Low- or Zero-Emission Multiple-Unit Feasibility Study

FEASIBILITY REPORT

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Executive Summary

The San Bernardino County Transportation Authority (SBCTA) is adding the Arrow railway service in the San Bernardino Valley, between San Bernardino and Redlands. SBCTA aims to improve air quality with the introduction of zero-emission rail vehicle technology by procuring a new zero-emission multiple unit (ZEMU) train and converting one of the diesel multiple unit (DMU) trains that will be used to provide Arrow service. Using a Transit and Intercity Rail Capital Program (TIRCP) grant, SBCTA will demonstrate low- or, ideally, zero-emission rail service on the Arrow route. The ZEMU is expected to be in service by 2024 and demonstrate low- or zero-emission railway motive power technology for similar passenger rail service in California as well as a possible technology transfer platform for other railway services.

SBCTA commissioned the Center for Railway Research and Education (CRRE) at Michigan State University (MSU) in collaboration with the Birmingham Centre for Railway Research and Education (BCRRE) at the University of Birmingham, United Kingdom, to assist with the comparison of low- and zero-emission technology suitable for railway motive power applications. The project seeks alternative railway motive power propulsion options to diesel power, (the current benchmark used in this report), since diesel power has had difficulties meeting current emissions requirements and will likely fail to meet future, more stringent standards. Renewable diesel, natural gas, hydrogen fuel cell, and hybrid options are considered.

The emphasis is on a vehicle technology suitable to initially provide the Arrow service with the possibility to expand service to Los Angeles Union Station. Zero-emission propulsion hydrail technology based on hydrogen fuel cells is given priority due to its zero-emission capability while having the potential to offer a practical range between refueling.

The Arrow and Los Angeles Union Station services have been evaluated using a simulation model for two-car and four-car train consists to reflect possible demand patterns. Three hydrogen production and delivery options have been evaluated. The production of hydrogen using 100% renewable electricity is the most environmentally sustainable option and true zero-emission from source to use (well-to-wheel).

Our methodology explored energy requirements and emission assessments during operation of the services. All hybrid options performed better than their conventional counterparts. Though hydrogen fuel cell technology has the capability to be totally zero-emission, a hydrogen fuel cell battery hybrid (hydrail) was found to be the better solution with lower energy consumption of the two options, resulting in an estimated 50% lower energy requirement than diesel performing the same service.

For the Arrow service, a hydrogen-battery hybrid is feasible and provides significant emissions reductions compared to diesel. Hydrogen fuel cell powered trains and battery hybrids are already running in revenue service in Europe. Bus services in California also use this technology successfully. The most cost-effective option of producing hydrogen is through on-site steam methane reforming (SMR). This technology is capable of scaling-up with proportionate emission and energy reductions.

The Los Angeles Union Station service will be best performed by a hydrogen-battery hybrid, which will require either additional hydrogen refueling at termini or additional hydrogen storage space on the train if daily refueling is required. The current growth of hydrogen fuel cell technology and hydrogen storage on-board vehicles as well as the development of refueling infrastructure will have the capability of supporting bus, truck, automobile as well as train requirements.

Potential for expansion of hydrail to other rail services in California includes SMART, eBART and SPRINTER. The synergistic demand for hydrogen as a fuel will support development of infrastructure to manufacture and deliver hydrogen as well as on-site manufacture where warranted. The total potential annual demand across these services could amount to between approximately 1.7 to 2.0 tonnes per day in addition to SBCTA requirements. The greenhouse gas emission reduction for these three services amounts to approximately 11,000 tonnes per year from operations (100%) and could lead to a 100% reduction on a well-to-wheel basis if on-site electrolysis powered by renewable electricity is utilized, for the other production methods reductions are estimated between 30% and 40% on a well-to-wheel basis.

The California services listed above are similar to the Arrow service because they can be performed using multiple-unit trains (where power is distributed throughout the train from point of generation to traction motors powering multiple axles in several vehicles).

In the services mentioned above, the nature of the terrain, distance and other factors influencing the duty cycle, indicates that hydrogen hybrid multiple unit trains would be a cost-efficient, zero-emissions option during operation with significant well-to-wheel emission reductions. eBART, having a short route and the potential option to recharge batteries at termini, is possibly achievable with a battery-only solution, subject to further study.

Other rail services such as streetcars, light rail, yard switchers, heavy rail commuter and long-distance services have been subject of initial hydrogen fuel cell and hydrogen-battery assessments. More work needs to be done, but hydrogen is already proving suitable for streetcars and light rail services as well as being a likely option for yard and road-switcher freight applications. Longer distance and heavier train applications of the technology may be achievable using a tender car to carry hydrogen fuel supply.

The report recommends proceeding with the hydrogen fuel cell hybrid option for the Arrow service if extension to Los Angeles Union Station is a priority. The succeeding phase is to expand the concept to the San Bernardino to Los Angeles Union Station service as demonstrator of technology feasibility and assess the viability on a longer route with a different set of performance requirements.

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Abbreviations

Term	Explanation / Meaning / Definition
AC	Alternating Current
BART	Bay Area Rapid Transit
BCRRE	Birmingham Centre for Railway Research and Education
BEMU	Battery Electric Multiple Unit
BoP	Balance-of-Plant
CA	California
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct Current
DEMU	Diesel Electric Multiple Unit
DMU	Diesel Multiple Unit
DOT	United States Department of Transportation
eBART	East Contra Costa Bay Area Rapid Transit Extension
EPA	United States Environmental Protection Agency
FC	Fuel Cell
FCEMU	Fuel Cell Electric Multiple Unit
FCS	Fuel Cell System
FRA	Federal Railroad Administration
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbons
HEP	Head-End Power
HFC	Hydrogen Fuel Cell
LCFS	Low Carbon Fuel Standard
LNG	Liquified Natural Gas
LTO	Lithium Titanate Oxide
MU	Multiple Unit train

Term	Explanation / Meaning / Definition
N_2O	Nitrous oxide
NG	Natural Gas
NH_3	Anhydrous ammonia
NOx	Oxides of nitrogen
O_2	Oxygen
PEM	Proton Exchange Membrane
PM	Particulate matter
RSSB	Rail Safety and Standards Board in the UK
SAE	Society of Automotive Engineers
SBCTA	San Bernardino Transportation Authority
SMART	Sonoma-Marin Area Rail Transit
SMR	Steam-Methane Reforming
SOC	State-of-Charge
SPRINTER	North County Transit District Sprinter
TIRCP	Transit and Intercity Rail Capital Program
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
WTW	Well-to-wheel
ZEMU	Zero-Emission Multiple Unit

1 INTRODUCTION

The San Bernardino County Transportation Authority (SBCTA) is expanding its public transit options through additional railway service offerings in the San Bernardino Valley with a line between San Bernardino and Redlands known as the Redland Passenger Rail Project (RPRP). Construction and upgrading of railway infrastructure between the two cities are underway. The railway service that is to be offered is marketed as the Arrow service and will initially be provided with diesel multiple unit (DMU) rail vehicles.

While expanding the public transportation options, SBCTA aims to reduce air quality impacting emissions and overall greenhouse gas (GHG) emissions through encouraging modal shift and with introduction of a zero-emission railway vehicle with the intention to convert the DMUs. In 2018, SBCTA was awarded a Transit and Intercity Rail Capital Program (TIRCP) grant for the development and purchase of an additional rail vehicle that will demonstrate the ability to provide low- or, ideally, zero-emission rail service in a multiple unit configuration also known as zero-emission multiple unit (ZEMU). The project will also explore the conversion of at least one DMU vehicle used on the Arrow service, so that regular revenue operations are provided by a zero-emission fleet, substantially reducing or eliminating emissions from Arrow service provision.

The Center for Railway Research and Education (CRRE) at Michigan State University (MSU) in collaboration with the Birmingham Centre for Railway Research and Education (BCRRE) at the University of Birmingham, United Kingdom, have been engaged by SBCTA to assist with comparison of low- and zero-emission technology suitable for railway motive power applications. The emphasis is on a vehicle suitable for Arrow service with possible operation expansion to Los Angeles Union Station (LAUS). Further, investigation of zero-emission propulsion technology with an emphasis on hydrogen-powered railway vehicles (hydrail) is given priority due zero-emission resulting from operation, not requiring continuous wayside infrastructure, and enabling a relatively long range. Additionally, high-level assessment of hydrail suitability for other multiple unit rail service in California and possible application to other types of railway motive power vehicles are part of the study. The intent of the ZEMU is to demonstrate low- or zero-emission railway motive power technology and serve as a demonstrator project for other multiple unit passenger rail services in California as well as a possible technology transfer platform for other railway services.

1.1 Existing Conditions Along Arrow Service Corridor

The Arrow service corridor is a nine-mile rail line with five new passenger rail stations. Currently, the proposed service frequency is every 30 minutes during the morning and afternoon peak while hourly service will be offered during off-peak times. SBCTA is procuring three DMUs to operate the Arrow service.

The DMU that is currently in procurement for Arrow is a bi-directional regional passenger train, see Figure 1-1. The train consists of three cars: two passenger end-cars with powered trucks and one power module car in the middle connected to the passenger cars with articulated trailing trucks. The power module houses the diesel engines and generators that generate the electricity for the traction motors in the powered trucks. This DMU vehicle is part of the Fast Light Intercity and Regional Train (FLIRT) family manufactured by Stadler and is currently in operation in other parts of the country. For the Arrow service, the FLIRT vehicles will be designed to accommodate two additional intermediate passenger cars, creating a train with higher passenger capacity while utilizing the same single power module. Ideally, the ZEMU vehicle will adopt a similar design employing many well-proven components while the power supply system will be the primary difference to the DMU. The ZEMU will operate on the same route as the DMU, therefore all necessary infrastructure components will have to be installed within the available clearance envelope and Arrow facilities, which begin at the new San Bernardino Transit Center (SBTC) and end at the University of Redlands.

Figure 1-1: Rendering of the DMU Ordered for the Arrow Service (MM, MSU CRRE, & SBCTA, 2019)

The Arrow service is an important element of SBCTA's Communities Sustainable Strategy to improve mobility and access for local communities. Implementation of a ZEMU vehicle would contribute to air quality improvements and subsequent higher quality of life for communities along the route. In Figure 1-2 the route of the Arrow service and regional connections are illustrated.

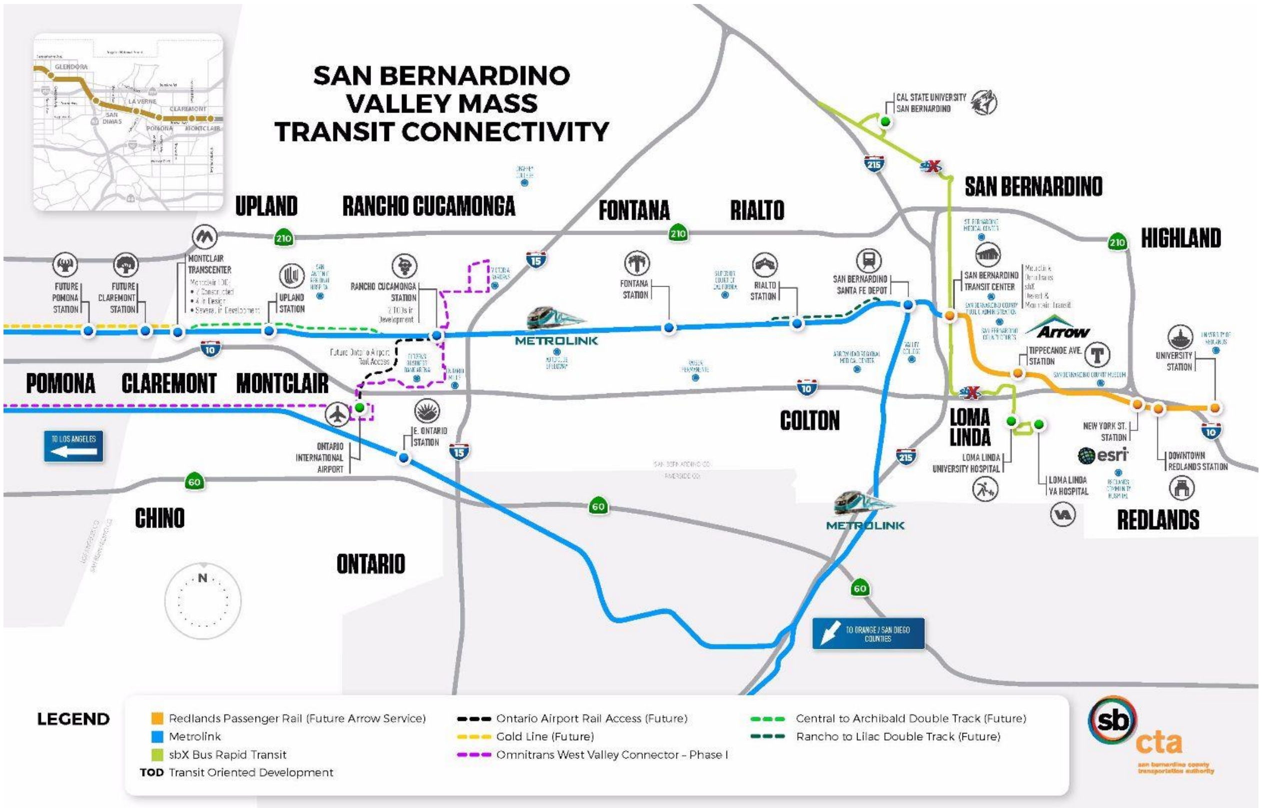
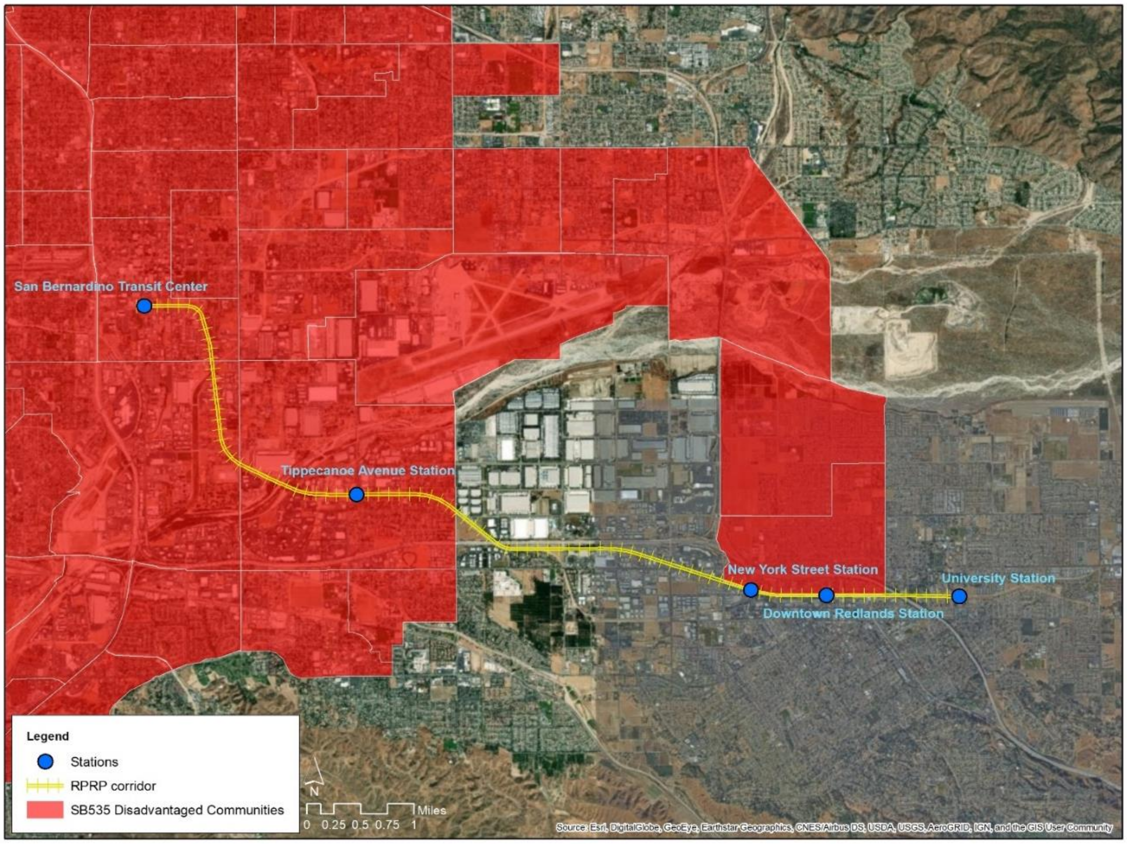


Figure 1-2: Illustration of the Arrow Service Route and Regional Connections (MM et al., 2019)

A ZEMU for the Arrow service supports the mission of the Authority to enhance the quality of life for all residents while contributing to California's ambition to reduce greenhouse gas (GHG) emissions. Population in the cities served by Arrow is projected to increase by ~17% by 2040 (MM et al., 2019). These projections reflect that the corridor will become increasingly important as a center of population and employment growth in the San Bernardino region. Residents along the proposed Arrow service corridor are under-served by existing transit options, which generally require transfers or long trips to destinations that cross city boundaries. The current transportation infrastructure will be further strained by forecasted future regional and local growth.

