	Reduction -48.36%	15463	Reduction -206.27%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	5351094	-250.21	10698585	-600.18	0	100.00	6553725	-328.917
NOx: Total	3756	-59.77	10984	-367.21	0	100.00	4055	-72.49
PM2.5: Total	222	-66.90	1558	-1069.63	0	100.00	525	-294.36
PM10: Total	296	-86.55	2401	-1413.74	0	100.00	746	-370.07
CO: Total	2608	-130.30	4349	-284.07	0	100.00	1894	-67.24
VOC: Total	805	-18.55	1174	-72.92	0	100.00	771	-13.66
SOx: Total	2292	-159.00	19482	-2101.64	0	100.00	5591	-531.86
CH4	16565	-67.39	20272	-104.84	0	100.00	14362	-45.12
N2O	110	-437.65	157	-670.29	0	100.00	66	-224.82
CO2 (w/ C in VOC & CO)	4825113	-301.10	10048857	-735.34	0	100.00	6105340	-407.53
BC: Total	19	16.57	103	-343.48	0	100.00	43	-88.05
OC: Total	35	10.10	231	-485.58	0	100.00	95	-139.67

H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON, WELL-TO-WHEEL (kWh)	23356	Reduction 24.73%	30993	Reduction 0.12%	20683	Reduction 33.34%	28656	Reduction 69.55%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	5351094	37.24	10698585	-25.48	0	100.00	6553725	23.13
NOx: Total	3756	95.83	10984	87.80	0	100.00	4055	95.49
PM2.5: Total	222	91.54	1558	40.70	0	100.00	525	80.00
PM10: Total	296	89.16	2401	12.01	0	100.00	746	72.68
CO: Total	2608	80.46	4349	67.41	0	100.00	1894	85.81
VOC: Total	805	81.36	1174	72.82	0	100.00	771	82.13
SOx: Total	2292	-145.66	19482	-1988.18	0	100.00	5591	-499.30
CH4	16565	-57.74	20272	-93.04	0	100.00	14362	-36.76
N2O	110	47.69	157	25.06	0	100.00	66	68.40
CO2 (w/ C in VOC & CO)	4825113	40.45	10048857	-24.02	0	100.00	6105340	24.65
BC: Total	19	91.71	103	55.91	0	100.00	43	81.31
OC: Total	35	98.42	231	89.72	0	100.00	95	95.79

Round-trip, RGH-CLT=RGH										
H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON,	**12784**	**Reduction** -153.21%	**18893**	**Reduction** -274.20%	**29098**	**Reduction** -476.34%	**8583**	**Reduction** -70.00%	**18789**	**Reduction** -272.14%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-PUMP EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3101108	-102.96	10946941	-616.44	13254464	-767.46	33114	97.83	19894	98.70
NOx: Total	4016	-70.82	11256	-378.77	13881	-490.41	36	98.46	121	94.85
PM2.5: Total	515	-286.91	1596	-1098.56	1955	-1367.82	5	96.14	3	97.40
PM10: Total	753	-374.58	2461	-1451.20	3012	-1798.81	8	95.01	4	97.49
CO: Total	1831	-61.69	4456	-293.57	5476	-383.66	14	98.73	29	97.46
VOC: Total	550	19.02	1203	-77.20	1478	-117.70	4	99.43	7	98.92
SOx: Total	7058	-697.64	19964	-2156.11	24407	-2658.23	64	92.74	2	99.83
CH4	6097	38.39	20773	-109.91	25420	-156.86	67	99.32	26	99.74
N2O	-325	1697.92	161	-689.35	197	-866.23	1	97.46	0	98.73
CO2 (w/ C in VOC & CO)	2999854	-149.37	10297213	-755.99	12604736	-947.81	33114	97.25	19059	98.42
BC: Total	74	-221.58	105	-354.45	129	-457.34	0	98.54	0	98.21
OC: Total	82	-107.68	237	-500.06	292	-638.36	1	98.07	2	95.19

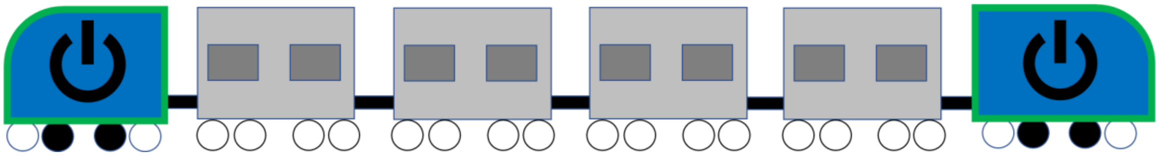
H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON, WELL-TO-WHEEL (kWh)	**25977**	**Reduction** 16.28%	**32086**	**Reduction** -3.40%	**42291**	**Reduction** -36.29%	**21776**	**Reduction** 29.82%	**31982**	**Reduction** -3.07%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3101108	63.63	10946941.03	-28.39	13254464	-55.45	33114	99.61	19894	99.77
NOx: Total	4016	95.54	11256	87.49	13881	84.58	36	99.96	121	99.87
PM2.5: Total	515	80.38	1596	39.23	1955	25.58	5	99.80	3	99.87
PM10: Total	753	72.42	2461	9.84	3012	-10.37	8	99.71	4	99.85
CO: Total	1831	86.28	4456	66.60	5476	58.96	14	99.89	29	99.78
VOC: Total	550	87.27	1203	72.14	1478	65.78	4	99.91	7	99.83
SOx: Total	7058	-656.53	19964	-2039.84	24407	-2516.09	64	93.11	2	99.84
CH4	6097	41.94	20773	-97.81	25420	-142.07	67	99.36	26	99.76
N2O	-325	255.47	161	23.20	197	5.99	1	99.75	0	99.88
CO2 (w/ C in VOC & CO)	2999854	62.98	10297213	-27.09	12604736	-55.57	33114	99.59	19059	99.76
BC: Total	74	68.03	105	54.82	129	44.59	0	99.85	0	99.82
OC: Total	82	96.35	237	89.46	292	87.04	1	99.97	2	99.92

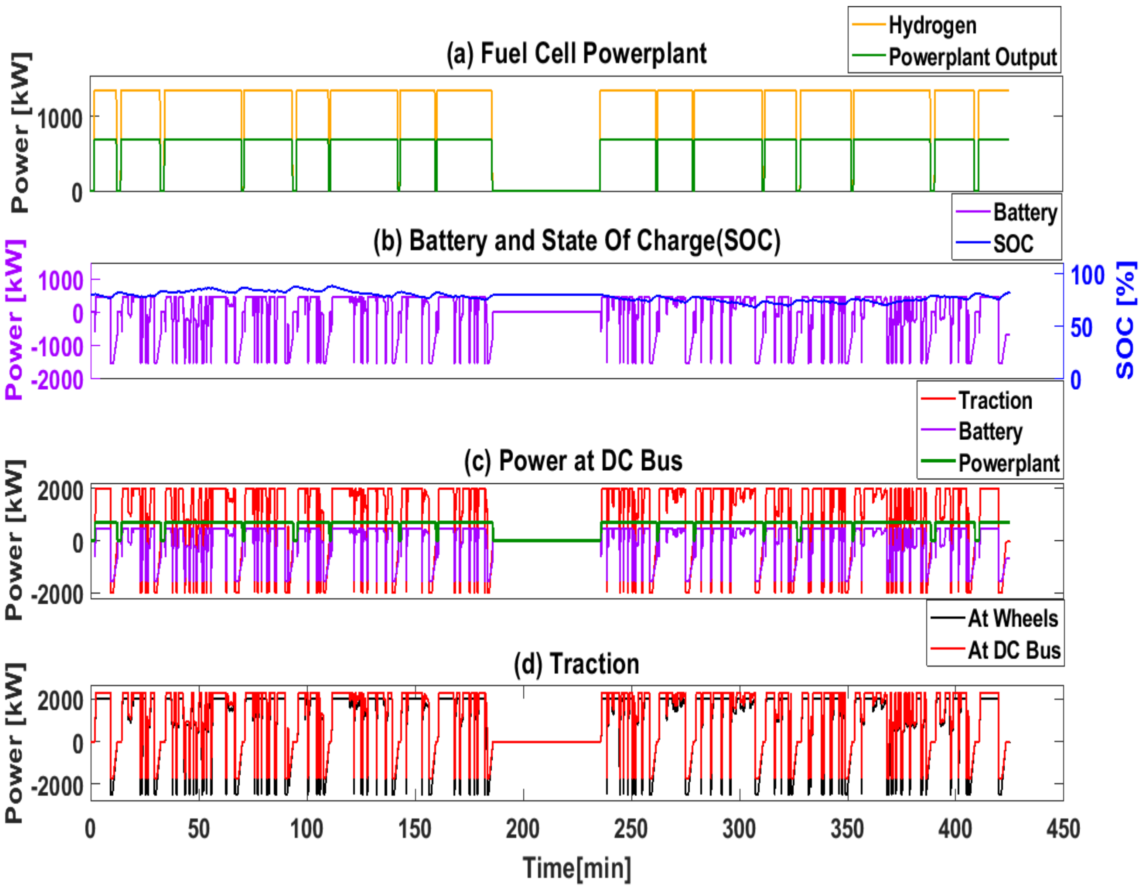
Round-trip, RGH-CLT-RGH		
Energy Requirements (in kWh), Electricity - 100% Renewable	**1504**	**Reduction** 62.16%
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	**Grams** *(Based on SERC)*	
GHGs	656252	
NOx: Total	674	
PM2.5: Total	96	
PM10: Total	147	
CO: Total	267	
VOC: Total	72	
SOx: Total	1195	
CH4	1243	
N2O	10	
CO2 (w/ C in VOC & CO)	616397	
BC: Total	6	
OC: Total	14	

H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON, WELL-TO-WHEEL (kWh)	24860	**Reduction** 19.88%	32496	**Reduction** -4.73%	20683	**Reduction** 33.34%	30159	**Reduction** 2.80%
PRODUCTION METHOD	**ONSITE SMR**		**ONSITE ELECTROLYSIS**		**ONSITE ELECTROLYSIS, 100% RENEW**		**LIQUID DELIVERY, SMR SERC**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**
GHGs	6007346	29.54	11354837	-33.17	0	100.00	7209977	15.44
NOx: Total	4430	95.08	11658	87.05	0	100.00	4729	94.75
PM2.5: Total	318	87.90	1653	37.06	0	100.00	621	76.37
PM10: Total	443	83.76	2549	6.62	0	100.00	893	67.28
CO: Total	2874	78.46	4615	65.41	0	100.00	2160	83.81
VOC: Total	877	79.70	1246	71.15	0	100.00	843	80.46
SOx: Total	3487	-273.75	20677	-2116.27	0	100.00	6786	-627.39
CH4	17809	-69.59	21515	-104.88	0	100.00	15605	-48.60
N2O	119	43.09	167	20.46	0	100.00	76	63.80
CO2 (w/ C in VOC & CO)	5441510	32.84	10665254	-31.63	0	100.00	6721737	17.04
BC: Total	26	89.00	109	53.21	0	100.00	50	78.60
OC: Total	50	97.79	245	89.09	0	100.00	109	95.16

Round-trip, RGH-CLT-RGH										
H2 FUEL CELL (DOWNSIZED) PLUS BATTERY PLUG-IN: ENERGY COMPARISON, WELL-TO-WHEEL (kWh)	27481	**Reduction** 11.44%	33589	**Reduction** -8.25%	43795	**Reduction** -41.14%	21776	**Reduction** 29.82%	31982	**Reduction** -3.07%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3757360	55.93	11603193	-36.09	13910716	-63.15	33114	99.61	19894	99.77
NOx: Total	4690	94.79	11930	86.75	14555	83.83	36	99.96	121	99.87
PM2.5: Total	611	76.74	1692	35.59	2050	21.94	5	99.80	3	99.87
PM10: Total	900	67.02	2608	4.44	3160	-15.76	8	99.71	4	99.85
CO: Total	2097	84.28	4723	64.61	5743	56.96	14	99.89	29	99.78
VOC: Total	622	85.60	1275	70.48	1550	64.11	4	99.91	7	99.83
SOx: Total	8253	-784.62	21159	-2167.93	25602	-2644.17	64	93.11	2	99.84
CH4	7341	30.10	22017	-109.66	26664	-153.91	67	99.36	26	99.76
N2O	-316	250.87	170	18.60	206	1.39	1	99.75	0	99.88
CO2 (w/ C in VOC & CO)	3616252	55.37	10913610	-34.69	13221133	-63.17	33114	99.59	19059	99.76
BC: Total	81	65.33	111	52.12	135	41.89	0	99.85	0	99.82
OC: Total	96	95.72	251	88.83	306	86.41	1	99.97	2	99.92

9.3.20 Two Fuel Cell Hybrid





Round-trip, RGH-CLT-RGH

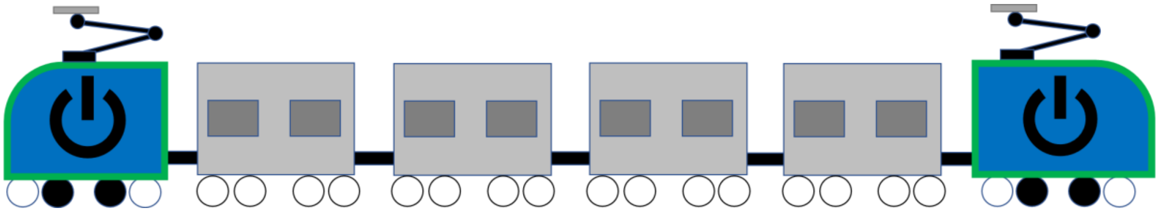
TWO HYDROGEN FUEL CELL LOCOMOTIVES: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	15930	Reduction 38.69%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	**Grams *(Based on SERC)***	**Reduct.**
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