The Arrow service will operate through one of the most severe air quality standard non-attainment areas in the County, so transitioning Arrow's service fleet to zero- or low-emissions will have positive impacts on the air quality in the San Bernardino region and demonstrate the potential benefits to other corridors in the region and throughout California. The CalEnviroScreen is an assessment tool that aims to evaluate multiple pollution sources and stressors and vulnerability to pollution of the communities in California's approximately 8,000 census tracts. This assessment is part of SB 535 which aims to identify disadvantaged communities for purposes of the cap-and-trade programs based on geographic, socioeconomic, public health, and environmental hazard criteria. As seen in Figure 1-3, there is a high proportion of SB 535 disadvantaged communities along the route of the Arrow service. The implementation of low- or zero-emissions technology will improve the air quality for these communities.

Figure 1-3: SB 535 Disadvantaged Communities Served by the Arrow Service (MM et al., 2019)



In July 2017, Assembly Bill (AB) 398 was passed in California, which extends the state's GHG reduction program to 2030. The original bill, AB 32, required California to reduce its GHG emissions to 1990 levels by 2020 and a new GHG emissions target of at least 40 percent below 1990 level of emissions by 2030 was established (MM et al., 2019). An example of California's ambitious goals regarding reduction of climate and environmental impacts is the "Innovative Clean Transit" rule, approved in December 2018, which is intended to gradually transition to a 100% zero-emission bus fleet by 2040 (CARB, 2018). Implementation is projected to reduce GHGs in the state by 19 million metric tons, and oxides of nitrogen by 7,000 tons during that same period in addition to reductions in particulate matter (CARB, 2018). CARB continues to describe that by 2029, 100% of annual new bus purchases in California will have to be zero-emission. As the new bus fleet rule illustrates, transportation is a major contributor to GHG emissions. The ZEMU Pilot project will supports SBCTA efforts to reduce emissions to align with California's targets while expanding service.

In addition to supporting Authority, regional, and state goals in reducing emissions, the ZEMU project is intended to demonstrate practical feasibility of low- or zero-emission railway motive power technology. Successful implementation could then encourage adoption in other similar rail services in California and serve as a possible technology transfer platform to other types of rail service.

1.2 Scope

The work provided in this document was commissioned by SBCTA to contribute to the Agency's assessment of the feasibility of low- and zero-emission multiple units for the proposed Arrow service. Michigan State University's and University of Birmingham's Centers for Railway Research and Education have contributed to this report in addition to contributions to an earlier report titled "ZEMU Concept Feasibility Study" led by Mott MacDonald. Some parts of this document or described work has already been provided to SBCTA through the Mott MacDonald document. Occasional reference to that document are made to avoid excessive duplication.

The work relied on existing literature and data while employing single train simulation to determine energy consumption at the wheels, which was then post-processed with fixed, indicative average efficiencies for powertrain components. Well-to-wheel estimates were computed with assistance of the U.S. Department of Energy's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by the Argonne National Laboratory. No actual experiments or demonstrator instrumentation were included in this work; therefore, all results are indicative estimates. No detailed designs of vehicles or possible refueling infrastructure were within the scope of the performed work nor any detailed risk assessment and safety plans. Nevertheless, they should provide useful insight enabling informed decision making. The focus was on multiple unit trains, primarily based on the route relevant to SBCTA and limited to California. However, several of the findings and assessments are applicable more broadly than the state on a national and potentially global level.

1.3 Report Structure

- First an introduction to the work with the operating context of the SBCTA Arrow service is provided.
- Next, general background to railway motive power with associated regulated emissions is presented, and the relationship between hydrogen and renewable energy is explored while finishing the section with details about hydrogen fuel cell technology for transportation applications.
- The next section provides a review of low- and zero-emission technology that could be applied to railways.
- A section describing the technical feasibility of primarily zero-emission technology suitable for multiple units and the Arrow service is provided.
- A description about single train simulation and the associated results for a 2-car and 4-car multiple unit operating on the Arrow service and the possible extension to Los Angeles Union Station are provided.
- Possible hydrogen production pathways with associate infrastructure requirements are explored in the next section.
- Energy and emissions impacts of multiple unit operation for the two SBCTA routes, are presented next, including both energy and emissions impactions from operation as well as well-to-wheel consideration for various fuels in addition to hydrogen.
- Capital and operating cost for the preferred hydrogen fuel cell hybrid solution, detailing the implications of the evaluated production and delivery pathways are provided next.

- Next, more generic information about the potential impact of hydrogen-powered multiple units if they were to displace diesel multiple units in California is presented.
- A more detailed examination of the individual multiple unit operating systems eBART, SMART, and SPRINTER is provided.
- The last primary content section provides a high-level assessment regarding the suitability of hydrogen-powered railway vehicles aside from regional multiple units, and more detailed information about switchers specifically is included as they are a further promising application in a freight rail context.
- The last part of the document provides conclusions for the SBCTA cases as well as for California in a broader railway context.

2 BACKGROUND

Transportation by rail is the most efficient mode on land. National statistics show that this is also the case in the United States (U.S.). Passenger rail requires approximately one third of the energy per passenger mile compared to passenger transportation via cars and light trucks while freight trucks require about 6-10 times as much energy per ton mile compared to rail (DOT, 2019; ORNL, 2019).

The majority of energy required by railways in the U.S. is provided by fossil fuels, primarily diesel. In 2016, consumption of diesel fuel within freight rail was approximately 3.4 billion gallons while an additional ~162 million gallons were used in intercity and passenger rail (ORNL, 2019).

Expense for diesel is typically among the top three operating expenses for railways in the U.S. see Figure 2-1 for the operating expenses distribution in 2017, but its relative proportion fluctuates yearly, see Figure 2-2. The Class I railroads spend approximately $6.3 billion on diesel at an average cost of $1.77 per gallon in 2017 (AAR, 2018). The approximate average price for a gallon of diesel since 2007 that Class I railroads paid is $2.50 per gallon. However, other railroads or operators are likely to pay higher prices for diesel, especially if their operation is geographically constraint, such as in the case for SBCTA.

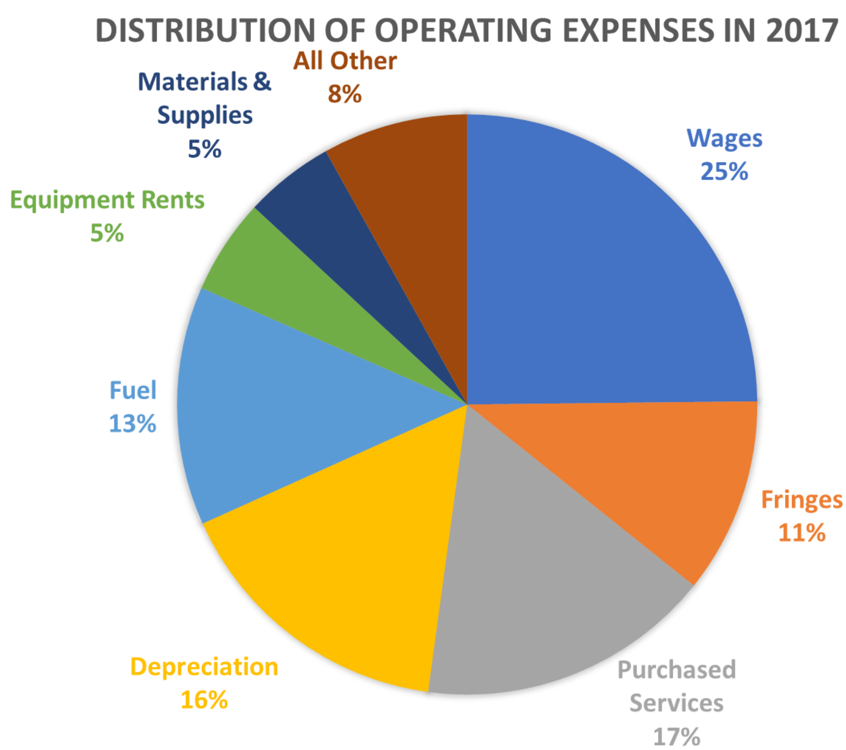


Figure 2-1: Distribution of Class I Railroad Operating Expenses in 2017 (AAR, 2018)

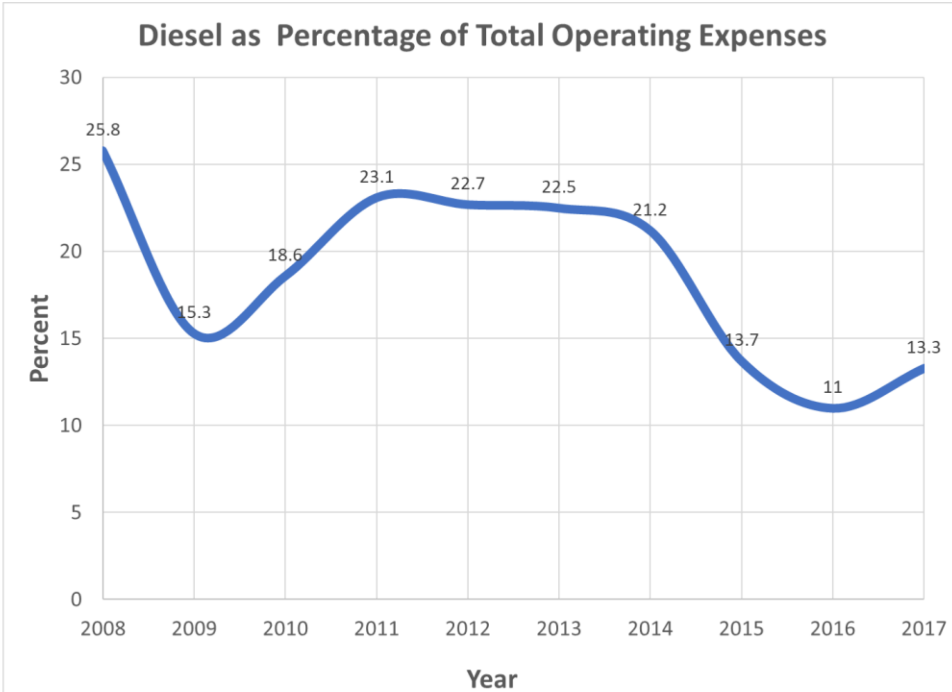


Figure 2-2: Diesel as Percentage of Total Operating Expenses for Class I Railroads in 2017 (AAR, 2018)

The high contributing factor of fuel expenses to total operating expenses results in pressure on alternative fuels to be cost-effective to ensure economic sustainability in the medium- and long-term.

2.1 Current Railway Motive Power

There are two primary power provision options for railways: wayside electrification and on-board generation. Wayside electrification, often simply referred to as electric, relies on continuous infrastructure on the right-of-way to supply electricity to the train, typically through overhead wires or ground-level third rail, popular in subway systems. In the U.S., on-board power generation is traditionally achieved with a diesel engine connected to a generator to create electricity, which is subsequently used to operate electric traction motors; this option is known as diesel-electric, often simply referred to as diesel. The illustration in Figure 2-3 outlines 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.

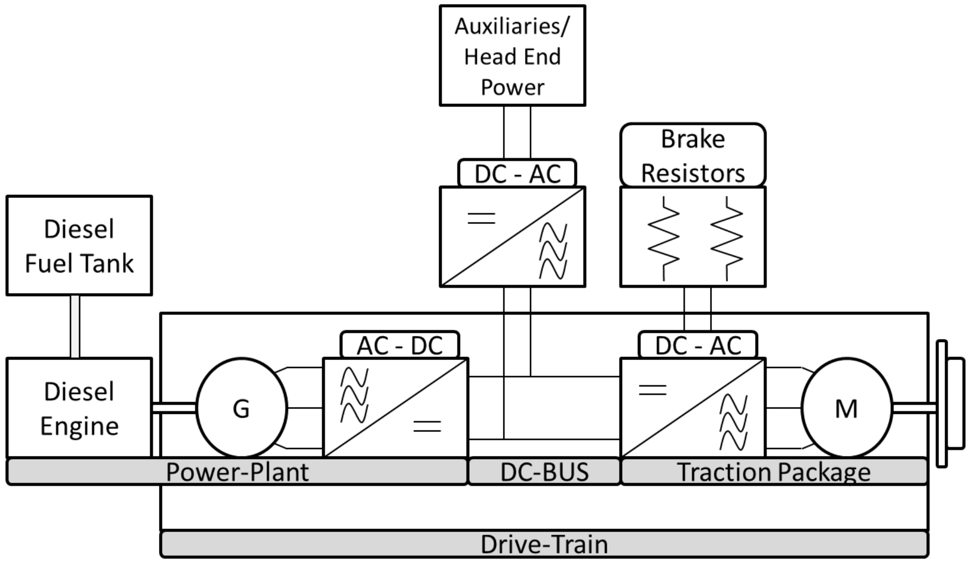


Figure 2-3: Illustration of a Diesel-Electric Powertrain (Hoffrichter, 2013)

Energy consumption from diesel-electric motive power dominates in the U.S., which is illustrated in Figure 2-4. Electricity supplied through wayside infrastructure is primarily utilized in urban railways and high-density passenger operation, such as in Amtrak's North-East Corridor.

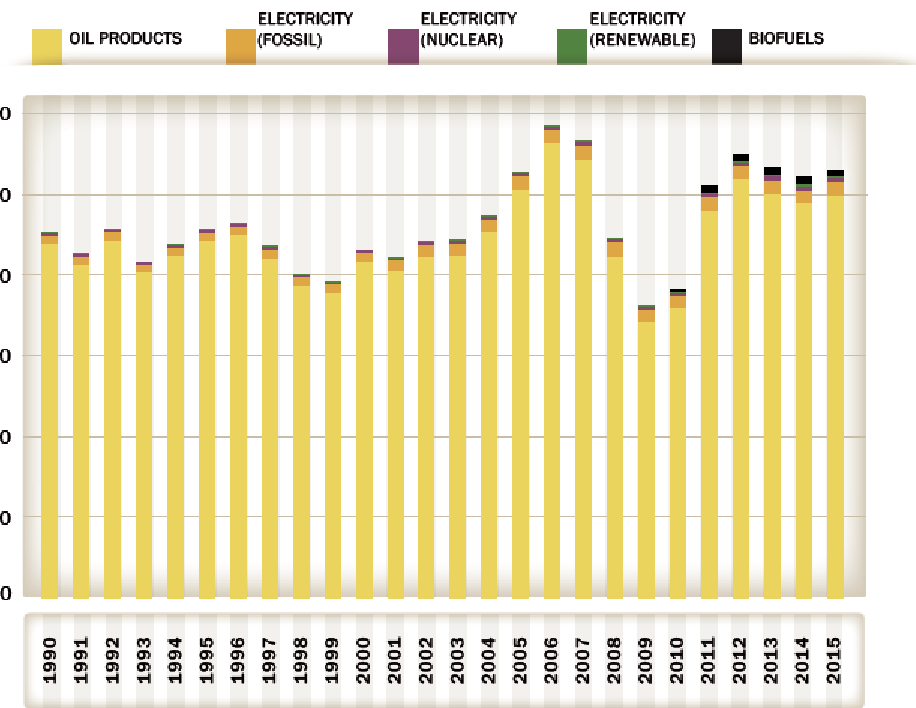


Figure 2-4: Railway Energy Consumption in Petra Joules in the U.S. (IEA & UIC, 2017)

2.2 Emissions From Diesel Combustion

Combustion of diesel results in air quality impacting and GHG emissions. This section provides a description of regulated exhaust emissions followed by a short description of GHG emissions.