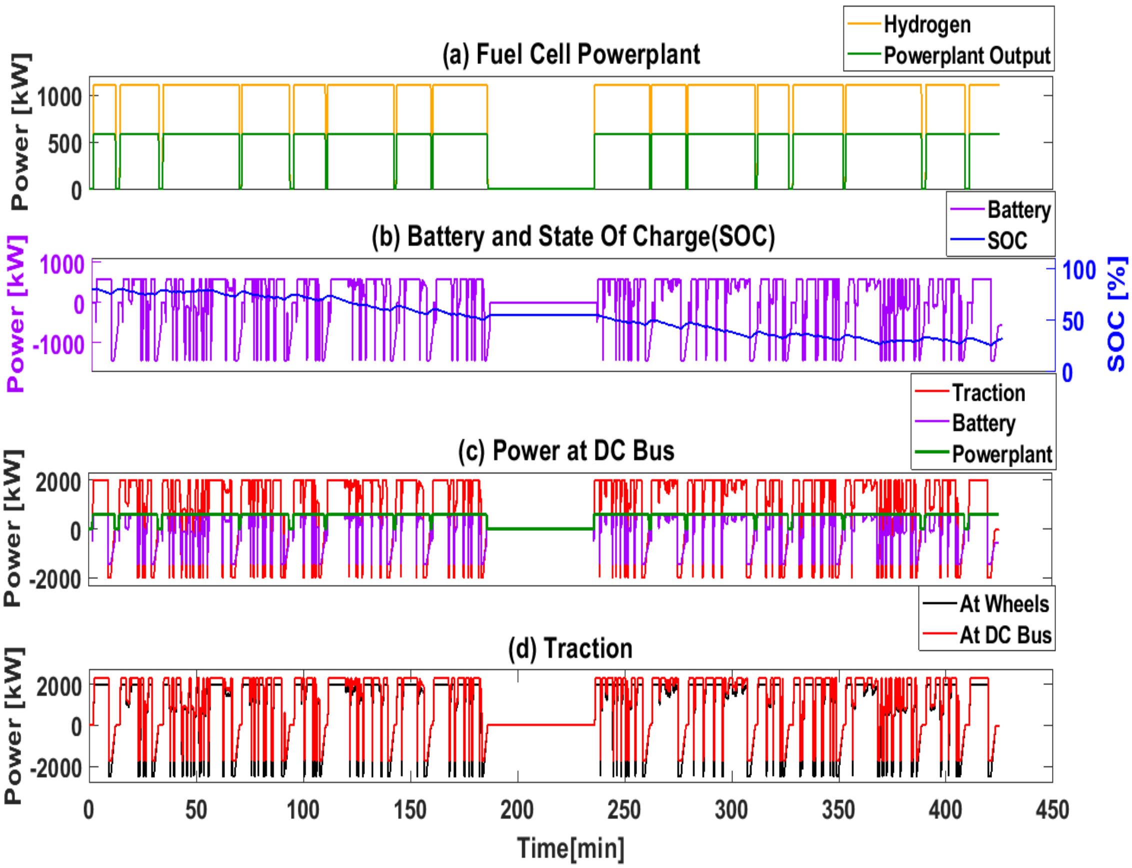
TWO HYDROGEN FUEL CELL LOCOMOTIVES: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12271	Reduction -143.06%	21492	Reduction -325.70%	9044	Reduction -79.13%	18671	Reduction -269.81%
PRODUCTION METHOD	**ONSITE SMR**		**ONSITE ELECTROLYSIS**		**ONSITE ELECTROLYSIS, 100% RENEW**		**LIQUID DELIVERY, SMR SERC**	
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	6461224	-322.86	12918097	-745.44	0	100.00	7913351	-417.90
NOx: Total	4535	-92.91	13263	-464.14	0	100.00	4897	-108.28
PM2.5: Total	268	-101.53	1881	-1312.28	0	100.00	634	-376.18
PM10: Total	357	-125.25	2900	-1727.78	0	100.00	900	-467.59
CO: Total	3148	-178.08	5251	-363.74	0	100.00	2286	-101.94
VOC: Total	972	-43.14	1417	-108.80	0	100.00	932	-37.24
SOx: Total	2767	-212.74	23524	-2558.39	0	100.00	6751	-662.95
CH4	20002	-102.11	24477	-147.33	0	100.00	17341	-75.23
N2O	132	-549.20	189	-830.10	0	100.00	80	-292.21
CO2 (w/ C in VOC & CO)	5826124	-384.32	12133578	-908.64	0	100.00	7371944	-512.82
BC: Total	23	-0.74	124	-435.48	0	100.00	52	-127.06
OC: Total	43	-8.55	279	-607.06	0	100.00	114	-189.39

TWO HYDROGEN FUEL CELL LOCOMOTIVES: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	28201	Reduction 9.11%	37422	Reduction -20.60%	24974	Reduction 19.52%	34601	Reduction -11.51%
PRODUCTION METHOD	**ONSITE SMR**		**ONSITE ELECTROLYSIS**		**ONSITE ELECTROLYSIS, 100% RENEW**		**LIQUID DELIVERY, SMR SERC**	
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**
GHGs	6461224	24.22	12918097	-51.51	0	100.00	7913351	7.19
NOx: Total	4535	94.96	13263	85.27	0	100.00	4897	94.56
PM2.5: Total	268	89.78	1881	28.39	0	100.00	634	75.86
PM10: Total	357	86.91	2900	-6.24	0	100.00	900	67.01
CO: Total	3148	76.40	5251	60.65	0	100.00	2286	82.87
VOC: Total	972	77.50	1417	67.18	0	100.00	932	78.42
SOx: Total	2767	-196.62	23524	-2421.39	0	100.00	6751	-623.63
CH4	20002	-90.47	24477	-133.09	0	100.00	17341	-65.13
N2O	132	36.84	189	9.51	0	100.00	80	61.84
CO2 (w/ C in VOC & CO)	5826124	28.09	12133578	-49.75	0	100.00	7371944	9.02
BC: Total	23	89.99	124	46.77	0	100.00	52	77.43
OC: Total	43	98.09	279	87.59	0	100.00	114	94.92

Round-trip, RGH-CLT-RGH										
TWO HYDROGEN FUEL CELL LOCOMOTIVES: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**15436**	**Reduction** -205.74%	**22812**	**Reduction** -351.84%	**35135**	**Reduction** -595.91%	**10364**	**Reduction** -105.27%	**22687**	**Reduction** -349.35%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-PUMP EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3744459	-145.06	13217977	-765.07	16004215	-947.42	39984	97.38	24021	98.43
NOx: Total	4849	-106.25	13591	-478.10	16760	-612.90	44	98.14	146	93.78
PM2.5: Total	622	-367.18	1927	-1347.22	2360	-1672.33	6	95.34	4	96.86
PM10: Total	909	-473.04	2971	-1773.00	3637	-2192.73	10	93.97	5	96.97
CO: Total	2210	-95.23	5381	-375.22	6612	-484.00	17	98.47	35	96.93
VOC: Total	664	2.22	1452	-113.96	1784	-162.86	5	99.31	9	98.70
SOx: Total	8522	-863.11	24106	-2624.17	29471	-3230.45	78	91.23	2	99.79
CH4	7362	25.61	25083	-153.45	30694	-210.15	81	99.18	31	99.69
N2O	-393	2029.42	194	-853.11	238	-1066.69	1	96.93	0	98.46
CO2 (w/ C in VOC & CO)	3622199	-201.11	12433457	-933.57	15219695	-1165.19	39984	96.68	23013	98.09
BC: Total	90	-288.29	127	-448.73	156	-572.96	0	98.23	1	97.84
OC: Total	99	-150.76	286	-624.55	352	-791.53	1	97.67	2	94.19
TWO HYDROGEN FUEL CELL LOCOMOTIVES: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**31366**	**Reduction** -1.08%	**38742**	**Reduction** -24.85%	**51065**	**Reduction** -64.57%	**26294**	**Reduction** 15.26%	**38617**	**Reduction** -24.45%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams *(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3744459	56.08	13217977	-55.03	16004215	-87.70	39984	99.53	24021	99.72
NOx: Total	4849	94.61	13591	84.90	16760	81.38	44	99.95	146	99.84
PM2.5: Total	622	76.31	1927	26.62	2360	10.14	6	99.76	4	99.84
PM10: Total	909	66.69	2971	-8.87	3637	-33.26	10	99.65	5	99.82
CO: Total	2210	83.43	5381	59.68	6612	50.45	17	99.87	35	99.74
VOC: Total	664	84.63	1452	66.36	1784	58.68	5	99.89	9	99.79
SOx: Total	8522	-813.48	24106	-2483.77	29471	-3058.81	78	91.68	2	99.80
CH4	7362	29.89	25083	-138.85	30694	-192.29	81	99.23	31	99.71
N2O	-393	287.72	194	7.27	238	-13.51	1	99.70	0	99.85
CO2 (w/ C in VOC & CO)	3622199	55.30	12433457	-53.45	15219695	-87.84	39984	99.51	23013	99.72
BC: Total	90	61.40	127	45.45	156	33.10	0	99.82	1	99.79
OC: Total	99	95.60	286	87.28	352	84.35	1	99.96	2	99.90