2.2.1 Exhaust Emissions Impacting Air Quality

To reduce exhaust emissions from railway motive power vehicles, the U.S. Environmental Protection Agency (EPA) has set standards regarding particulate matter (PM), hydrocarbons (HC), oxides of nitrogen (NOx), and carbon monoxide (CO), which have become progressively stricter, see Figure 2-5. The latest standard, Tier 4, applies to railway motive power vehicles built in 2015 or later. Meanwhile, California has already encouraged the EPA to consider adopting a stricter Tier 5 standard (Nichols, 2017). The proposed standard, see Figure 2-6, would for the first time, seek to limit GHGs emitted by locomotives and require zero-emission operation in designated areas.

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 [l] [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 2-5: Locomotive Emission Standards
(EPA, 2016)

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 2-6: Potential Tier 5 Emission Standards Applicable to Railway Motive Power as Proposed by California
(Nichols, 2017)

2.2.2 Greenhouse Gas Emissions

There are several GHGs and 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 fossil fuels are combusted, which is the case in transportation, 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. CH_4 is commonly used in electricity generation and as fuel in some transportation applications.
- Nitrous Oxide (N_2O) is one of many by-products of fossil fuel combustion and its GWP is 265-298 times of CO_2, or approximately ten times that of methane.

Modal shift from road to rail would reduce 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 with lower emission options in the road sector.

2.3 Renewables and Hydrogen

Current electricity generation relies primarily on fossil fuels, traditionally coal, and there is a trend to utilize lower impact energy sources, such as natural gas, and renewables have an increasing share. The electricity sector faces the substantial difficulty of balancing the supply and demand on the grid, and this mismatch intensifies with increasing shares of renewable power sources, such as solar and wind. In California, the impact stems primarily from increased solar electricity generation (CISO, 2016).

This mismatch dilemma became of particular concern in the late 2000's, when researchers began to project a future mismatch in energy supply and demand that would result from diurnal variations in solar energy generation and the times of day when demand on the electric grid is high (NREL, 2018). The effect was named "duck curve" by the California Independent System Operator (CISO), for the shape that this mismatch creates in a diagram of daily load in regions where solar energy has high levels of penetration (NREL, 2018). The duck curve illustrated in Figure 2-7, shows that the electricity production peak, resulting from renewables, occurs in the early afternoon while the peak consumption occurs in the evening. This difference demonstrates the key role that energy storage will need to play as the proportion of renewables within the total energy supply increases.

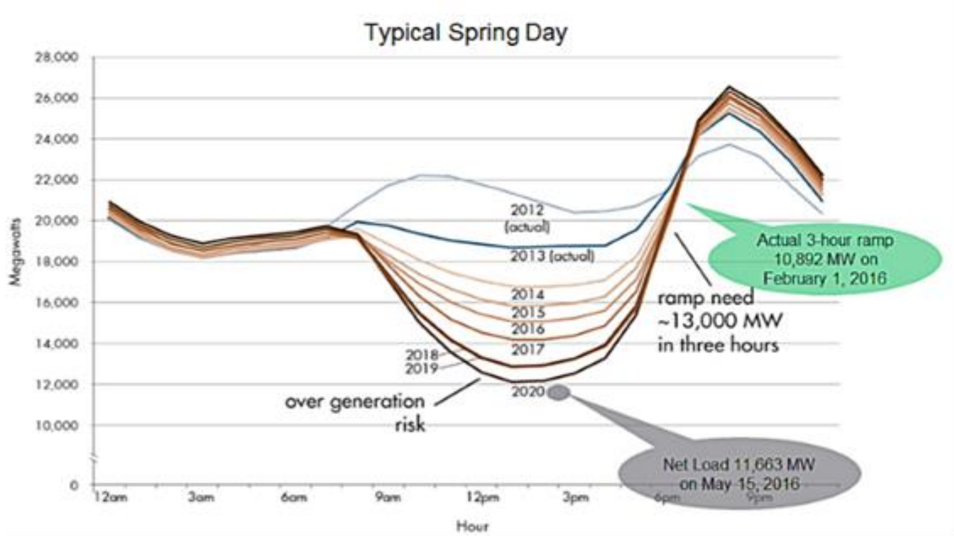


Figure 2-7: California Duck Curve
(CISO, 2016)

Given the relationship of supply and demand on price as well as physical constraints of the energy transmission grid, the impact from the duck curve could be favorable for organizations that can be flexible with their demand.

Batteries and hydrogen can serve as power sources for transportation and as energy storage mediums. A comparison of various technologies for large-scale energy storage are illustrated in Figure 2-8.

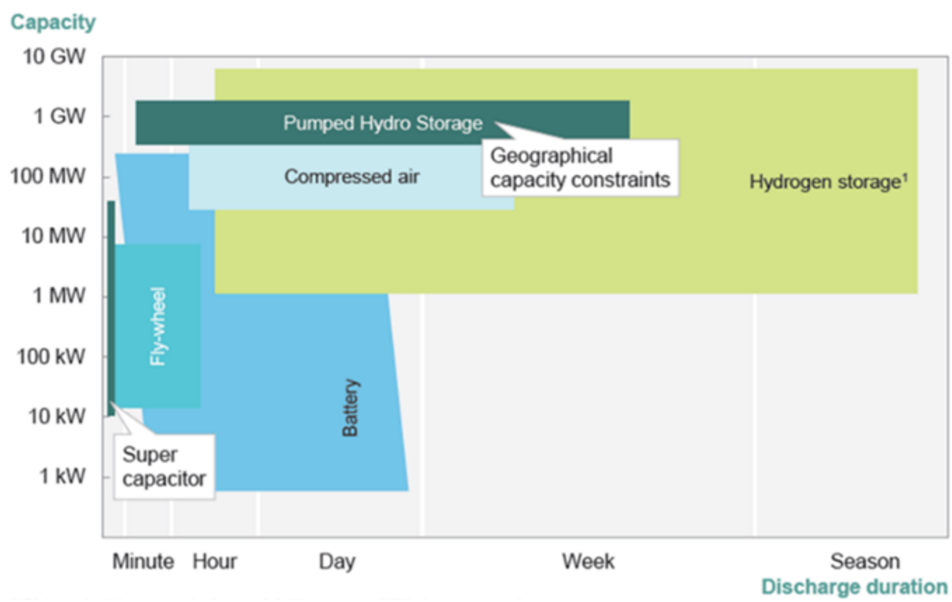


Figure 2-8: Large-Scale Energy Storage Options
(Satyapal, 2019a)

Combining the duck curve effect with energy storage technologies could create an opportunity for railways, and SBCTA, where energy is stored in batteries or as hydrogen during peak production time and utilized on the railway vehicles throughout the day. This offers the potential to obtain attractive prices for energy with a direct impact on operating cost for the railway service.

2.4 Introduction to Hydrogen

Hydrogen (H_2) is the most common element in the universe and a common element here on Earth, where it primarily occurs in compounds such as water (H_2O) and hydrocarbons such as natural gas or petroleum. To obtain pure hydrogen, the compound must be split and, 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.

At ambient temperature and pressure hydrogen is a colorless, odorless gas and the lightest element. It has the largest energy density by mass, ~120MJ/kg low heating value, of any fuel but a low volumetric energy density, requiring compression or liquification to enable storage densities that allow practical ranges for vehicle applications. One kilogram of hydrogen has approximately the same energy as a gallon of diesel. In Figure 2-9, the energy density by mass and volume of various fuels, hydrogen, and batteries is illustrated, including typical container/tank systems, and adjusted with representative powertrain efficiencies. It can be seen that diesel has the highest energy density while batteries have the lowest. To achieve practical ranges with hydrogen technology compared to diesel, additional volume on the vehicle is required (total mass is often similar when the mass of the powertrain components are considered, not illustrated in Figure 2-9). Additional volume might be available in railway service applications enabling practical ranges.

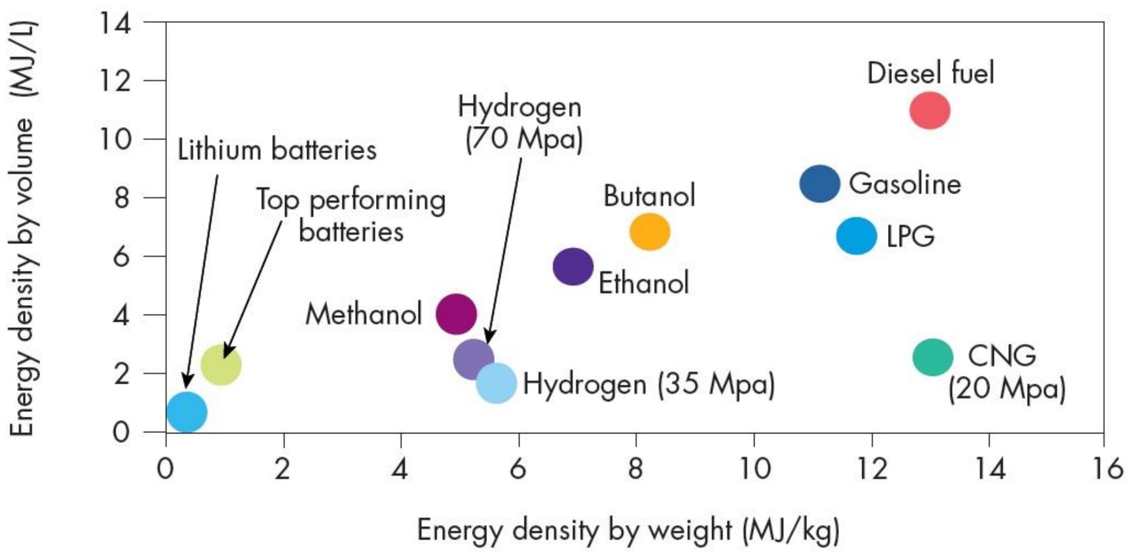


Figure 2-9: Energy Density of Various Fuels and Energy Carriers (IEA, 2009)

Hydrogen is not a greenhouse gas itself and its combustion with air results in water and small amounts of NOx, but the latter can be avoided if hydrogen is used in a fuel cell. Hydrogen is an attractive option for an alternative fuel as it does not contain any carbon, can be utilized in fuel cells therefore avoiding 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 merchant gas.

2.4.1 Introduction to Hydrogen Production

Hydrogen, as an energy carrier, can be produced from many different sources, illustrated in Figure 2-10. Currently, the most common feedstock in the U.S. is natural gas, where water and natural gas a reformed to create hydrogen and CO_2. An alternative method is electrolysis of water, where water is split into oxygen and hydrogen with an electric current, the opposite process of a fuel cell. Electrolysis is attractive as electricity from renewable power sources could be used for hydrogen generation, as described in section 2.3.

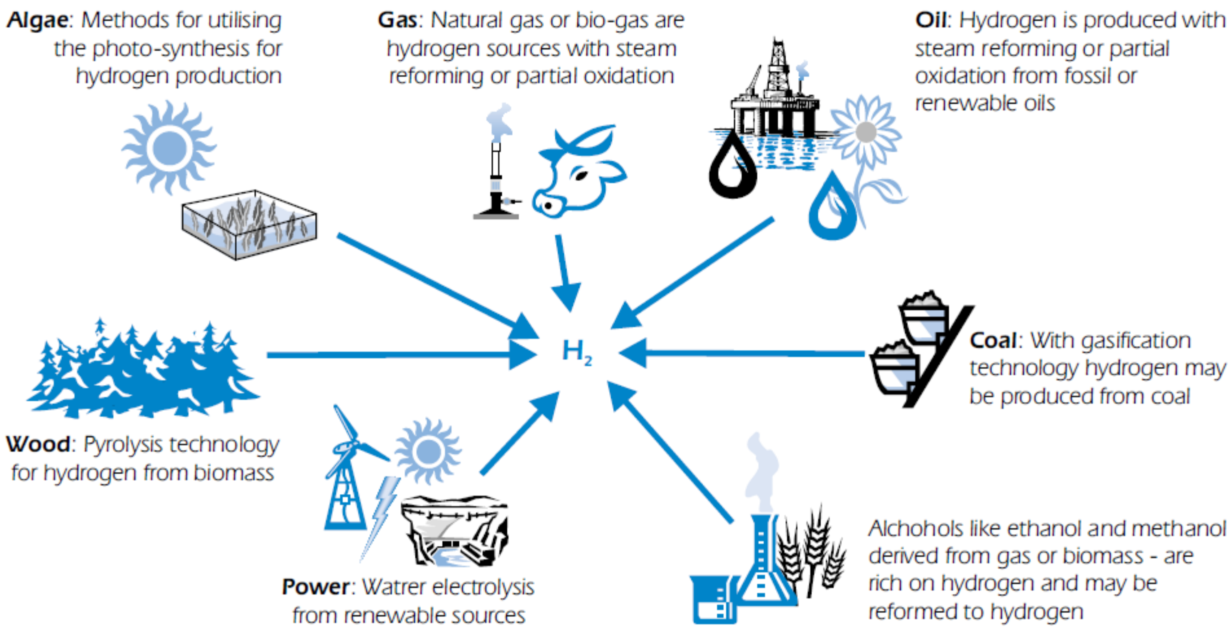


Figure 2-10: Illustration of Feedstocks for Hydrogen Production (IEA, 2006)

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 dependent on railway objectives, availability, and price of H_2 and trade-offs are likely required.

2.4.2 Hydrogen Fuel Cells

Fuel cells are electrochemical devices where a fuel, in this case hydrogen, is combined with oxygen from the air to produce electricity, heat, and as exhaust pure water, predominantly as vapor. Several different types of fuel cell technologies exist and the most popular option for vehicle applications is the proton exchange membrane also known as polymer electrolyte membrane (PEM) (DOE, 2016). In almost all vehicle applications (aside from space craft), such as cars, buses, forklifts, and trains, PEM fuel cells are being employed. Their high efficiency, low operating temperature, start-up capabilities, and relatively long operating lifetime make them the preferred option. An illustration of the operation of a PEM fuel cell is provided in Figure 2-11.

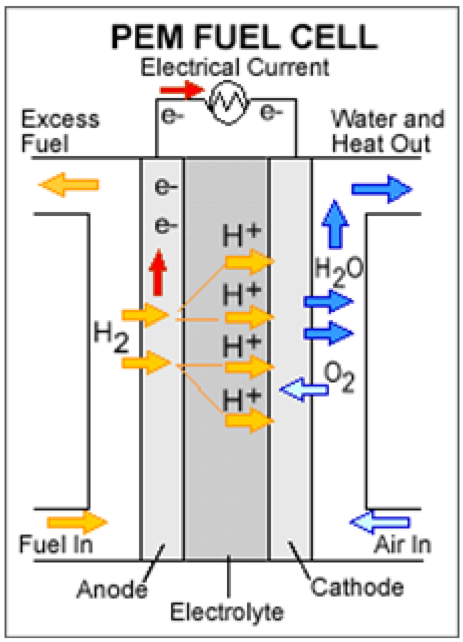


Figure 2-11: Diagram of a Proton Exchange Membrane (PEM) Fuel Cell (DOE, 2011)

The process can be explained in three 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 have to move across an electric circuit to arrive at the cathode.
3. Oxygen is directed to the cathode, where it combines with the hydrogen ions and electrons to form water, which then leaves the cell.

Individual cells do not produce sufficient power for most applications, including for vehicles, so several cells are combined into a stack. Hydrogen, air, and thermal management components, referred to as balance-of-plant, combined with one or several fuel cell stacks create a fuel cell system (FCS), also referred to as modules, and the generic components are illustrated in Figure 2-12. For heavy-duty vehicle applications, typical power output levels are 30kW, 50kW, 80kW, 100kW, and 200kW; if more power is required several FCS are combined.

FCS efficiency curves, as measured in on-road hydrogen fuel cell cars, are provided in Figure 2-13. As can be seen the efficiency of FCS is higher than for a comparable diesel engine and some of the tested systems never drop below 50%. A further observation is that the highest efficiencies occur at partial load.