9.3.21 Two Fuel Cell Hybrid Plugin





Round-trip, RGH-CLT-RGH		
TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	13012	Reduction 49.92%
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	10024	Reduction -98.54%	17556	Reduction -247.72%	7387	Reduction -46.32%	15251	Reduction -202.07%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5277680	-245.40	10551807	-590.58	0	100.00	6463812	-323.03
NOx: Total	3705	-57.57	10834	-360.80	0	100.00	4000	-70.13
PM2.5: Total	219	-64.61	1536	-1053.58	0	100.00	518	-288.95
PM10: Total	292	-83.99	2368	-1392.98	0	100.00	735	-363.62
CO: Total	2572	-127.14	4289	-278.80	0	100.00	1868	-64.95
VOC: Total	794	-16.92	1158	-70.55	0	100.00	761	-12.10
SOx: Total	2260	-155.45	19215	-2071.44	0	100.00	5515	-523.19
CH4	16338	-65.09	19993	-102.03	0	100.00	14165	-43.13
N2O	108	-430.28	155	-659.72	0	100.00	65	-220.37
CO2 (w/ C in VOC & CO)	4758915	-295.60	9910992	-723.88	0	100.00	6021578	-400.56
BC: Total	19	17.72	101	-337.39	0	100.00	43	-85.47
OC: Total	35	11.33	228	-477.54	0	100.00	93	-136.38

TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	23036	Reduction 25.76%	30568	Reduction 1.49%	20399	Reduction 34.26%	28263	Reduction 8.92%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5277680	38.10	10551807	-23.76	0	100.00	6463812	24.19
NOx: Total	3705	95.88	10834	87.96	0	100.00	4000	95.56
PM2.5: Total	219	91.65	1536	41.51	0	100.00	518	80.28
PM10: Total	292	89.31	2368	13.22	0	100.00	735	73.05
CO: Total	2572	80.73	4289	67.86	0	100.00	1868	86.00
VOC: Total	794	81.62	1158	73.19	0	100.00	761	82.38
SOx: Total	2260	-142.29	19215	-1959.53	0	100.00	5515	-491.08
CH4	16338	-55.58	19993	-90.39	0	100.00	14165	-34.88
N2O	108	48.41	155	26.08	0	100.00	65	68.83
CO2 (w/ C in VOC & CO)	4758915	41.27	9910992	-22.32	0	100.00	6021578	25.68
BC: Total	19	91.82	101	56.52	0	100.00	43	81.56
OC: Total	35	98.44	228	89.86	0	100.00	93	95.85

Round-trip, RGH-CLT-RGH

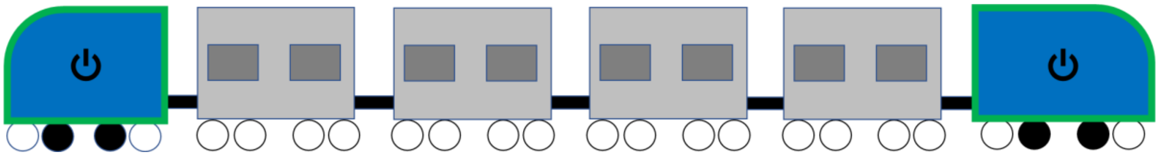
TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	12609	Reduction -149.74%	18634	Reduction -269.07%	28699	Reduction -468.44%	8465	Reduction -67.67%	18531	Reduction -267.04%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3058563	-100.17	10796756	-606.61	13072621	-755.55	32660	97.86	19621	98.72
NOx: Total	3961	-68.47	11102	-372.20	13690	-482.31	36	98.48	119	94.92
PM2.5: Total	508	-281.61	1574	-1082.12	1928	-1347.68	5	96.19	3	97.43
PM10: Total	743	-368.07	2427	-1429.91	2971	-1772.76	8	95.08	4	97.52
CO: Total	1806	-59.47	4395	-288.17	5401	-377.02	14	98.75	28	97.49
VOC: Total	542	20.13	1186	-74.77	1457	-114.71	4	99.44	7	98.93
SOx: Total	6961	-686.69	19690	-2125.16	24072	-2620.39	63	92.84	2	99.83
CH4	6014	39.23	20488	-107.03	25071	-153.34	66	99.33	25	99.75
N2O	-321	1676.00	159	-678.52	194	-852.98	1	97.49	0	98.75
CO2 (w/ C in VOC & CO)	2958698	-145.95	10155941	-744.25	12431806	-933.43	32660	97.29	18797	98.44
BC: Total	73	-217.17	104	-348.22	127	-449.69	0	98.56	0	98.23
OC: Total	81	-104.83	234	-491.83	288	-628.23	1	98.09	2	95.26

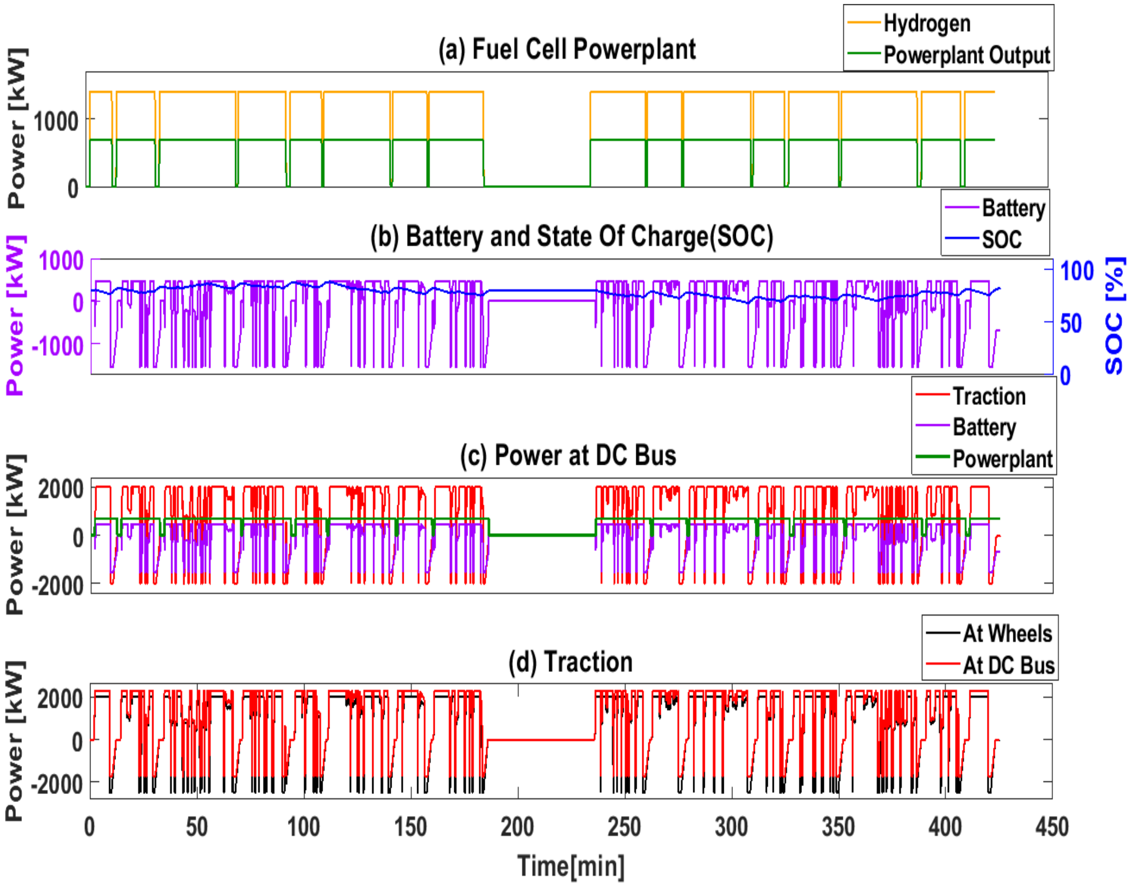
TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	25621	Reduction 17.43%	31646	Reduction -1.98%	41711	Reduction -34.42%	21477	Reduction 30.78%	31543	Reduction -1.65%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3058563	64.13	10796756	-26.63	13072621	-53.32	32660	99.62	19621	99.77
NOx: Total	3961	95.60	11102	87.67	13690	84.79	36	99.96	119	99.87
PM2.5: Total	508	80.65	1574	40.06	1928	26.60	5	99.81	3	99.87
PM10: Total	743	72.79	2427	11.07	2971	-8.85	8	99.71	4	99.86
CO: Total	1806	86.47	4395	67.06	5401	59.52	14	99.89	28	99.79
VOC: Total	542	87.44	1186	72.53	1457	66.25	4	99.91	7	99.83
SOx: Total	6961	-646.15	19690	-2010.49	24072	-2480.19	63	93.21	2	99.84
CH4	6014	42.73	20488	-95.10	25071	-138.75	66	99.37	25	99.76
N2O	-321	253.33	159	24.26	194	7.28	1	99.76	0	99.88
CO2 (w/ C in VOC & CO)	2958698	63.48	10155941	-25.34	12431806	-53.43	32660	99.60	18797	99.77
BC: Total	73	68.47	104	55.44	127	45.35	0	99.86	0	99.82
OC: Total	81	96.40	234	89.61	288	87.21	1	99.97	2	99.92

Round-trip, RGH-CLT-RGH								
ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP, PLUG (kWh)	1372.041209	56.72%						
Energy Requirements (in kWh), Electricity - 100% Renewable		0.00%						
WELL-TO-PUMP EMISSIONS, PLUG ELECTRICITY	Grams (Based on SERC)							
GHGs	598845							
NOx: Total	615							
PM2.5: Total	87							
PM10: Total	134							
CO: Total	243							
VOC: Total	66							
SOx: Total	1090							
CH4	1135							
N2O	9							
CO2 (w/ C in VOC & CO)	562477							
BC: Total	6							
OC: Total	13							
TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	24407.64118	Reduction	31940	Reduction	20400	Reduction	29635	Reduction
	21.34121409	21.34%		-2.93%		34.26%		4.50%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams (Based on SERC)	% Reduct.
GHGs	5876525	31.08	11150652	-30.78	0	100.00	7062656	17.17
NOx: Total	4319	95.20	11448	87.28	0	100.00	4615	94.87
PM2.5: Total	306	88.33	1624	38.19	0	100.00	605	76.96
PM10: Total	426	84.38	2503	8.30	0	100.00	870	68.13
CO: Total	2815	78.90	4532	66.03	0	100.00	2111	84.18
VOC: Total	859	80.10	1223	71.67	0	100.00	827	80.86
SOx: Total	3351	-259.17	20305	-2076.42	0	100.00	6605	-607.96
CH4	17473	-66.39	21128	-101.20	0	100.00	15299	-45.69
N2O	117	44.21	164	21.89	0	100.00	74	64.64
CO2 (w/ C in VOC & CO)	5321392	34.32	10473469	-29.26	0	100.00	6584055	18.74
BC: Total	25	89.35	107	54.05	0	100.00	49	79.09
OC: Total	48	97.87	241	89.28	0	100.00	106	95.27

Round-trip, RGH-CLT-RGH										
TWO HYDROGEN FUEL CELL HYBRID LOCOMOTIVES, PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	26993	Reduction	33018	Reduction	43083	Reduction	21478	Reduction	31543	Reduction
		13.01%		-6.41%		-38.84%		30.78%		-1.66%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams (Based on SERC)	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3657408	57.10	11395600	-33.65	13671465	-60.35	32660	99.62	19621	99.77
NOx: Total	4576	94.92	11716	86.98	14305	84.11	36	99.96	119	99.87
PM2.5: Total	595	77.33	1662	36.74	2015	23.28	5	99.81	3	99.87
PM10: Total	877	67.87	2561	6.15	3105	-13.78	8	99.71	4	99.86
CO: Total	2049	84.64	4638	65.24	5644	57.70	14	99.89	28	99.79
VOC: Total	608	85.92	1252	71.00	1523	64.73	4	99.91	7	99.83
SOx: Total	8052	-763.04	20781	-2127.37	25163	-2597.08	63	93.21	2	99.84
CH4	7148	31.93	21623	-105.91	26206	-149.55	66	99.37	25	99.76
N2O	-312	249.14	167	20.06	203	3.09	1	99.76	0	99.88
CO2 (w/ C in VOC & CO)	3521175	56.54	10718418	-32.29	12994283	-60.37	32660	99.60	18797	99.77
BC: Total	79	66.00	109	52.97	133	42.89	0	99.86	0	99.82
OC: Total	94	95.83	247	89.03	300	86.64	1	99.97	2	99.92