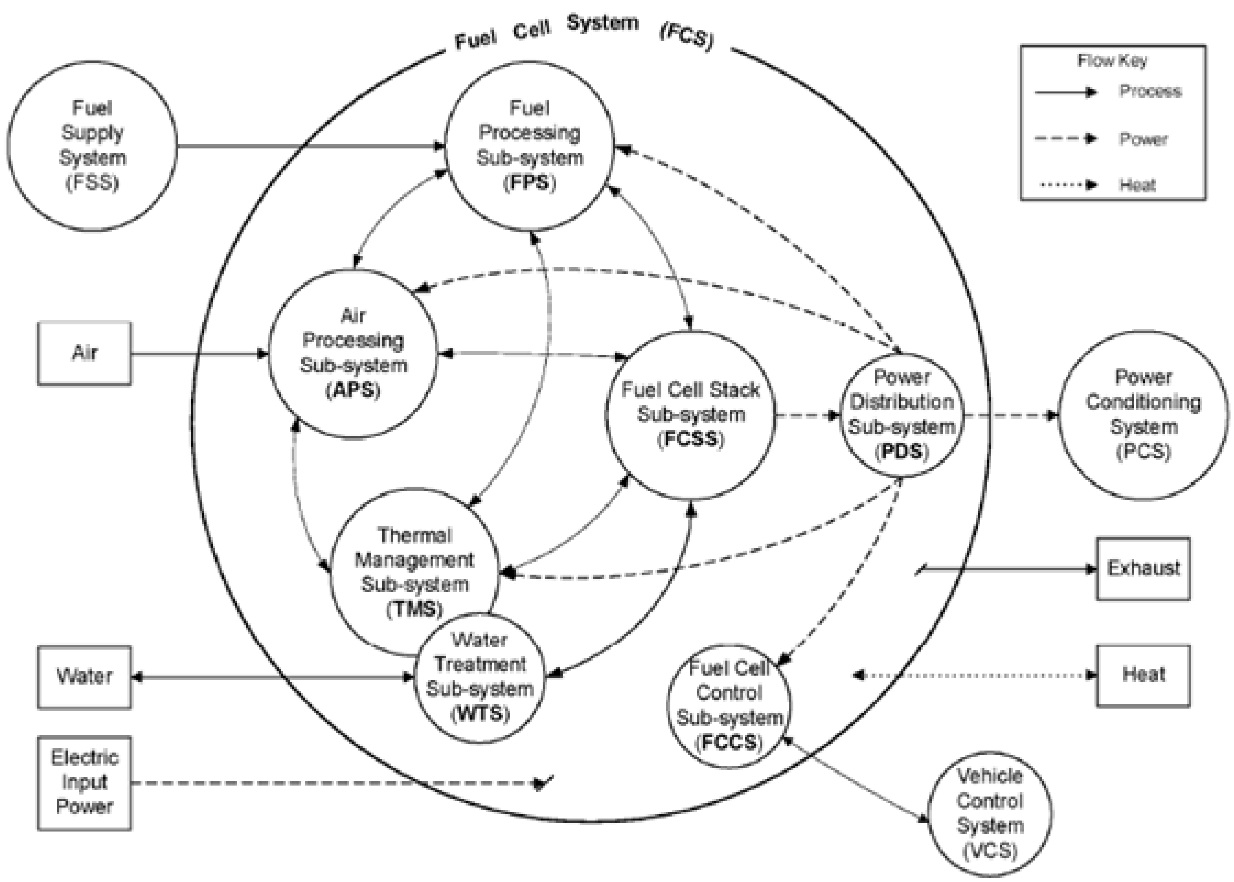


Figure 2-12: General Schematic of a Fuel Cell System (SAE International, 2011)

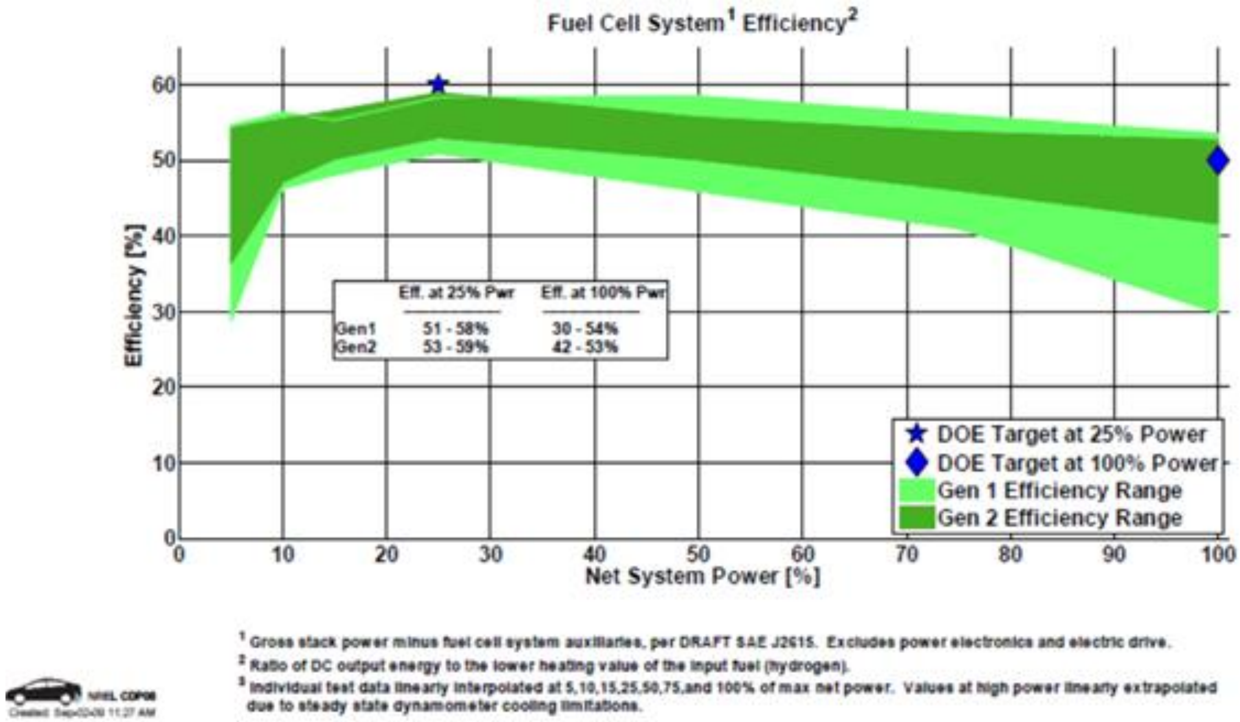


Figure 2-13: Illustration of Fuel Cell System Efficiency (Wipke et al., 2012)

The higher overall efficiency enables a reduction in energy consumption and allows less on-board energy storage for a comparable range to a gasoline or diesel vehicle. 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.

2.4.3 On-Board Hydrogen Storage

Hydrogen is typically stored at a pressure of 350bar or 700bar on-board of vehicles; the former often used in bus and truck applications while the latter is usually preferred in automotive applications. The higher pressure allows more hydrogen storage in a given volume, providing a longer range, and this is especially important in space constraint applications such as cars. A schematic of a compress gas tank is provided in Figure 2-14.

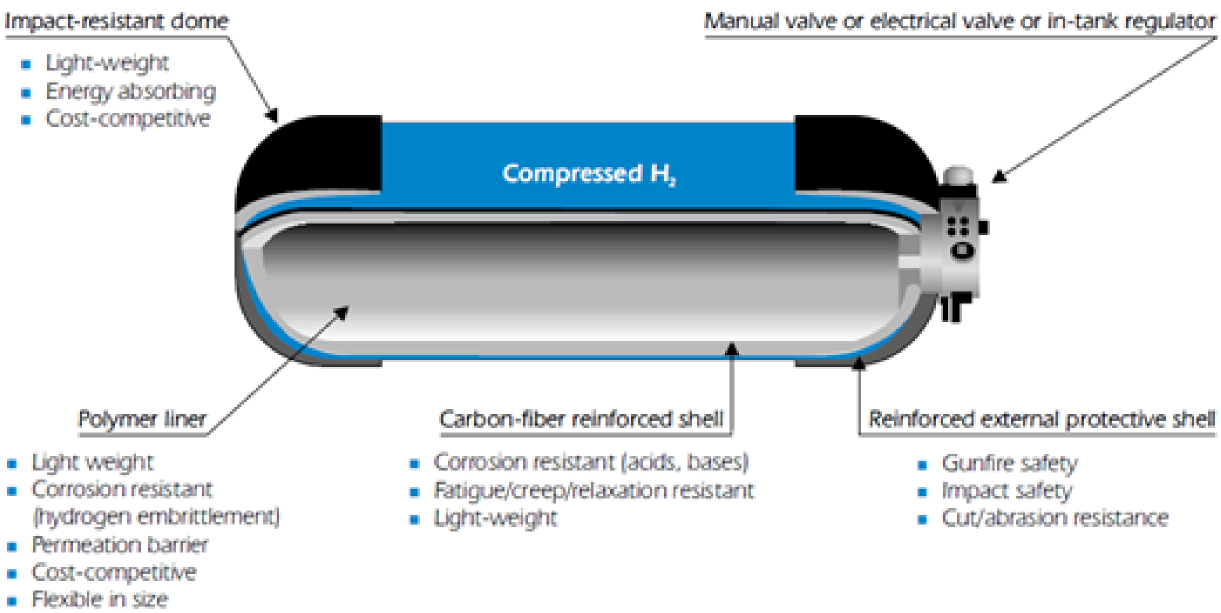


Figure 2-14: Schematic of a Compressed Hydrogen Tank Made from Composite Material (IEA, 2006)

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 multiple units in California would also employ compressed-gas storage as they are commercially available and already used in other transportation applications, further, the Alstom Coradia iLINT train uses both compressed gas tanks and PEM fuel cells. In Figure 2-15 a composite tank that stores hydrogen at 350bar in a truck is illustrated while in Figure 2-16 a composition of hydrogen tanks, also 350bar, in a demonstrator train is depicted.

Figure 2-15: 350bar Hydrogen Tank Installed in a Truck (Hoffrichter, 2019)

Figure 2-16: 350bar Hydrogen Tanks Installed on a Train

2.4.4 Hydrogen Fuel Cells in Transportation Applications

Hydrogen has been transforming warehousing and distribution centers with more than 25,000 hydrogen fuel cell forklifts operating in the U.S. (Satyapal, 2019a). Fuel cell cars or trucks are also available to consumers, currently manufactured by Toyota, Honda, and Hyundai. It is estimated that there are currently more than 6,500 fuel cell vehicles on the road in the U.S. (Satyapal, 2019a). Increasingly, hydrogen fuel-cell buses are being introduced in the U.S. and there are more than 30 hydrogen fuel cell buses on the road, most are operating in California (Eudy, 2019). For example, Sunline Transit Agency in the Coachella Valley in California has been operating hydrogen fuel-cell buses for over 15 years. Sunline produces its own hydrogen and invested in hydrogen fueling infrastructure to serve its growing fleet and reduce the cost of hydrogen (MM et al., 2019). The agency has progressed from hydrogen FCS pilot projects to proliferation of this technology into their regular operating fleet, aided by the availability of a relatively "off the shelf" hydrogen-battery hybrid 40 ft bus. Another agency, the Orange County Transportation Authority (OCTA) is nearing construction completion of its hydrogen fueling facility. Unlike Sunline, OCTA will have liquid hydrogen delivered to its facility in Santa Ana, California, then vaporize the hydrogen to a high-pressure gas, which will then be pumped into the buses. AC Transit in the San Francisco Bay Area has also been operating hydrogen fuel cell buses for several years.

In the following two sections 3 and 4, additional examples of heavy-duty hydrogen fuel cell vehicle application, with a focus on rail, are provided.

3 HIGH-LEVEL MOTIVE POWER TECHNOLOGY REVIEW

Railways operate many different types of services and often have dedicated motive power vehicles for these, including locomotives for mainline and switch operations and multiple units for passenger operation. In this section, a high-level review of several alternative fuels utilized in railway motive power vehicles is provided followed by a segment on hybrid powertrain options. The analysis is focused on on-board options, wayside electrification is briefly reviewed in section 4.

Currently, internal combustion engines are the primary form of power generation on-board of railway vehicles, with the dominant form being diesel engines. Many of the alternative fuel options would retain combustion engines, for example, renewable fuels and natural gas. Therefore, some information about improvements in combustion engine technology is presented first, before describing alternative fuels.

3.1 Improvements in Combustion Engines

There are two generic types of combustion engine, those that work on compression ignition such as diesel engines, and those where a spark is generated to ignite the fuel, i.e. spark ignition. Diesel / compression ignition engines have been favored over their spark ignition counterparts for rail and other heavy-duty applications due to their higher power density, higher torque output, and higher efficiency. But diesel engines produce more nitrogen oxide and particulate emissions than spark ignition engines due to higher combustion temperatures and the nature of the fuel.

Historically diesel engines were permitted to emit higher NOx and particulates levels, but more recently, emission standards have applied parity to the exhaust emissions of each engine type. The advent of emission standards (US 1976 Clean Air Act and EU Euro 1 in 1992) introduced three-way catalytic converters for spark ignition engines, but additional and more numerous technologies have been required to incrementally improve tailpipe exhaust emissions from diesel engines, as discussed in greater depth below.

3.1.1 Diesel Engines

The latest on-road or non-road emission standards emission standards tend to require diesel engines to employ several technologies to control air quality related emissions, commonly including:

- A diesel oxidation catalyst
- An optional lean NOx trap
- A diesel particulate filter
- A selecslips catalytic reduction catalyst
- An ammonia slip catalyst

Further advances are starting to appear in the automotive applications including exhaust gas recirculation, which is another technique adopted for diesel engines in order to decrease NOx emissions. In this technology option, a portion of the exhaust gas is recirculated back into the air inlet system and mixed with the fresh charge of air reducing NOx emissions.

Although these technologies can enable diesel engines to meet current exhaust emission standards, they do not achieve zero-emission as they rely on a hydrocarbon fuel and combustion with air, both resulting in air quality impacting and GHG emissions. The improvements that can be made with regards to emissions are therefore limited. A recent study published by the UK Rail Safety & Standards Board (RSSB) suggests that at best a 40% reduction in GHG emissions from diesel engines could be achieved by employing a combination of stop-start, Advanced Driver Advisory Systems, and hybridization (i.e. where the combustion engine works in partnership with on-board energy storage, such as a battery) (Kent, 2018). Therefore, diesel engines cannot offer a zero-emission solution regardless of the technology employed. For substantial improvement a change in fuel would be required.

3.1.2 Spark Ignition Engines

Spark ignition engines are popular in light duty applications such as cars. Compared to compression ignition engines, they offer lower torque, power density, and efficiency which have limited their adoption in the heavy-duty sector, including railway applications. To meet the latest on-road or non-road emission standards, spark ignition engines use a three-way catalytic converter, and in some instances are now also adopting a gasoline particulate filter (GPF).

In terms of heavy-duty spark ignition engines, to date methane, ethane, propane and butane, methanol, ethanol, butanol and hydrogen have been demonstrated and, in some cases, adopted as alternative fuels. But other than hydrogen, they are in the first instance, fossil fuel-derived, albeit with lower carbon emissions due to the shorter hydrocarbon chains releasing less carbon dioxide for a similar amount of energy as longer chain hydrocarbons, such as diesel.

Compressed natural gas (CNG), liquefied natural gas, and a propane-butane mix known as liquefied petroleum gas (LPG) have seen the most widespread adoption in the transportation sector, with some railway applications. These fuels are attractive due to relatively low cost and lower carbon content. Government incentives have favored these fuels, but until recently suitable combustion engines did not have widespread manufacturer support.

In the light-duty sector, retrofit conversions are offered, but the tendency of medium-duty and heavy-duty applications to adopt diesel engines has meant there has been limited scope for these fuels in these sectors, primarily due to the lack of pre-existing spark ignition engines (i.e. gasoline engines) that could be evolved to use CNG or LPG. But nonetheless, heavy-duty spark ignition engines are now produced by Iveco, Scania, and Cummins, and in the large non-road engine sector by Caterpillar, Cummins, GE, and Perkins.

However, as with diesel engines, spark ignition engines still run on a carbon-based fuel and, therefore, offer limited improvement regarding emissions. Hydrogen can be utilized in a combustion engine but NOx emission result in the combustion with air and the energy carrier can be more efficiently used in a fuel cell without air quality-impacting or GHG emissions, therefore fuel cells have been the favored devices.

3.2 Biofuels

Renewable fuels are produced from biomass feedstocks, e.g., wood, corn, soybean, palm oil, algae, and these fuels can be gaseous, often referred to as biogas, or liquid, referred to as biofuel, which encompasses biodiesel and renewable diesel in this document. These fuels are hydrocarbons of various carbon and hydrogen composition and typically used in internal combustion engines, similar to gasoline or diesel as described in the previous section 3.1. Biofuels can be combined with conventional fuels and typical substitution ratios are 10%, 20%, 50%, 80%. European fuel legislation and standards, e.g. EN590, mandate a 5 to 8% biofuel content mixed with the fossil fuel. In the U.S., almost all gasoline sold contains ~10% biofuel. Railroads in the U.S. also utilize some biofuels with an approximate share of 5% in the fuel mix (IEA & UIC, 2017).