9.3.22 Two Fuel Cell Hybrid Downsized

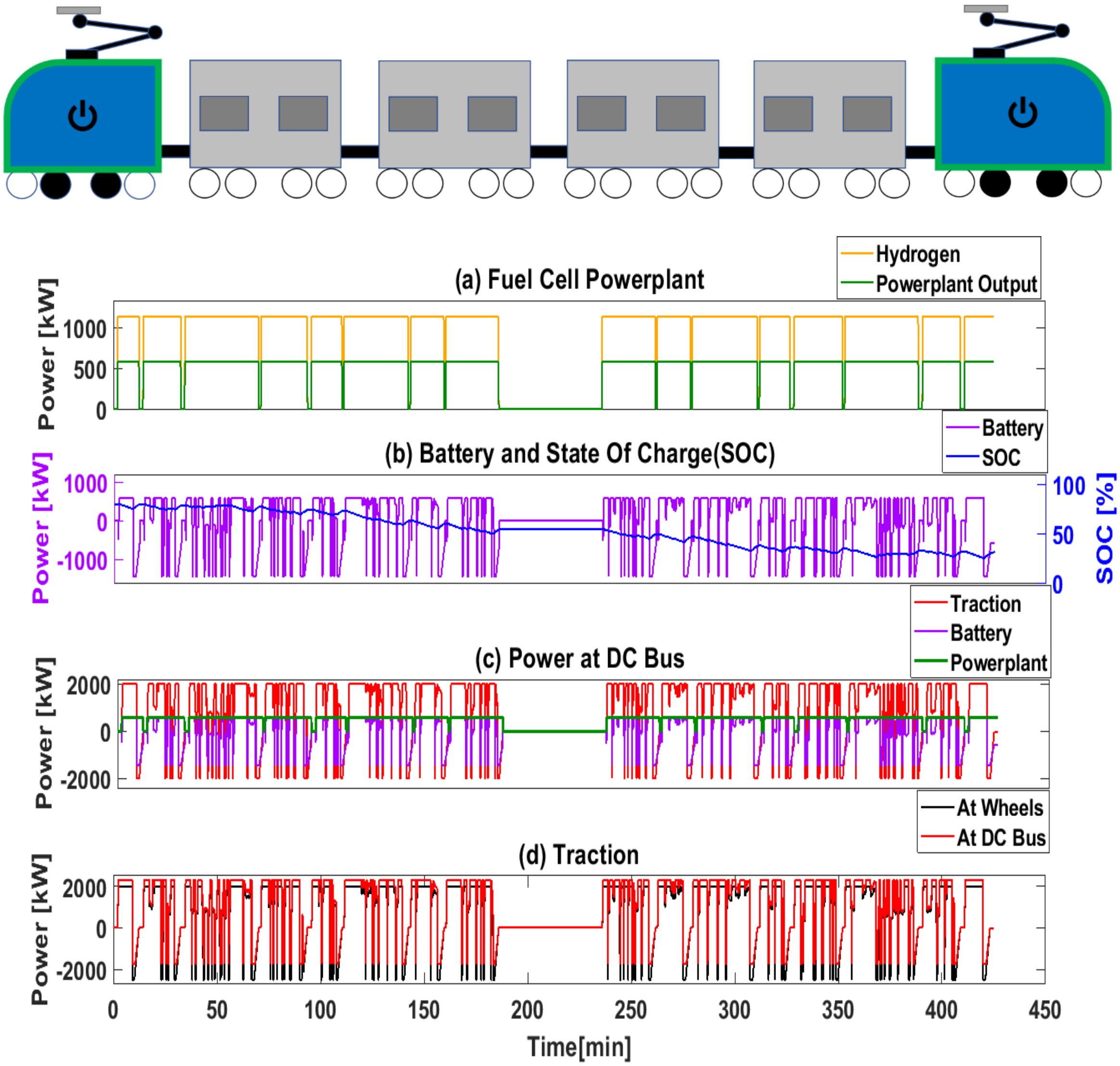




Round-trip, RGH-CLT-RGH								
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOS: ENERGY CONSUMPTION, POINT-OF-USE (KwH)	16585 36.16488973							
ALL PRODUCTION METHODS								
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	Reduct.						
GHGs	0	100.00						
NOx: Total	0	100.00						
PM2.5: Total	0	100.00						
PM10: Total	0	100.00						
CO: Total	0	100.00						
VOC: Total	0	100.00						
SOx: Total	0	100.00						
CH4	0	100.00						
N2O	0	100.00						
CO2 (w/ C in VOC & CO)	0	100.00						
BC: Total	0	100.00						
OC: Total	0	100.00						
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOS: ENERGY CONSUMPTION, WELL-TO-PUMP (KwH)	12776	-153.05%	22376	-343.20%	9416	-86.50%	19438	-285.01%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6726892	-340.25	13449256	-780.20	0	100.00	8238727	-439.19
NOx: Total	4722	-100.84	13808	-487.34	0	100.00	5098	-116.84
PM2.5: Total	279	-109.81	1958	-1370.35	0	100.00	660	-395.76
PM10: Total	372	-134.51	3019	-1802.94	0	100.00	937	-490.92
CO: Total	3278	-189.51	5467	-382.81	0	100.00	2380	-110.24
VOC: Total	1012	-49.03	1475	-117.38	0	100.00	970	-42.89
SOx: Total	2881	-225.60	24491	-2667.70	0	100.00	7029	-694.32
CH4	20824	-110.42	25484	-157.50	0	100.00	18054	-82.43
N2O	138	-575.89	197	-868.34	0	100.00	83	-308.34
CO2 (w/ C in VOC & CO)	6065679	-404.23	12632479	-950.12	0	100.00	7675059	-538.01
BC: Total	24	-4.88	129	-457.50	0	100.00	55	-136.40
OC: Total	45	-13.01	291	-636.13	0	100.00	119	-201.29
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOS: ENERGY CONSUMPTION, WELL-TO-WHEEL (KwH)	29361	5.38%	38961	-25.56%	26001	16.21%	36023	-16.09%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	6726892	21.10	13449256	-57.74	0	100.00	8238727	3.37
NOx: Total	4722	94.75	13808	84.66	0	100.00	5098	94.34
PM2.5: Total	279	89.36	1958	25.45	0	100.00	660	74.86
PM10: Total	372	86.37	3019	-10.61	0	100.00	937	65.65
CO: Total	3278	75.43	5467	59.03	0	100.00	2380	82.16
VOC: Total	1012	76.57	1475	65.83	0	100.00	970	77.54
SOx: Total	2881	-208.82	24491	-2525.06	0	100.00	7029	-653.38
CH4	20824	-98.30	25484	-142.67	0	100.00	18054	-71.92
N2O	138	34.24	197	5.79	0	100.00	83	60.27
CO2 (w/ C in VOC & CO)	6065679	25.14	12632479	-55.91	0	100.00	7675059	5.28
BC: Total	24	89.57	129	44.58	0	100.00	55	76.50
OC: Total	45	98.02	291	87.07	0	100.00	119	94.71

Round-trip RGH-CLT-RGH										
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOS: ENERGY CONSUMPTION, WELL-TO-PUMP (KwH)	16071	-218.31%	9872	-95.54%	13670	-170.76%	10790	-113.71%	23619	-367.82%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3898422	-155.14	13761466	-800.64	16662267	-990.48	41628	97.28	25008	98.36
NOx: Total	5048	-114.73	14150	-501.87	17450	-642.21	46	98.06	152	93.53
PM2.5: Total	648	-386.39	2007	-1406.72	2457	-1745.20	6	95.15	4	96.73
PM10: Total	946	-496.60	3093	-1850.02	3787	-2287.00	10	93.72	5	96.85
CO: Total	2301	-103.26	5602	-394.76	6884	-508.01	18	98.41	36	96.81
VOC: Total	691	-1.80	1512	-122.76	1857	-173.67	5	99.28	9	98.64
SOx: Total	8873	-902.71	25097	-2736.18	30682	-3367.39	81	90.87	2	99.78
CH4	7665	22.55	26114	-163.87	31956	-222.90	84	99.15	32	99.68
N2O	-409	2108.75	202	-892.30	247	-1114.66	1	96.81	0	98.40
CO2 (w/ C in VOC & CO)	3771135	-213.49	12944688	-976.07	15845489	-1217.21	41628	96.54	23959	98.01
BC: Total	93	-304.26	132	-471.29	162	-600.63	0	98.16	1	97.75
OC: Total	103	-161.07	298	-654.34	366	-828.19	1	97.57	2	93.95
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOS: ENERGY CONSUMPTION, WELL-TO-WHEEL (KwH)	32656	-5.24%	26457	14.74%	30255	2.50%	27375	11.78%	40204	-29.57%
PRODUCTION METHOD	LIQUID DELIVERY, BIOMASS		GASEOUS DELIVERY, ELECTROLYSIS		LIQUID DELIVERY, ELECTROLYSIS		GASEOUS DELIVERY, ELECTROLYSIS 100%		LIQUID DELIVERY, ELECTROLYSIS 100%	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams	% Reduct.
GHGs	3898422	54.28	13761466	-61.40	16662267	-95.42	41628	99.51	25008	99.71
NOx: Total	5048	94.39	14150	84.28	17450	80.61	46	99.95	152	99.83
PM2.5: Total	648	75.34	2007	23.60	2457	6.44	6	99.75	4	99.83
PM10: Total	946	65.32	3093	-13.34	3787	-38.74	10	99.64	5	99.82
CO: Total	2301	82.75	5602	58.02	6884	48.41	18	99.86	36	99.73
VOC: Total	691	84.00	1512	64.98	1857	56.98	5	99.89	9	99.79
SOx: Total	8873	-851.04	25097	-2590.01	30682	-3188.70	81	91.34	2	99.79
CH4	7665	27.01	26114	-148.67	31956	-204.30	84	99.20	32	99.69
N2O	-409	295.44	202	3.46	247	-18.18	1	99.69	0	99.84
CO2 (w/ C in VOC & CO)	3771135	53.46	12944688	-59.76	15845489	-95.56	41628	99.49	23959	99.70
BC: Total	93	59.81	132	43.21	162	30.35	0	99.82	1	99.78
OC: Total	103	95.42	298	86.76	366	83.70	1	99.96	2	99.89

9.3.23 Two Fuel Cell Hybrid Downsized Plugin



Round-trip, RGH-CLT

TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, POINT-OF-USE (kWh)	13346	Reduction
	48.63169239	
ALL PRODUCTION METHODS		
POINT-OF-USE-EMISSIONS	Grams *(Based on SERC)*	Reduct.
GHGs	0	100.00
NOx: Total	0	100.00
PM2.5: Total	0	100.00
PM10: Total	0	100.00
CO: Total	0	100.00
VOC: Total	0	100.00
SOx: Total	0	100.00
CH4	0	100.00
N2O	0	100.00
CO2 (w/ C in VOC & CO)	0	100.00
BC: Total	0	100.00
OC: Total	0	100.00

TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	10281	Reduction -103.63%	18006	Reduction -256.64%	7577	Reduction -50.08%	15642	Reduction -209.82%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-PUMP EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5413151	-254.27	10822657	-608.30	0	100.00	6629729	-333.89
NOx: Total	3800	-61.62	11112	-372.63	0	100.00	4102	-74.49
PM2.5: Total	225	-68.84	1576	-1083.19	0	100.00	531	-298.94
PM10: Total	299	-88.71	2429	-1431.30	0	100.00	754	-375.52
CO: Total	2638	-132.97	4399	-288.52	0	100.00	1915	-69.18
VOC: Total	814	-19.92	1187	-74.93	0	100.00	780	-14.98
SOx: Total	2318	-162.01	19708	-2127.18	0	100.00	5656	-539.19
CH4	16757	-69.33	20507	-107.21	0	100.00	14528	-46.80
N2O	111	-443.89	159	-679.23	0	100.00	67	-228.59
CO2 (w/ C in VOC & CO)	4881070	-305.75	10165394	-745.03	0	100.00	6176144	-413.41
BC: Total	20	15.60	104	-348.62	0	100.00	44	-90.23
OC: Total	36	9.06	234	-492.37	0	100.00	96	-142.45

TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	23627	Reduction 23.86%	31352	Reduction -1.04%	20923	Reduction 32.57%	28988	Reduction 6.58%
PRODUCTION METHOD	ONSITE SMR		ONSITE ELECTROLYSIS		ONSITE ELECTROLYSIS, 100% RENEW		LIQUID DELIVERY, SMR SERC	
WELL-TO-WHEEL EMISSIONS	Grams *(Based on SERC)*	% Reduct.	Grams *(Based on SERC)*	% Reduct.	Grams	% Reduct.	Grams *(Based on SERC)*	% Reduct.
GHGs	5413151	36.51	10822657	-26.93	0	100.00	6629729	22.24
NOx: Total	3800	95.78	11112	87.66	0	100.00	4102	95.44
PM2.5: Total	225	91.44	1576	40.01	0	100.00	531	79.77
PM10: Total	299	89.03	2429	10.99	0	100.00	754	72.36
CO: Total	2638	80.23	4399	67.03	0	100.00	1915	85.64
VOC: Total	814	81.15	1187	72.50	0	100.00	780	81.92
SOx: Total	2318	-148.51	19708	-2012.40	0	100.00	5656	-506.25
CH4	16757	-59.57	20507	-95.28	0	100.00	14528	-38.35
N2O	111	47.08	159	24.19	0	100.00	67	68.03
CO2 (w/ C in VOC & CO)	4881070	39.76	10165394	-25.46	0	100.00	6176144	23.77
BC: Total	20	91.61	104	55.40	0	100.00	44	81.09
OC: Total	36	98.40	234	89.60	0	100.00	96	95.74

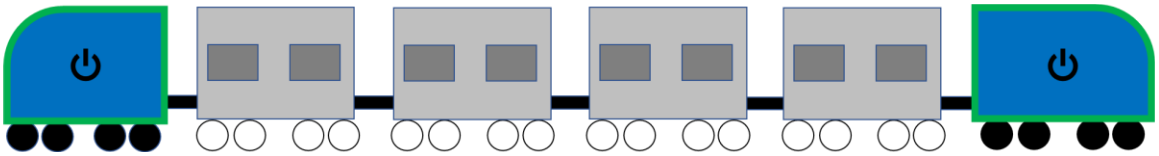
Round-trip, RGH-CLT-RGH										
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, WELL-TO-PUMP (kWh)	**12932**	**Reduction** -156.15%	**19112**	**Reduction** -278.54%	**29436**	**Reduction** -483.03%	**8683**	**Reduction** -71.98%	**19007**	**Reduction** -276.46%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-PUMP EMISSIONS	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3137072	-105.31	11073893	-624.75	13408176.67	-777.52	33498	97.81	20124	98.68
NOx: Total	4062	-72.80	11387	-384.32	14042	-497.26	37	98.44	122	94.79
PM2.5: Total	521	-291.40	1615	-1112.46	1978	-1384.84	5	96.10	4	97.37
PM10: Total	762	-380.09	2489	-1469.19	3047	-1820.83	8	94.95	4	97.46
CO: Total	1852	-63.56	4508	-298.13	5540	-389.27	15	98.72	29	97.43
VOC: Total	556	18.08	1217	-79.25	1495	-120.22	4	99.42	7	98.91
SOx: Total	7140	-706.89	20196	-2182.28	24690	-2690.22	65	92.65	2	99.83
CH4	6168	37.67	21014	-112.34	25715	-159.84	68	99.32	26	99.74
N2O	-329	1716.45	163	-698.50	199	-877.44	1	97.43	0	98.71
CO2 (w/ C in VOC & CO)	3034644	-152.26	10416630	-765.92	12750913	-959.96	33498	97.22	19280	98.40
BC: Total	75	-225.31	106	-359.72	130	-463.80	0	98.52	0	98.19
OC: Total	83	-110.09	240	-507.02	295	-646.92	1	98.05	2	95.13
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**26278**	**Reduction** 15.31%	**32458**	**Reduction** -4.60%	**42782**	**Reduction** -37.87%	**22029**	**Reduction** 263.71%	**32353**	**Reduction** -4.26%
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams** ***(Based on SERC)***	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	3137072	63.21	11073893	-29.88	13408177	-57.26	33498	99.61	20124	99.76
NOx: Total	4062	95.49	11387	87.35	14042	84.40	37	99.96	122	99.86
PM2.5: Total	521	80.15	1615	38.52	1978	24.71	5	99.80	4	99.87
PM10: Total	762	72.10	2489	8.79	3047	-11.65	8	99.71	4	99.85
CO: Total	1852	86.12	4508	66.22	5540	58.48	15	99.89	29	99.78
VOC: Total	556	87.12	1217	71.82	1495	65.38	4	99.91	7	99.83
SOx: Total	7140	-665.30	20196	-2064.66	24690	-2546.42	65	93.03	2	99.83
CH4	6168	41.26	21014	-100.11	25715	-144.87	68	99.36	26	99.75
N2O	-329	257.27	163	22.31	199	4.90	1	99.75	0	99.87
CO2 (w/ C in VOC & CO)	3034644	62.55	10416630	-28.56	12750913	-57.37	33498	99.59	19280	99.76
BC: Total	75	67.66	106	54.30	130	43.95	0	99.85	0	99.82
OC: Total	83	96.31	240	89.34	295	86.89	1	99.97	2	99.91