The combustion of biofuels results in emissions that impact air quality as carbon is present in the chemical composition and combustion with air takes place instead of pure oxygen. However, there is emission reduction potential with biofuels. For example, the operation of a locomotive with 100% biodiesel in North Carolina for several months has shown up to a 60% reduction of CO, HC, and PM 2.5. Nitrogen oxide (NOx) emissions were unaffected or marginally higher, which is typical for biofuel combustion.

The overall well-to-wheel carbon emissions resulting from the biofuel supply chain can sometimes be considered as carbon neutral, as the carbon released during the combustion process was previously captured by the biomass. However, if energy crops are cultivated on land that was previously forested then there is an overall GHG increase, while there is an GHG benefit if pastureland is used or the biofuel is produced from a by-product of the timber or food industry.

Some waste could be used for biofuel production, for example, collection of fat used in restaurants, parts of corn used for high fructose corn syrup, and waste material from building lumber. Nevertheless, crop-based or crop-derived (e.g. those chosen for improved ethanol yield through fermentation) biofuels have placed pressure on agricultural land leading to increased food prices and/-or restricted food supply and has increased deforestation to provide additional land for these non-food crops in some regions globally. The situation has led to the EU capping the supply and consumption of biofuels meaning this production route cannot continue to further displace fossil fuels. However, co-production with food crop and second-generation biofuels are still being pursued. For example, algae and non-crop supplied fuels circumvent these issues, but these are still in their infancy as a technology and are not in volume production.

There is little or no scope for energy reduction as the same or slightly modified engines compared to conventional diesel combustion would be employed. Utilization of biofuels or a conventional diesel / biofuel blend with a high substitution ratio can create difficulty during cold weather operation as the fuel will become increasingly less liquid with colder temperatures; this can be managed with additives or heating systems. A summary of the advantages and disadvantages for biofuel is provided in Table 3-1.

Table 3-1: Biofuel Summary
(MM et al., 2019)

Advantages	Disadvantages
Can use existing diesel engine (potentially requires relatively minor modifications).	Results in significant amount of local emissions but some improvement over conventional diesel.
Can be progressively introduced in a blend with diesel.	Considered to not sufficiently reduce GHG and local emissions during operations.
Reduces some local emissions.	Fuel is toxic and an environmental hazard, needs to be managed carefully.
Only requires minor modifications to refueling infrastructure.	Little to no energy reduction potential compared to conventional diesel.
Significant range capability, no additional in-route infrastructure required.	

3.2.1 Operational Application to Arrow

Biofuels could be implemented in the rail vehicle for the Arrow service but would most likely not result in the desired reduction of emissions required by the TIRCP grant that SBCTA received. Therefore, biofuels are considered an incompatible option for a low- or zero-emission vehicle. However, biofuel and conventional diesel blends might be an option to reduce some of the emissions resulting from DMU operation.

3.2.2 Safety Hazard Considerations

Biofuels are combustible liquids that pose hazards from burns, explosions, and chemical exposure. Hazard controls are similar to the ones that are in place for regular diesel vehicles.

3.3 Natural Gas

Natural gas (NG) results in the lowest emissions of any fossil fuel combustion (in oxygen or air) and, currently, has an economic advantage compared to diesel. It has a low energy density by volume at ambient conditions and, therefore, requires compression, called compressed natural gas (CNG), or liquification, called liquified natural gas (LNG). Typically, the majority of NG is formed of methane, therefore it has a significantly lower carbon content compared to diesel resulting in reduced carbon emissions during combustion. NG is a hydrocarbon that is used in combustion engines similar to gasoline or diesel engines, as described earlier in 3.1.

Combustion with air leads to NOx emissions and these can be managed in a similar process to conventional diesel combustion with after-treatment systems.

NG engines or conversion kits for conventional diesel engines are available from many manufactures, including Cummins, Caterpillar, General Electric and EMD. Engines with conversion kits can operate with natural gas or diesel or a blend of natural gas and diesel, typical NG contribution is between 60% and 80% while the remainder is diesel. Due to the lower carbon content and subsequent cleaner combustion, NG can reduce local air quality impacting emissions as well as well-to-wheel GHG emissions.

However, the efficiency of NG engines is typically a few percentage points lower than the comparable diesel engine, resulting in a slightly increased fuel consumption of approximately 8%. On-going research in NG engine technology is aimed at reaching the same efficiency as diesel engines and in stationary applications this has been achieved.

Methane is a major GHG with an approximately 28-36 times higher global warming potential than carbon dioxide, therefore it is important to avoid leakage to retain the GHG benefits of the cleaner fuel. Typical GHG reduction compared to diesel in rail operation is approximately 20%, taking account of typical leakage and boil-off rates, while particulate matter can be reduced by approximately 90%. Current developments suggest that engines operating 100% on NG will meet the proposed Tier 5 locomotive emission standards (aside the zero-emission requirement, which would lead to a hybrid solution as described in the hybrid section 3.5). Methane is usually derived from natural gas extracted from the ground, which is then purified. In addition to this fossil fuel method, methane can be generated from biomass in a similar process to biofuels.

LNG has been the preferred solution for longer-haul rail applications as it enables the necessary range with the addition of a tender car. An example of this option is Florida East Coast Railway, which converted its mainline fleet of 24 locomotives to LNG, upgrading the previous emission certification to be Tier 3 compliant (Keefe, 2018), an illustration of the locomotives and tender is provided in Figure 3-1.

Figure 3-1: LNG Locomotives and Tender Car on the Florida East Coast Railway

In a CNG system less energy can be carried on-board in the same volume compared to LNG, but the implementation is simpler as liquification through cooling to approximately -163°C and a cryogenic tank are not required. For many applications this has been the preferred option such as in CNG busses, which are used by many transit agencies. There are also railway implementations where CNG can provide the desired range. An example is the Indiana Harbor Belt railroad, which has begun the conversion of their switcher locomotive fleet to CNG in 2017, and the company expects to have 70% of their fleet corresponding to 21 locomotives converted by 2020 (Progressive Railroading, 2017). The locomotives have two Caterpillar ~560kW (750 HP) gas engines, store CNG at ~350 bar (5070 PSI) in 11 tanks providing the equivalent of 700 diesel gallons and meet or exceed Tier 4 emission regulations (Myers, 2019). An illustration of the Indiana Harbor Belt locomotives is show in Figure 3-2.

Figure 3-2: Indiana Harbor Belt CNG Switch Locomotive

The table below summarizes the advantages and drawbacks of natural gas.

Table 3-2: Natural Gas Summary
(MM et al., 2019)

Advantages	Disadvantages
Existing diesel engines can be used (may require minor modifications)	Slightly reduced energy efficiency
Significant reduction in local emissions (but not zero)	Results in local emissions and GHG
Reduction in GHG emissions	Methane is a worse GHG than carbon dioxide so leaks and boil-off need to be minimized
Cost effective fuel available	Requires new refueling infrastructure and natural gas delivery, either via truck or pipeline (cannot easily be generated on-site)
Significant range capability, no additional in-route infrastructure required	Flammable fuel – concerns with operations and maintenance, needs to be managed appropriately
	Compressed gas tanks require large volume to achieve similar range to diesel or liquid storage at very low temperatures with safety hazards

3.3.1 Operational Application to Arrow

A natural gas option could be implemented for the Arrow service vehicle and would require new refueling infrastructure. It is anticipated that natural gas storage tanks and corresponding engine could fit into the space within the power module of the Stadler FLIRT vehicle. CNG would be more appropriate as the desired range could most likely be achieved while being technically less complex and less hazardous as the low temperatures required to maintain natural gas in a liquid state can be avoided. This option would result in a significant reduction of emissions but will not lead to zero, and to meet the proposed Tier 5 emission standards a hybrid powertrain is required (see hybrid section 3.5). A slightly higher energy consumption compared to conventional diesel is anticipated but this is currently compensated by lower energy cost.

This option may not be suitable for the TIRCP grant received by SBCTA as it does not lead to zero emissions while other examined options can achieve zero emissions. Future ambitions to achieve zero emissions or regulation requiring zero emission, similar to the requirements for busses in California from 2040 onwards, leave this option with a relatively high risk of obsolescence, potentially not recovering the capital investment and in addition requiring a further change in the future. Reliance on a single fuel with limited feedstock choice, such as natural gas and some biogas, create a similar dependency to price fluctuations as diesel.

3.3.2 Safety Hazard Considerations

Natural gas is flammable when mixed with oxygen or air and, similar to hydrogen, the hazards becomes serious when release occurs in enclosed spaces. Natural gas has already been approved by the FRA for use on freight applications, the hazard controls required to implement on rail vehicles are known.

Unlike hydrogen, an odorant is typically added to natural gas to make it detectable by humans.

3.4 Hydrogen Fuel Cell Options

Hydrogen is a gas at ambient temperature with a low energy content by volume, therefore it is either compressed or liquified to increase the energy density and stored in tanks on-board the vehicle. The currently preferred option for vehicle applications is compressed storage, which has also been the case for railway vehicles. Hydrogen is refueled in a similar process to diesel, so a supporting system for fuel storage and dispensing as well as potential hydrogen production will have to be provided. It is anticipated that refueling would occur at the ends of the route or at the maintenance and storage facility, ideally at a frequency of once a day or less. To operate a passenger rail service with hydrogen fuel cell technology, supporting infrastructure and services including fuel storage and dispensing facilities will be required, even if hydrogen is not produced on site. Hydrogen is not a GHG and its utilization in a fuel cell will not result in any harmful emissions, as described in section 2.4, and is therefore considered a zero-emission option.

On-board hydrogen gas tanks are typically maintained at pressures ranging from 350–700 bar (5,000–10,000 psi) and currently the preferred pressure for automotive applications is 700 bar while for heavy-duty applications such as buses and trucks the preferred pressure is 350 bar. All railway implementations have used 350 bar or less for on-board storage, but 700 bar storage might be an option if the additional energy content is required to realize the desired range given existing volume considerations.

Storage pressure in stationary tanks at the filling station are typically higher to aid faster refueling in the range of 400-450 bar for the 350 bar on-board case, and 800-1000 bar for the 750 bar case, pressures depend on the station design. Certain safety features need to be incorporated in any facilities where significant quantities of hydrogen are present. Hydrogen can either be supplied by pipeline if very large quantities are required, for example in petroleum refining, delivered by truck similar to diesel, or generated on-site. For the Arrow service, either delivery by truck or on-site generation would be possible options.

Recent developments mean that hydrogen fuel cell technology could be applied to rail vehicles, for example the Alstom Coradia iLINT rail vehicle, which is similar to the FLIRT diesel vehicles employed for the Arrow service. In September 2018, two trains powered by hydrogen fuel cells entered commercial service in the Lower Saxony region of Germany. The route is nearly 100km in length and the trains have a range of 1,000km with the on-board gaseous hydrogen tanks. A train can be fully refueled in 15 minutes, and hydrogen is provided by a mobile filling station (Alstom, 2018).

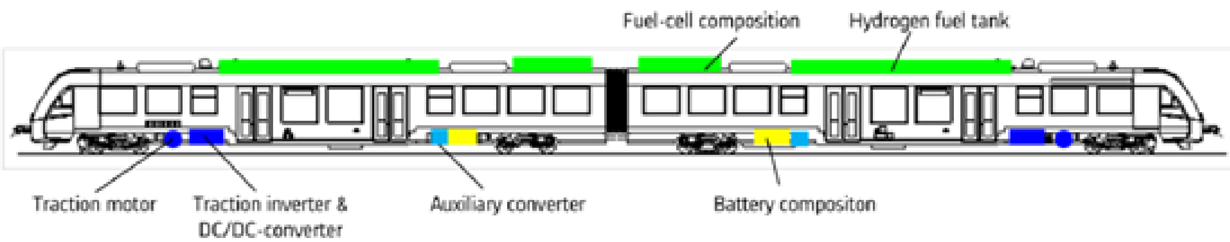


Figure 3-3: Location of Key Components for Alstom's Coradia iLint Vehicle (Ernst & Young, 2016)

Table 3-3: Hydrogen Fuel Cell Summary (MM et al., 2019)

Advantages	Disadvantages
Zero local emissions (except water) from operation.	Fuel deliveries required or development of on-site hydrogen production facilities (potentially high capital costs).
Hydrogen is not toxic.	Flammable fuel – concerns with operations and maintenance, needs to be managed appropriately.
Technology approved for passenger service in Germany – viability has been demonstrated.	Potential for a modified maintenance building to manage hydrogen venting in case of release
Significant range capability, no additional in-route infrastructure required.	Hydrogen tanks require a large volume to achieve a range similar to a DMU.
Reduction in operating noise of vehicle.	FCS may require a larger volume than the comparable diesel generator set
Improvements to ride conditions for passengers (compared to DMUs).	Hydrogen FCS could increase the weight of the vehicle; resulting in potential for modifications to the vehicle structure, suspension or brakes.
High energy efficiency (compared to combustion engines) leading to significant energy reduction	
Hydrogen is not a GHG.	

3.4.1 Operational Application to Arrow

Typical FCS modules for railway applications have a power output of 100kW to 200kW, and often several modules are combined to achieve the required power. To provide equivalent power output to the planned rail vehicle, five 200kW FCS would be required. The volume required for such a FCS including hydrogen storage tanks may be larger than the available spaces in the FLIRT DMU power module and there might also be a small increase in mass, but a more detailed analysis would be required. The FCS can be combined with batteries in a hybrid system that can supply peak power loads for short durations, this also enables energy from regenerative braking to be captured. The majority of hydrogen fuel cell vehicles are hybrids and FCS and hybrid systems are both zero emission during operation. FCS / battery hybrid systems are further discussed in the next section 3.5.

The hydrogen fuel cell option also offers the possibility of on-site hydrogen production with potential to take advantage of low electricity prices for hydrogen generation when power demand is low while also offering potential of energy independence from suppliers through generation via solar or wind power if space is available for such equipment. Many different production feedstocks are available; therefore, a hydrogen solution is not dependent on a single fuel like diesel or natural gas.

3.4.2 Safety Hazard Considerations

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, 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 this ZEMU application. 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, 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. The Department of Energy offers guidance on the safe design and handling of hydrogen.

3.5 Hybrid Systems

In a hybrid powertrain system at least two power sources are combined, e.g., a diesel engine and a battery, to allow for operational benefits such as reduced emissions and energy consumption. The primary powerplant (e.g., diesel generator set or FCS) provides the average power with an additional power margin due to redundancy and reliability considerations while the batteries meet the peak power demand, e.g., during acceleration, and enable the use of regenerative braking reducing energy consumption. In Figure 3-4 a hybrid powertrain configuration is illustrated.

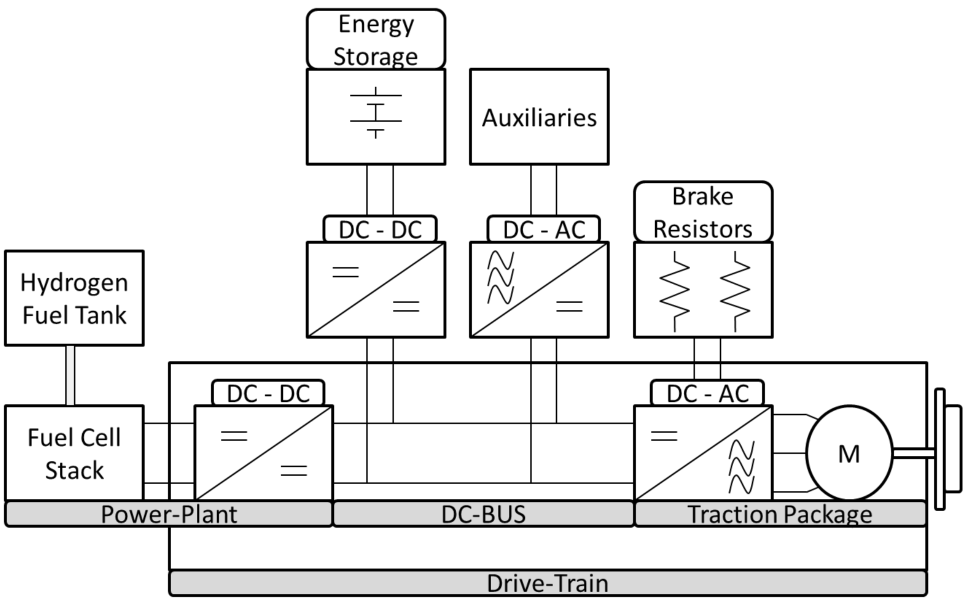


Figure 3-4: Illustration of a Hybrid Powertrain (Hoffrichter, 2013)

Batteries and the corresponding powerplant are sized according to the anticipated duty cycle; a 'mild' hybrid is where the average power is relatively close to peak power and a small battery system is installed while a 'heavy' hybrid, where the peak power is significantly higher than the average power, would have a large battery system. Hybrids can also be designed with 'plug-in' capability, which allows the charging of the battery from wayside source, such as wayside electrification or a charge cable. Such an arrangement can be implemented to enable charging of the batteries overnight while in the vehicle storage area or from infrastructure at stops and terminals. Design options can involve the planned charging at all available wayside infrastructure while the on-board powerplant is only used as a range extender, e.g., when the distance to the next charging infrastructure is longer than the battery capacity allows or when a not anticipated longer stop away from infrastructure is required. A 'plug-in' option can reduce overall energy consumption and emissions.

3.5.1 Diesel-Battery Hybrid

This technology combines a diesel engine together with a battery system. In addition to enabling regenerative braking, a further benefit could be that during station stops the battery would provide all the power requirements of the train and enable acceleration away from the station on battery power only before the diesel generator set is turned-on to charge and supply power to the traction motors. This hybrid combination offers zero-emission operation for short periods while having the long range of a DMU and allow train operators to reduce noise and air pollution near stations.

In Japan diesel-hybrid multiple units have been used in regional passenger train operation since 2007 and local emission reductions of ~60% have been achieved (Shiraki, Satou, & Arai, 2010). Hybrid powertrains have also be used in switcher locomotives in the U.S. (Cousineau, 2006) reducing emissions.

Table 3-4: Diesel / Battery Summary
(MM et al., 2019)

Advantages	Disadvantages
Potential to convert current diesel with reuse of engines.	Heavily diesel-based and not considered to sufficiently reduce GHG emissions during operations.
Diesel technology approved for passenger service in the U.S., but batteries likely need approval.	Replacement of batteries is required at a higher frequency then vehicle replacement.
Does not require additional infrastructure.	Investment in batteries does not result in substantial GHG benefits when combined with diesel engines
	Fuel is toxic and an environmental hazard, needs to be managed carefully.
	Diesel is flammable, needs to be managed appropriately.

Operational application to Arrow

A diesel-battery hybrid could be more easily implemented on the Arrow service vehicles due to the limited infrastructure needed. It is anticipated that the additional battery system could fit into the space in the power module of the Stadler FLIRT vehicle with sufficient hybrid power for the route. However, this option may not be suitable for the TIRCP grant received by SBCTA as it is still heavily diesel-based and not considered to sufficiently reduce GHG emissions during operations in comparison to the other options examined.

Safety Hazard Considerations

The hybrid system will introduce hazards described for both the battery and diesel / biofuel technologies and will require controls for both. A safety analysis will be required to determine if any unique hazards are introduced by combining the systems.

3.5.2 Biofuel or Natural Gas – Battery Hybrid

This technology, similar to the diesel-battery hybrid discussed above, combines an internal combustion engine with a battery system. The internal combustion engine could be configured to run on the various alternative fuels, i.e. biofuels, CNG or LNG. Refer to earlier parts of this section 3 for details of these fuel technologies. The hybrid of these fuel systems with batteries provides the same benefits as described for diesel-battery systems and can offer an overall reduction in GHG emissions if NG would be used as an alternative fuel. A NG hybrid is anticipated to meet the proposed Tier 5 emission standards.

Table 3-5: Biofuel or Natural Gas / Battery Summary (MM et al., 2019)

Advantages	Disadvantages
Easier to convert as diesel engines are already installed and could be converted to alternative fuel engines with minor modifications.	Is not zero-emission in operations.
Alternative fuel technology approved freight service in the United States, but batteries likely need approval.	Replacement of batteries is required at a higher frequency then vehicle replacement.
	Investment in batteries alone does not result in substantial GHG benefits when combined with combustion engines.
	Fuels can be hazardous, needs to be managed carefully.
	New fueling infrastructure would be required.

Operational application to Arrow

A biofuel-battery hybrid could be relatively easily implemented on the Arrow service vehicles, requiring only minor modifications but this option is anticipated to not meet Tier 5 emission standards. This option is not suitable for the TIRCP grant received by SBCTA as it is still combustion-based and not considered to sufficiently reduce GHG emissions during operations in comparison to the other options examined.

A 100% NG-battery hybrid would require significant changes to the vehicle, including addition of the batteries, different combustion engines, and new fuel storage, e.g., compressed gas tanks in addition to a new fueling infrastructure. However, substantial emission reduction is possible, both regulated and GHG, likely meeting Tier 5 emission standards. It is anticipated that the required equipment would fit into the space available in the power module of the Stadler FLIRT vehicle. This option may not be suitable for the TIRCP grant received by SBCTA as it is still combustion-based and possibly considered to not sufficiently reduce GHG emissions during operations in comparison to the other options examined.

Safety Hazard Considerations

The hybrid system will introduce hazards related to the battery and natural gas or biofuel technologies and will require controls for both (MM et al., 2019). A safety analysis will be required to determine if any unique hazards are introduced by combining the systems.

3.5.3 Hydrogen Fuel Cell - Battery Hybrid

This technology combines hydrogen fuel cells with a battery system. For many duty cycles this arrangement allows downsizing of the FCS, which is comparatively high cost per power unit, allows less drastic cycling of the FCS increasing its lifetime, and enables the use of regenerative braking reducing overall energy consumption. Batteries would provide the peak power demands for short period, for example during acceleration, while the hydrogen FCS would provide the base load power over the duty cycle. The FCS is typically sized to be larger than average power requirements for redundancy and reliability considerations. The majority of hydrogen FC vehicles have a hybrid powertrain. More examples of hydrogen fuel cell hybrid developments are provided in the next section 3.5.

Table 3-6: Hydrogen Fuel Cell / Battery Summary (MM et al., 2019)

Advantages	Disadvantages
Zero local emissions (except water) from operation.	Fuel deliveries required or development of on-site hydrogen production facilities (potentially high capital costs).
Hydrogen is not toxic.	Flammable fuel – concerns with operations and maintenance, needs to be managed appropriately.
Technology approved for passenger service in Germany – viability has been demonstrated.	Potential for a modified maintenance building to manage hydrogen venting in case of release.
Significant range capability, no additional in-route infrastructure required.	Hydrogen tanks require large volume to achieve similar range to diesel.
Batteries provide significant power capability for short durations.	Hydrogen fuel cell system plus batteries likely increase the weight of the vehicle; resulting in potential for modifications to the vehicle structure, suspension or brakes.
Reduction in operating noise of vehicle.	Battery maintenance and management is required.
Improvements to ride conditions for passengers (compared to DMUs).	More complex powertrain than non-hybrid.

Advantages	Disadvantages
High energy efficiency (compared to combustion engines).	
Hydrogen is not a GHG.	
Anticipated lower energy consumption compared to FCS only (as regenerative braking can be employed).	

Operational application to Arrow

Typical FCS modules for railway applications have a power output of 100kW to 200kW, and often several modules are combined to achieve the required power. In most railway cases, FCS would be combined with batteries to enable regenerative braking and allow a lower FCS power provision meeting at least the average power demand of the vehicle over the duty cycle, while the batteries meet the relatively short peak power demand, for example during acceleration. This hybrid approach would likely be implemented for a vehicle on the Arrow service route. The aforementioned Coradia iLINT has two 200kW FCS and two 225kW battery packs (Ernst & Young, 2016). It is anticipated that the FCS, hydrogen tanks and batteries can be accommodated on-board the vehicle, with the majority if not all of the components installed in the power module, but a more detailed analysis would be required. This option offers the possibility of on-site hydrogen production and a complete zero emissions system.

Safety Hazard Considerations

The hybrid system will introduce hazards related to the battery and hydrogen fuel cell technology and will require controls for both. A safety analysis will be required to determine if any unique hazards are introduced by combining the systems.

4 TECHNICAL FEASIBILITY

A review was conducted for a range of motive power technologies that could be employed to provide low- or zero-emission propulsion and auxiliary power for rail vehicles. The review included examples from the rail and heavy-duty road sector, concentrating on those options that offer zero or near-zero emissions. Contrasting road and rail, the advantage of lower energy consumption and lower emissions of rail, even utilizing conventional diesel technology has to be considered. This advantage will remain with rail when both options have zero-emission powertrains due to the low rolling resistance of a steel wheel on a steel rail and convoy formation, i.e., trains.

Alternative powertrains have begun to penetrate not only the light-duty sector, but also the heavy-duty road sector, which shares some similarities with rail applications, including larger sizes and higher power requirements, and the fact that both are frequently sold in large number to fleet operators, either public or private. Therefore, some examples have been included. There is an emphasis on hydrogen fuel cell technology due to the suitability for heavy-duty applications, relative long range, zero-emission at the point-of-use, and possibility of zero-emission supply chain. More detailed technical information for some of the options is provided in Appendix 14.1 Alternative Propulsion Options.

4.1 Wayside Electrification

Providing electricity to railway motive power vehicles through wayside infrastructure is common for several service, examples in the U.S. include Amtrak's North East Corridor and several transit agencies, such as Bay Area Rapid Transit, New York City subway, and Denver Regional Transportation District. The share of mainline railway electrification is low in the U.S. compared with other regions, such as Europe. Electrification leads to zero-emissions at the point-of-use and has the potential for a zero-emission supply chain depending on the generation mix. A recent study by the RSSB suggested that an electric train produces 60% less carbon emissions per kWh consumed than the current generation of diesel trains given the present UK generation mix (which is comparable to the one in California in terms of emissions), and emission reductions are expected to improve to 90% as the electricity generation grid decarbonizes further (Kent, 2018).

Electrification is expensive, in the UK cost is approximately $3.2 million a per single track mile (Railway Industry Association, 2019). In California, Caltrain is currently electrifying the majority of their network at a cost of approximately $697 million for a 51 mile long corridor (Ackemann, 2016). The high cost of wayside electrification is mostly justified with very frequent rail service provision, in Europe it is estimated at six or more passenger trains per hour (IEA & UIC, 2019), which in the U.S. would likely require a higher frequency due to typically larger electrification cost and lower diesel prices. The other main reason for wayside electrification is for rail service that cannot otherwise be reasonably offered, such as for very high speed trains where the required energy for operation cannot be practically stored on-board. Conventional overhead electrification has impacts on existing infrastructure requiring clearance and has visual impact. An example of modern overhead electrification is illustrated in Figure 4-1. For the aforementioned reasons, continuous wayside electrification is deemed unsuitable for the Arrow service.

Figure 4-1: Wayside Electrification in Denver
(Hoffrichter, 2016)

However, there are alternative solutions involving bi-mode (or dual-mode) trains whereby routes can be part-electrified, with the train reverting to an on-board energy source such as a diesel engine or an energy store such as a battery to cover travel across non-electrified section of line. The option can reduce the cost and complexity of electrification schemes by avoiding the need to install the overhead contact system for difficult sections of line, e.g., tunnels, bridges, viaducts, or complex road intersections in the case of streetcars operating on city streets. Examples include the extensions to the streetcar network in Birmingham (UK), streetcars in Dallas, TX, and streetcars in Nice, depicted in Figure 4-2.

Figure 4-2: Streetcar in Nice, France
On the left operating on batteries, on the right operating from electrification
(Hoffrichter, 2014)

It is also possible to electrify just part of the line, with extended sections being operated by battery, as recently selected for Schleswig-Holstein where Stadler are to supply a new fleet of bi-mode regional trains (Stadler, 2019).

But infrastructure costs for lines with no pre-existing electrification will remain high, and further expensive immunization may be required for signaling and control equipment. Furthermore, the routes being considered for this study for the Arrow service as well as possible extension to Los Angeles Union Station (LAUS) also have large numbers of road crossings which would present an additional challenge. For these reasons, it is suggested that conventional wayside electrification is likely to prove an expensive and challenging option for SBCTA. However, a battery dominated option with charging at terminals and stops might be an option.

4.2 Battery-Only Trains

While battery technology is improving, the energy and power required for heavy-duty applications such as trains is an order of magnitude greater than in the automotive sector. A RSSB published report stated that "*Fully autonomous mainline trains powered by battery only are unlikely to be realised in the medium term*" (Kent, 2018). However, there are several heavy-duty, battery-only applications in the transit systems, which include rapid recharge buses such as those operating in Geneva, Switzerland, see Figure 4-3, with more information provided in Appendix 14.1 Alternative Propulsion Options.

Figure 4-3: Rapid Charging Bus in Geneva
(ABB Switzerland, 2016)

The buses utilize battery chemistries suitable to be rapidly recharged at multiple points along the route. A U.S. example of primarily battery-operated vehicles is the Q Line in Detroit, where streetcars travel 80% off-wire. In addition to conventional wayside electrification, the system employs other charging options, such as charge bars, see Figure 4-4, and overnight ground-level charging in the depot.

Figure 4-4: Battery-Powered Streetcar in Detroit at Charge Bar (Hoffrichter, 2018)

The Arrow service may have similar characteristics to the bus and light rail examples, and this option is deemed as possibly feasible for the Arrow service and was considered in more detail by project partner Mott MacDonald (MM et al., 2019).

4.3 Heavy-Duty Hydrogen Fuel Cell Examples

A limited number of alterative self-powered propulsion options for railway applications have been developed to date and majority of trains still operate with diesel power. However, with the pressures of increasing air quality and decarbonization, there is a clear emerging trend for regional self-powered trains in Europe to be powered by hydrogen fuel cells. These have been hybridized, where the FCS is operating in conjunction with an on-boar energy store, typically a battery.

4.3.1 Alstom iLINT

The most advanced project is that being undertaken by Alstom in Norther Germany where two regional passenger fuel cell trains have been in regular passenger service since September 2018 (Alstom, 2018), see Appendix 14.1 Alternative Propulsion Options for more technical information. The two multiple units have covered over 100,000km to date and are soon to be supplemented by 12 additional trains, with a second order placed for an additional 27 trains for operation elsewhere on the German network. The iLINT is depicted in Figure 4-5 and Figure 4-6.

Figure 4-5: Alstom iLint
(Kent, 2019)

Figure 4-6: Alstom iLINT Multiple Unit
(Hoffrichter, 2019)

The design is based on a modified DMU, the Coradia LINT, with the diesel engine and transmission replaced by power electronics and a traction motor. A fuel cell module is mounted to the roof, which also accommodates the hydrogen storage tanks. An underfloor lithium-based battery pack works in partnership with the fuel cell to boost power during acceleration and stores braking energy, with overall performance improved performance compared to diesel train. The operating range between refueling is approximately 1000km in the current service, and the maximum operating speed is 90mph.

The hydrogen for the two in-service trains is suppled as a liquid by truck, which was chosen due to the requirement of a mobile refueling station. A permanent refueling station to serve the full fleet of 14 trains is currently under construction. Hydrogen will be delivered as a compressed gas in a tube trailer in the next project phase, followed by construction of an on-site electrolyzer to produce hydrogen utilizing locally generated electricity from wind power.

Figure 4-7: iLINT Mobile Refuelling Installation
(Kent, 2019)

4.3.2 Alstom / Eversholt Breeze

In the UK, Alstom is working with one of the 'big three' train leasing companies on a related project called "Breeze", see Figure 4-8, where mid-life electric multiple units will be converted to hydrogen fuel cell power, more information can be found in Appendix 14.1 Alternative Propulsion Options. The design is understood to be quite advanced, with serious interest for operating in the North of England. However, the first order has yet to be placed.

Figure 4-8: Alstom / Eversholt Breeze
(Alstom website, 2019)

4.3.3 Porterbrook HydroFLEX

A similar project to Breeze is underway involving Porterbrook Leasing (another of the 'big three'), the University of Birmingham and Ballard, where mid-life electric multiple units are converted to fuel cell power, see Appendix 14.1 Alternative Propulsion Options. This has resulted in the development of a demonstrator train, see Figure 4-9, that has successfully operated at a national industry event on a private track, and funding has been secured to move this to trial operation on the conventional mainline network in England.

Figure 4-9: Porterbrook HydroFLEX
(Kent, 2019)

4.3.4 Siemens Mireo

Siemens is also developing a hydrogen fuel cell variant of their new Mireo train for use on regional lines. Working with Ballard, they expect to introduce the train into service around 2021/22, Appendix 14.1 Alternative Propulsion Options for more information. An electric multiple unit Mireo is illustrated in Figure 4-10.