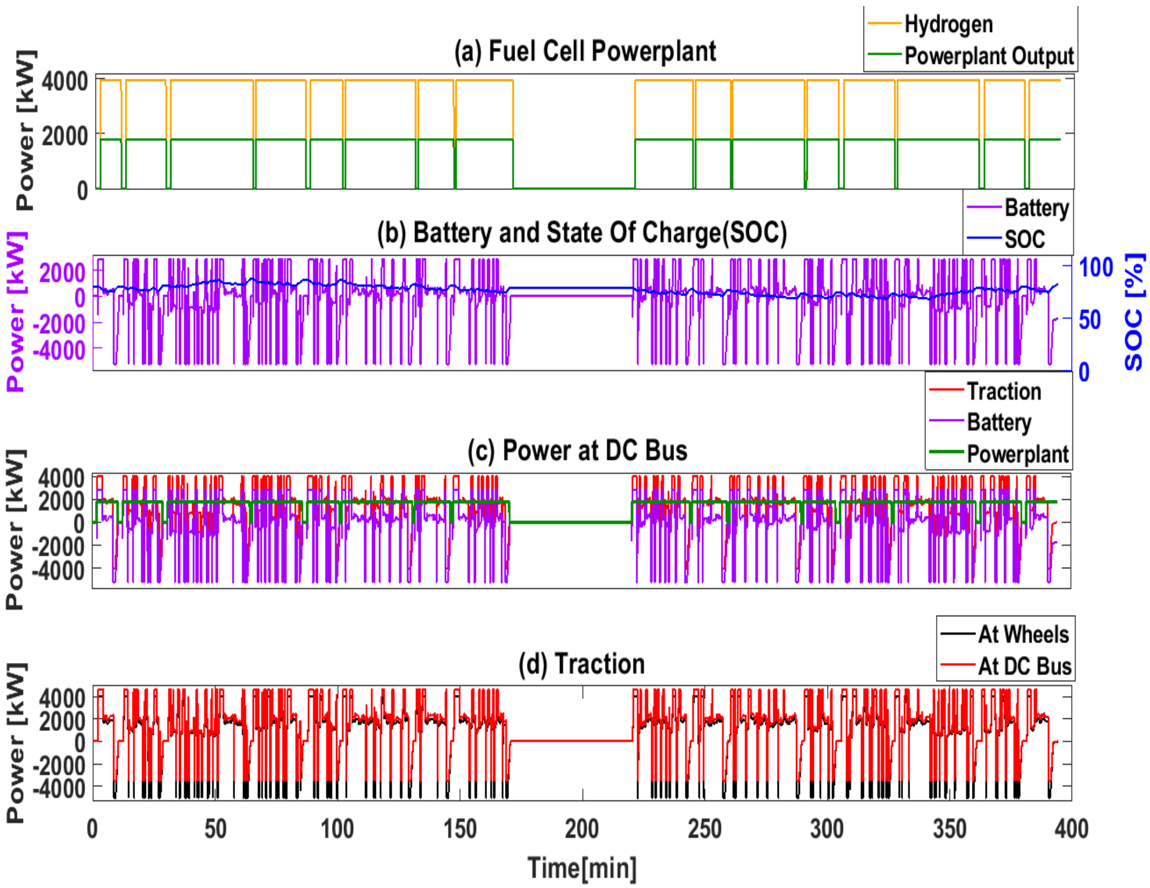
Round-trip RGH-CLT-RGH		
ENERGY CONSUMPTION & COMPARISON, WELL-TO-PUMP, PLUG (kWh)	**1372**	
Energy Requirements (in kWh), Electricity - 100% Renewable		**0.00%**
	Grams *(Based on SERC)*	
GHGs	**598845**	
NOx: Total	**615**	
PM2.5: Total	**87**	
PM10: Total	**134**	
CO: Total	**243**	
VOC: Total	**66**	
SOx: Total	**1090**	
CH4	**1135**	
N2O	**9**	
CO2 (w/ C in VOC & CO)	**562477**	
BC: Total	**6**	
OC: Total	**13**	

TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**24999**	**Reduction** **19.44%**	**32724**	**Reduction** **-5.46%**	**20923**	**Reduction** **32.57%**	**30360**	**Reduction** **2.16%**
PRODUCTION METHOD	**ONSITE SMR**		**ONSITE ELECTROLYSIS**		**ONSITE ELECTROLYSIS, 100% RENEW**		**LIQUID DELIVERY, SMR SERC**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**
GHGs	**6011996**	**29.49**	**11421502**	**-33.96**	**0**	**100.00**	**7228574**	**15.22**
NOx: Total	**4415**	**95.10**	**11726**	**86.97**	**0**	**100.00**	**4717**	**94.76**
PM2.5: Total	**312**	**88.12**	**1663**	**36.69**	**0**	**100.00**	**619**	**76.45**
PM10: Total	**434**	**84.11**	**2564**	**6.07**	**0**	**100.00**	**889**	**67.44**
CO: Total	**2881**	**78.41**	**4642**	**65.21**	**0**	**100.00**	**2159**	**83.82**
VOC: Total	**880**	**79.63**	**1253**	**70.98**	**0**	**100.00**	**846**	**80.40**
SOx: Total	**3409**	**-265.39**	**20798**	**-2129.28**	**0**	**100.00**	**6747**	**-623.13**
CH4	**17892**	**-70.38**	**21641**	**-106.08**	**0**	**100.00**	**15663**	**-49.15**
N2O	**120**	**42.89**	**168**	**19.99**	**0**	**100.00**	**76**	**63.84**
CO2 (w/ C in VOC & CO)	**5443547**	**32.82**	**10727871**	**-32.40**	**0**	**100.00**	**6738620**	**16.83**
BC: Total	**25**	**89.14**	**109**	**52.93**	**0**	**100.00**	**50**	**78.62**
OC: Total	**49**	**97.83**	**247**	**89.02**	**0**	**100.00**	**109**	**95.17**

Round-trip, RGH-CLT-RGH										
TWO HYDROGEN FUEL CELL HYBRID (DOWNSIZED) LOCOMTIVES WITH PLUG-IN: ENERGY CONSUMPTION, WELL-TO-WHEEL (kWh)	**27650**	**Reduction** **10.89%**	**33830**	**Reduction** **-9.02%**	**44154**	**Reduction** **-42.29%**	**22029**	**Reduction** **29.01%**	**32353**	**Reduction** **-4.26%**
PRODUCTION METHOD	**LIQUID DELIVERY, BIOMASS**		**GASEOUS DELIVERY, ELECTROLYSIS**		**LIQUID DELIVERY, ELECTROLYSIS**		**GASEOUS DELIVERY, ELECTROLYSIS 100%**		**LIQUID DELIVERY, ELECTROLYSIS 100%**	
WELL-TO-WHEEL EMISSIONS	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams** *(Based on SERC)*	**% Reduct.**	**Grams**	**% Reduct.**	**Grams**	**% Reduct.**
GHGs	**3735917**	**56.18**	**11672738**	**-36.90**	**14007022**	**-64.28**	**33498**	**99.61**	**20124**	**99.76**
NOx: Total	**4677**	**94.80**	**12001**	**86.67**	**14657**	**83.72**	**37**	**99.96**	**122**	**99.86**
PM2.5: Total	**608**	**76.84**	**1702**	**35.20**	**2065**	**21.39**	**5**	**99.80**	**4**	**99.87**
PM10: Total	**896**	**67.17**	**2624**	**3.87**	**3182**	**-16.57**	**8**	**99.71**	**4**	**99.85**
CO: Total	**2095**	**84.30**	**4751**	**64.39**	**5783**	**56.66**	**15**	**99.89**	**29**	**99.78**
VOC: Total	**622**	**85.60**	**1282**	**70.30**	**1560**	**63.86**	**4**	**99.91**	**7**	**99.83**
SOx: Total	**8231**	**-782.19**	**21286**	**-2181.54**	**25781**	**-2663.31**	**65**	**93.03**	**2**	**99.83**
CH4	**7303**	**30.46**	**22149**	**-110.91**	**26850**	**-155.68**	**68**	**99.36**	**26**	**99.75**
N2O	**-320**	**253.07**	**171**	**18.12**	**208**	**0.71**	**1**	**99.75**	**0**	**99.87**
CO2 (w/ C in VOC & CO)	**3597121**	**55.60**	**10979107**	**-35.50**	**13313390**	**-64.31**	**33498**	**99.59**	**19280**	**99.76**
BC: Total	**81**	**65.19**	**112**	**51.83**	**136**	**41.48**	**0**	**99.85**	**0**	**99.82**
OC: Total	**96**	**95.74**	**253**	**88.77**	**308**	**86.31**	**1**	**99.97**	**2**	**99.91**

9.3.24 Two Fuel Cell Hybrid Downsized with Eight Traction Motors





9.3.25 Two Fuel Cell Hybrid Downsized Plugin with Eight Traction Motors