Figure 4-10: Siemens Mireo Electric Multiple Unit
(Wikipedia "Siemens Mireo", 2019)

4.3.5 CRRC Light Rail Vehicles

There is also interest in the use of fuel cells for streetcar and light rail applications, with two well-advanced projects in China by CRRC, Appendix 14.1 Alternative Propulsion Options. Figure 4-11 shows a prototype of the streetcar. The first is a fleet of streetcars for the city of Quingdao, the vehicles are based on a modified design produced by Skoda. The trams are powered by Ballard fuel cells but have only a modest operating range due to limited on-board hydrogen storage capacity. A second fleet of similar design are already in service in the city of Foshan.

Figure 4-11: CRRE Prototype Streetcar (Bloomberg, 2015)

4.3.6 Zillertahlbahn

In Austria, the Zillertalbahn is working with Stadler to supply a fleet of fuel cell powered narrow gauge trains for operation on a popular tourist route, Appendix 14.1 Alternative Propulsion Options. Hydro power will be used to generate the hydrogen. Figure 4-12 depicts a current train of the Zillertalbahn.

Figure 4-12: Current Zillertalbahn Train (Wikipedia "Zillertal Railway", 2019)

4.3.7 Heavy Duty Road Applications

Globally, there are many hydrogen fuel cell busses in operation and in California projects started in 2000, when Sunline Transit began a thirteen-month in-service demonstration of an early generation fuel cell bus (FTA, 2001). By 2006, AC Transit, in the Bay Area, had begun to operate three fuel cell buses in revenue service (Chandler & Eudy, 2010). Since then, fuel cell bus usage has expanded, with over 30 now in operation in the U.S. (Eudy, 2019).

Appendix 14.1 Alternative Propulsion Options presents a case in Aberdeen, UK, as part of the Joint Initiatives for Hydrogen Vehicles across Europe which aims to introduce 300 fuel cell buses in 22 cities by 2020 (Fuel Cell Electric Buses, 2019).

Heavy-duty hydrogen FCS are currently also being demonstrated for trucks. Two U.S. examples are provided. The first is a truck designed to carry containers from Californian ports to distribution centers inland, Project Portal, Appendix 14.1 Alternative Propulsion Options. The project is a collaboration between Kenworth and Toyota, and two Mirai fuel cell stacks from their fuel cell automobile are combined with a modest traction battery. The estimated driving range is 320km (200 miles) per fill, under normal operation.

**Figure 4-13: Toyota Project Portal Prototype
(Toyota website, 2019)**

The second is the development of various semi-trucks by Nikola, see Appendix 14.1 Alternative Propulsion Options. This ambitious start-up is expecting to deliver fleets of hydrogen fuel cell semi-trucks by 2022, accompanied by a network of refueling stations along key routes.

Figure 4-14: Nikola Pre-Production Semi-Truck
(Wikipedia "Nikola Motor Company", 2019)

Switzerland has a large amount of hydro power and operates a 100% electrified mainline rail network. The country is in the process of electrifying their road vehicles, and Hyundai is planning to bring 1600 hydrogen fuel cell trucks to market by 2025 (Hyundai, 2019) having had a small fleet in operation since 2018, see Appendix 14.1 Alternative Propulsion Options for more information. The effort includes hydrogen supply and truck operators.

Figure 4-15: Hyundai Fuel Cell Truck
(Hyundai, 2019)

4.4 Heavy-Haul Freight Rail

Both in the UK and mainland Europe, there are a number of bi-mode trains that have been developed for freight applications. These locomotives can operate from wayside overhead electrification to cover the majority of the route while power for the typically shorter sections is provided by an on-board diesel generator set. In the UK, a fleet of ten Class 88 locomotives, depicted in Figure 4-16, are operated by Direct Rail Services, manufactured by Stadler Vossloh while Rail Operations Group is planning to purchase a fleet of Class 93 locomotives, which will feature a battery in addition to a diesel generator to boost short-term output.

Figure 4-16: UK Class 88 Bi-Mode Locomotive (Wikipedia "British Rail Class 88", 2019)

In Europe, Siemens have launched their Vectron Dual Mode, illustrated in Figure 4-17, which is able to draw power from overhead electrification where available, swapping to its on-board 2,400kW diesel engine for operation on non-electrified sections.

Figure 4-17: Siemens Vectron Dual Mode (Siemens website "Vectron Dual Mode", 2019)

Dual mode options are useful in areas where wayside electrification is already present and the conventional practice of operating with the on-board diesel while on electrified track can be avoided.

However, there are currently no on-board, zero-emission solutions for mainline heavy-haul freight; the difficulty being high power requirements, large energy storage necessity, and interchange between different railroads. Research and development is necessary to determine possible options and hydrogen fuel cell technology has promise to provide a viable solution (Zenith, Isaac, Hoffrichter, Thomassen, & Møller-Holst, 2019).

Currently, a battery locomotive intended to operate in a consist with diesel locomotives, effectively creating a hybrid, is being developed by BNSF and Wabtec (BNSF Railway, 2019) reducing energy consumption and emissions.

In less demanding, typically more localized services, such as switching, road-switching, and shortline operations alternatives could be potentially implemented. There have been projects with diesel-hybrid switchers since 2002 (Cousineau, 2006), and battery or hydrogen fuel cell options might be suitable. Low-power battery switcher locomotives are relatively commonplace in Europe and in the U.S. Norfolk Southern tested a battery-powered switcher for several years starting in 2009 (Norfolk Southern, 2014).

Vehicle Projects in collaboration with BNSF, developed a hydrogen fuel cell hybrid proof-of-concept switching locomotive, see Figure 4-18. It had 250kW of fuel cell power with total power above 1MW and (Hess, Miller, Erickson, & Dippo, 2010). The locomotive was demonstrated in 2009/2010.

Figure 4-18: Hydrogen Fuel Cell Switcher (Hoffrichter, 2009)

4.5 Summary

In terms of on-board, alternative power sources for heavy-duty applications suitable for railway vehicles, hydrogen fuel cells appear to offer the closest option to conventional diesel. There are a number of projects in Europe either already in-service or at an advanced stage of development. Due to the duty cycles, involving frequent stops, these vehicles are hydrogen fuel cell hybrids, allowing for regenerative braking reducing energy consumption. The power requirement and associated energy storage that can sensibly be installed are suitable for regional passenger trains operating at moderate speeds (<100mph) with ranges generally sufficient for a full day of operation between re-fueling. A hydrogen fuel cell hybrid could be a viable solution for the RPRP corridor as well as possible extension to LAUS. In general, hydrogen FCS offer the potential to replace mainline diesel-powered railway service, but difficulties are present when very long ranges, such as intercity freight is required due to the high-volume requirement for hydrogen storage, possibly requiring tender cars.

In some cases, battery-only trains could be viable solution, where the line speed is more modest (<60mph), stops are relatively frequent, and dwell times are reasonably generous enabling quick recharging of the battery. This could be a solution for the RPRP corridor but extension to LAUS would be involve installation of recharging equipment at many locations along the route. In general, battery technology has to improve significantly to be suitable for heavy-haul mainline applications.

5 OPERATIONAL PERFORMANCE

In this section, the operational performance of various powertrain options has been estimated with single train simulation. Two service routes for a regional passenger train were considered:

- The RPRP, a new route being developed from San Bernardino Transit Centre (SBTC) to Redlands / University of Redlands, which is a relatively short route of approximately 9.5 miles with a maximum line speed limit of 50mph;
- The existing route from SBTC to LAUS via Fontana, which is approximately 60 miles in length and has a maximum line speed of 80mph.

Additionally, the combination of the two route segments were considered in additional simulations presented in this section. More detail is presented in Appendix 14.2 Simulation Results with Corresponding Emissions. The study was based on 2-car and 4-car variants of the Stadler FLIRT multiple unit, similar to those in operation with TexRAIL in the USA, see Figure 5-1, and on various routes across Europe, including both electric and bi-mode versions currently being introduced by the Greater Anglia train franchise in the UK.

Figure 5-1: Stadler FLIRT Train as Utilized by TEXRail (Wikipedia "TEXRail", 2019)

The diesel or bi-mode FLIRTs typically have 4 passenger cars plus a central power module that can be equipped with various power options. For example, the TexRAIL FLIRTs are equipped with 2 x Deutz 520 kW diesel engines, while the higher-speed UK version has 4 x Deutz 520 kW diesel engines.

Several possible powertrain options for both variants with a view to minimizing energy consumption, local and global emissions were simulated. Models were constructed for variants that included the following options:

- Diesel Electric Multiple Unit (DEMU): The power module is equipped with diesel engines that produce electrical power to both drive the traction package and supply power to auxiliary loads;

- Hybrid Diesel Electric Multiple Unit (Hybrid DEMU): The power module is equipped with lower output diesel engines that work in conjunction with on-board battery packs to boost acceleration, and which absorb, store, and reuse braking energy;
- Fuel Cell Electric Multiple Unit (FCEMU): The power module is equipped with hydrogen fuel cells that produce electrical power to both drive the traction package and supply power to auxiliary loads;
- Hybrid Fuel Cell Electric Multiple Unit (Hybrid FCEMU): The power module is equipped with lower output cells that work in conjunction with on-board battery packs to boost acceleration, and which absorb, store, and reuse braking energy;
- Battery Electric Multiple Unit (BEMU): The power module is equipped with a larger number of battery packs that are used to provide electrical power to both drive the traction package and supply power to auxiliary loads. These battery packs are recharged while the train is stationery at terminal stations.

Models were constructed of the various power options for both 2- and 4-car FLIRTs, an illustration of the ZEMU vehicle consist is provided in Figure 5-2.

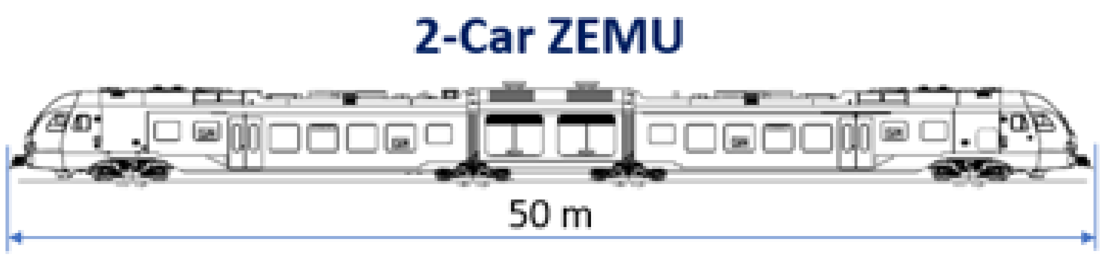


Figure 5-2: Illustration of 2-Car ZEMU Concept (MM et al., 2019)

Power requirements and energy consumption were predicted using the University of Birmingham's Single Train Simulator (STS), which is a simulation program created in MATLAB to model train performance, estimate power requirements, and predict energy consumption for a single train on a given route. The STS has been utilized for several previous studies of a similar nature (Hoffrichter, Hillmansen, & Roberts, 2016; Lu, Hillmansen, & Roberts, 2011; Meegahawatte et al., 2010). The at-wheel data from the STS model were then transferred to a spreadsheet to calculate fuel consumption, estimate the overall weight and volume of fuel required, and determine other key parameters, such as the number of hydrogen storage tanks required. In the case of the BEMU, further calculations were undertaken to check that the dwell time at terminal stations would be sufficient to recharge the battery packs prior to making the return journey.

5.1 The Simulation Package

The STS is a program written in MATLAB that calculates the energy and power consumed by a train for a specified journey. The simulation contains a model of a train, including its mass, installed power, and resistance characteristics, and alignment information, including line speed limits, gradients, and stopping points. The equations of motion are then solved in a distance-based step algorithm to calculate energy values 'at the wheel'. The STS has been developed over several years and has been well-validated across a wide range of applications and projects, globally. It is also used to support the teaching activities at master's level in Birmingham.

The train is 'driven' using the full power available to accelerate up to the line speed, with full braking then applied at a specified rate (typically a UK Step 2 brake application ≈ 0.6 m/s^2) in order to stop at the specified stopping points, usually stations, along the route. Dwell times are specified for each station, as are terminal dwell times prior to making a return journey.

The simulation can take curving forces into account where curvature data is available for a given route. However, where this data is not available, the simulations remain realistic as the impact of curvature on energy consumption predictions for passenger trains is limited. This may not be the case for long heavy-haul freight trains where a higher proportion of the resistance relates to curving forces.

5.2 The Routes

The two routes considered in this study run east from San Bernardino to Redlands, and west to LAUS as illustrated in Figure 5-3.

Figure 5-3: Route Map
(Background Map from Google Earth Pro, 2019)

The start for both routes was the SBTC, and data provided by Mott MacDonald on behalf of SBCTA was used to generate the route profiles and validated against data from Google Earth Pro. From this data, models of the alignment, such as gradient, curvature, line speed, station locations, and dwell times, were constructed for use with the STS. The key parameters of each are presented in Table 5-1.

Table 5-1: Route Parameters

Parameter	SBTC to Redlands	SBTC to LAUS
Route length	15 km / 9.5 miles	92 km / 57.5 miles
Height gain or (loss)	135 m / 443 ft rise	(225 m) / (738 ft) fall
Maximum line speed	80 km/h / 50 mph	129 km/h / 80 mph
Approximate end-to-end one-way journey time	20 minutes	90 minutes

It is important to note that the general gradient profile is uphill from LAUS to SBTC, with a total gain of 225m / 738ft, and then rising further from SBTC to Redlands, gaining additional 135m / 443ft altitude.

It was assumed that the target return journey time for the Redlands route was one hour including dwell time at both ends, and that the train would repeatedly shuttle between SBTC and Redlands for 16 hours per day, i.e., would make 16 return journeys.

The journey time to LAUS was less straightforward to determine as there were several existing services in and out of LAUS with a variation at peak and off-peak times. Therefore, it was assumed that the train would make a total of four return journeys per day, which would be comfortably achievable in a 16-hour period as the journey time, excluding dwell, in one direction was estimated to be around 90 minutes.

5.3 Train Models

A limited amount of information was available for the DEMU vehicles, so the team collaborated to develop realistic range of concept designs for both 2- and 4-car variants of the Stadler FLIRT. The base case was taken to be the 2-car DEMU equipped with 2 x diesel engines, which was used to set the benchmark and target journey time for the other variants. The model assumed the AW3 loading condition, i.e. heavily loaded, and the head-end power (HEP), consisting of hotel and auxiliary loads, was taken to be a constant 117kW for the 2-car train, which is understood to be the worst-case load.

Several iterations of the concept designs for alternative powertrains, with the versions developed as follows, were simulated:

- DEMU: The 2-car was modelled with 2 x 520kW diesel engines, but this was insufficient power for the 4-car to match the journey times achieved by the 2-car. A function of the additional mass (a 50% increase, approximately) and the higher expected HEP load, estimated at 200kW were the reason. Therefore, the concept design assumed that the 4-car would be equipped with 3 x 520 kW diesel engines, i.e. 50% increase in installed power.

- Hybrid DEMU: Both the 2- and 4-car variants were modelled initially with 2 x 520 kW diesel engines working in conjunction with 2 x 69 kWh traction battery packs, as used on European fast charging electric bus fleets (ABB Switzerland, 2016). These battery packs are based on Lithium Titanate Oxide (LTO) chemistry, which enables them to repeatedly provide and absorb high levels of power relative to other chemistries. In addition, it is a relatively safe chemistry for transport applications. More information on battery chemistries and reasoning for LTO can be found in the report already provided to SBCTA (MM et al., 2019). This initial concept design was used to estimate the average power draw for each variant of train and route, which was then used to determine the number of engines that would actually be required, based on the average load with an additional 20% margin.

- FCEMU: The 2-car variant was modelled with 100 kW railway specification fuel cell modules and composites 350 bar hydrogen storage tanks. In order to meet the peak power requirements, the 2-car model has 10 fuel cell modules providing 1 MW, and the 4-car has 14 fuel cell modules providing 1.4 MW.

- Hybrid FCEMU: Similar to the diesel hybrid, an initial set of models and simulations were used to determine the peak and average power draw, with the number of fuel cell modules determined by the average power draw with an additional 20% margin, and the peak power draw determined the number of battery packs required to supplement the output from the fuel cells.

- BEMU: As with the hybrid models, an initial set of models and simulations were used to assess the likely maximum and average power and energy requirements, and the number of battery packs required to meet these requirements.

The simulations were then re-run with the configurations shown in Table 5-2 to generate the results provided later in this report.

Table 5-2: Train Configurations Modelled

Configuration	Power Components	Redlands		LAUS	
		2-Car	4-Car	2-Car	4-Car
DEMU	520kW engines	2	3	2	3
Hybrid DEMU	520kW engines	1	1	1	2
	69kWh LTO battery packs, max. power 828kW	2	3	2	1
FCEMU	100kW FC modules	10	14	10	14
FCEMU Hybrid	100kW FC modules	3	4	4	6
	69kWh LTO battery packs, max. power 828kW	2	3	2	3
BEMU	69kWh LTO battery packs, max. power 828kW	4	4	20	25

Additional technical detail about the simulated configurations is provide in Appendix 14.2 Simulation Results with Corresponding Emissions including assumed static, average efficiency values of the various components. The DEMU vehicle was the baseline for all other vehicles as aforementioned. Further, it also served as the base for other combustion-engine technologies, such as natural gas and biofuels, while the hybrid DEMU was the basis for the hybrid versions of these fuels. Results for these configurations are provided in the Appendix 14.2 Simulation Results with Corresponding Emissions as they do not provide a zero-emission option.

5.4 Simulation Results

All trains achieve a roundtrip journey time of approximately 40 minutes, including 1-minute dwell time at intermediate station stops, enabling a 10-mintue dwell at the terminals of SBTC and University of Redlands. An hourly service in off-peak times is possible with a single train while a half-hourly service in peak periods could be realized with addition of a second train.

The traction energy ‘at the wheel’ per roundtrip journey predicted by the STS is summarized in 14.2 The traction energy consumed ‘at the wheel’ is used to accelerate the train. Hybrid and BEMU models also show the amount of energy ‘at the wheel’ that can be generated by the traction motors for storage in the on-board battery packs. This is limited by either the amount of power that the motors can generate during regenerative braking or the power that the battery packs can absorb, depending on the number of battery packs installed, and referred to in the table as ‘Regen’.

Table 5-3: Traction and Braking Energy ‘At the Wheel’ for a Roundtrip Journey

		Redlands		**LAUS**	
		2-Car	**4-Car**	**2-Car**	**4-Car**
DEMU	Traction energy (kWh)	119	174	940	1338
Hybrid DEMU	Traction energy (kWh)	119	173	940	1330
	Regen at wheel (kWh)	66	85	327	385
FCEMU	Traction energy (kWh)	118	173	942	1341
Hybrid FCEMU	Traction energy (kWh)	118	173	940	1343
	Regen at wheel (kWh)	65	85	327	387
BEMU	Traction energy (kWh)	118	170	1056	1481
	Regen at wheel (kWh)	81	111	576	695

The traction energy required for a return journey on the LAUS route is considerably higher than that for the Redlands route. This is to be expected given the significantly longer distance and higher line speeds. The 4-car variants consume approximately 50% more energy than the 2-car variant. This is as a result of the higher mass that needs to be accelerated, the increase in resistance to motion, and the higher HEP load required for the additional two passenger saloons. The energy regenerated ‘at the wheel’ follows a similar pattern.

Please note that all model variants assume that the same overall braking rate is achieved through a combination of friction and dynamic braking. For those models without energy storage, i.e. the DEMU and FCEMU, the energy from dynamic braking is assumed to be dissipated as heat in resistor banks, as is the current practice with diesel locomotive and DMUs. For those models with energy storage, i.e. the hybrids and BEMU, it is assumed that the power from braking is, to the maximum possible, absorbed by the battery pack, with any surplus dissipated as heat by resistor banks.

The at-wheel results from the STS were then post-processed in a spreadsheet to predict overall energy consumption, refer to Appendix 14.2 Simulation Results with Corresponding

Emissions for details and results of individual journeys for the various configurations. The energy consumption for the options is presented in Table 5-4, based on 16 roundtrip journeys per day for the Redlands route and four roundtrip journeys per day for the LAUS route, i.e., also having a 16 hour service day.

Table 5-4: Predicted Energy Consumption

Configuration	Parameter		Redlands		LAUS	
			2-Car	4-Car	2-Car	4-Car
DEMU	Diesel consumed per day	liters	1359	2134	2076	3127
		kWh	13512	21222	20647	31099
Hybrid DEMU	Diesel consumed per day	liters	1010	1646	1611	2513
		kWh	10045	16367	16025	24988
FCEMU	Hydrogen consumed per day	kg	242	381	372	561
		kWh	7947	12502	12216	18408
Hybrid FCEMU	Hydrogen consumed per day	kg	206	337	330	518
		kWh	6762	11077	10846	17024
BEMU	Electricity consumed per day	kWh	3534	4526	4759	7364

The daily energy requirements for the 4-car version are roughly 55% higher than for the 2-car, and the LAUS route requires approximately 53% more energy per day than the Redlands route. Hybridization is predicted to result in between a 15-25% fuel consumption saving. All options aside from the diesel-powered version are zero-emission at the point-of-use. Improvements in emissions with consideration of the energy supply chains are presented in section 7 .

5.5 Practicality of Powertrain Options

The power module of the Stadler FLIRT is understood to have four ‘bays’ that can be equipped with a variety of different power options. An initial analysis was undertaken to establish the practicality of the different powertrain options from a space and mass point of view. It was assumed that the total maximum mass for the powertrain is 16,000kg on the basis that the FLIRT fleet for operation on the Anglian region, England, is equipped with four 500kW diesel engines, each of 4,000kg including engine, alternator, frame, and balance-of-plant (BoP).

No detailed information about the internal size of the bays was available, so an approximate overall estimate was made for the Power Module based on the general arrangement drawings that were supplied. This suggested a space of the opening hatches of approximately 24m^3 for the four bays, i.e. approximately 6m^3 per hatch. Additional internal space is available around the hatches and possibly above the corridor in the power module, and at total space assumption of 40m^3 was made. In a more detailed conceptual design these estimates would have the be more precisely measured. Any possible rearrangement of equipment on the roof to create additional space has not been considered, for the 4-car in particular this might be an option to accommodate additional equipment.

5.5.1 DEMU

The FLIRT fleet for Anglian in the UK is equipped with four 500kW diesel engines, so accommodating three such engines ought not to present an issue from a space of mass point of view. In terms of fuel, the diesel tank on the Anglian fleet is mounted underneath the floor, and it is understood that this is sufficient for an operating range of at least 600 miles.

5.5.2 Hybrid DEMU

From a mass perspective, each bay ought to accommodate up to two LTO battery packs (2,000kg each) or a single diesel engine assembly. Therefore, from a mass perspective, it ought to be possible to accommodate the equipment required for all variants.

Given that battery packs tend to have a very high density, it is reasonable to assume there would be sufficient space in each bay to accommodate two battery modules. So again, on this basis, it ought to be possible to accommodate the equipment required for all variants of the Hybrid DEMU.

5.5.3 FCEMU

The worst-case variant, the 4-car on the LAUS route, is estimated to require 7,000kg of fuel cell and BoP, plus around 8,000kg of hydrogen storage tanks – so 15,000kg in total. As this is less than the combined mass of four diesel engines, from a mass perspective, it ought to be possible to accommodate the equipment required for all variants.

From a space perspective, it is estimated that a 100kW fuel cell module requires 0.5m$^{\mathbf{3}}$ of space, and that this is doubled when the BoP is considered to give a total of 1m^3. Each hydrogen storage tank is estimated to require 0.5m$^{\mathbf{3}}$ with a capacity of approximately 8kg. On this basis, it is likely to be possible to accommodate the fuel cells, BoP, and tanks for the 2-car on the Redlands route, but not for the other three variants.

5.5.4 Hybrid FCEMU

Applying a similar logic to the FCEMU variant, again the total mass of the components is unlikely to be an issue. As for space requirements, it is likely to be possible to accommodate fuel cells, BoP, LTO battery pack and hydrogen storage tanks for the 2-car variants on both the Redlands and LAUS route, but the 4-car operating on the Redlands route will be challenging, and not possible for the 4-car operating on the LAUS route.

5.5.5 BEMU

In terms of both mass and volume, it is almost certainly possible to accommodate the four LTO battery packs within the power module for operation on the Redlands route. However, the LAUS route would require a substantial number of battery packs with associated mass implication, which render this option likely impractical.

5.6 Suggested Powertrain Selection

A summary of the likely practicality of the different powertrain options is as follows:

- The DEMU is a practical solution for both 2-car and 4-car variants on either route.
- Likewise, the Hybrid DEMU is a practical option for both 2-car and 4-car variants on either route and offers a 20-25% saving in fuel consumption compared to the DEMU.
- The FCEMU may be a practical solution for the 2-car variant running on the shorter Redlands route. But the large number of fuel cells and the volume of hydrogen tanks required may be an issue for the 4-car option. For the LAUS route, space for either variant is likely problematic given the assumed number of roundtrips.
- The Hybrid FCEMU is more practical, particularly for the 2-car operating on the Redlands route, requiring fewer fuel cell modules and a lower number of hydrogen storage tanks thanks to energy savings due to hybridization. It is likely to remain challenging to accommodate the hydrogen storage tanks within the power module for the 4-car on the Redlands route, or either variant on the LAUS route given the assumed number of roundtrips.
- The BEMU is a practical solution for the Redlands route for both 2-car and 4-car variants, but not for the LAUS route in either configuration.

A high-level preliminary analysis suggests that the required hydrogen storage and other powertrain components could be installed on a 2-car train. For example, the 2-car hydrogen-hybrid Alstom Coradia iLINT train has been estimated to store 180kg of hydrogen at 350bar (Ernst & Young, 2016). Increased pressure to 700bar would reduce the volume requirement for the hydrogen tanks extending range if the same space for installation would be utilized. Further, if a power-module arrangement, such as in the Stadler FLIRT vehicles, is employed, additional volume for components is available compared to the Alstom arrangement, which does not utilize a power-module.

For the FCEMU and Hybrid FCEMU there might be the possibility to refuel trains during the operating day as the refueling process is quick and clean. Such alternative service arrangements would reduce the on-board hydrogen requirements, for example, if a train is designed for a 12-hour shift or refueling of the train occurs for a second time during the operational day. It may also be possible to accommodate hydrogen storage tanks on adjacent vehicles to the power module in order to achieve the required range. On the LAUS route, two roundtrips with a 2-car train between refueling is likely possible while the same train could provide 16 hours of service on the Redlands route.

To summarize, a hydrogen fuel cell or hydrogen fuel cell hybrid powertrain arrangement would be feasible for the Arrow route with the potential of daily refueling.

The LAUS route and the LAUS to University of Redlands route can be realized with a hydrogen or hydrogen hybrid option. A 2-Car ZEMU it is expected to be capable of two round trips on these routes, roughly equivalent to 10 hours of service, however refueling would have to occur twice a day due to volume limitations on a 2-car train. It is possible that with additional cars, and therefore additional storage space, this fueling requirement may be reduced, however a detailed analysis of the vehicle design is required to determine this.

In conclusion, while the shorter Arrow service on the Redlands route could be operated by a battery-only option, a hydrogen fuel cell powertrain is necessary for the longer LAUS route, with the Hybrid FCEMU likely to be the most practical option. If service to LAUS with a ZEMU has a high priority, then it is suggested that a single fleet of Hybrid FCEMUs would be preferable to a mixed fleet of BEMUs and Hybrid FCEMUs in order to provide operational flexibility, i.e., a fleet that could operate on either route.

5.7 Further Modelling of Hybrid FCEMU Powertrain

In order to verify the suggested ratings of fuel cell modules and battery elements, additional simulations were undertaken to evaluate the likely energy flows between the key elements of the powertrain for the Hybrid FCEMU. The predicted power flow along the DC-Bus (i.e. the power line connecting the fuel cell, battery, traction system, and HEP) was calculated firstly for a roundtrip journey from Redlands to SBTC and then for a roundtrip on the more demanding Redlands to LAUS route.

5.7.1 Power Flow Modelling for a Roundtrip Redlands to SBTC

For the roundtrip journey Redlands-SBTC-Redlands, the fuel cell output was set to meet the average power requirement for the journey, and the initial battery State of Charge (SoC) was set at 50% so that the train could benefit from energy recovery on the downhill run from Redlands to SBTC through regenerative braking. The results are shown in Figure 5-4.

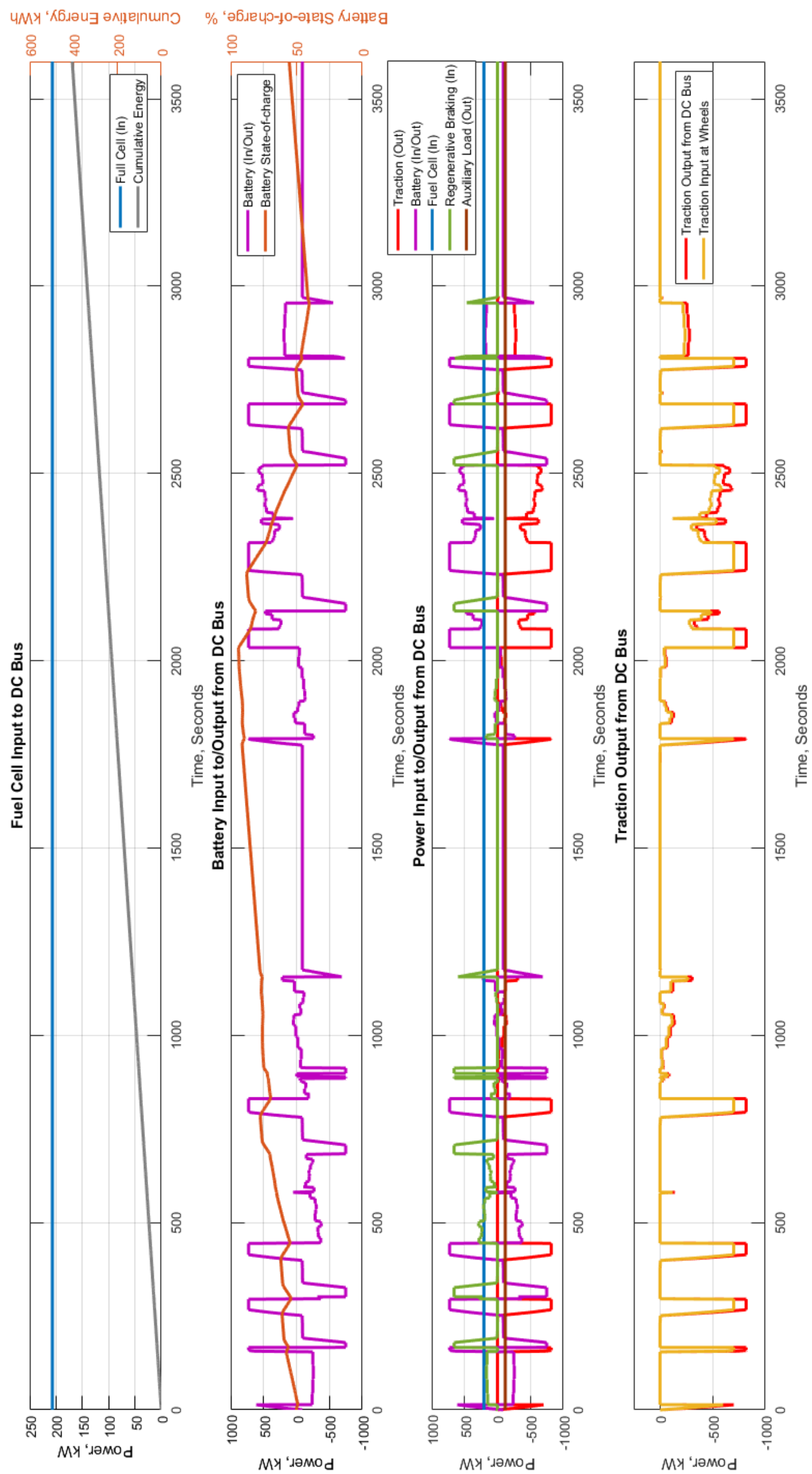


Figure 5-4: Predicted Power Flows for a Roundtrip Journey Redlands – SBTC

Figure 5-4 consists of four separate charts as follows, with the sign convention that power flowing into the DC-Bus is shown as positive, and power flowing out from the DC-Bus is shown as negative:

1. Power output by the fuel cell and overall energy produced
2. Energy input and output from the battery, plus its predicted SoC
3. All various power flows along the DC-Bus
4. Power output from the DC-Bus to the traction systems, plus power delivered 'at the wheel'

The results showed that the battery SoC would remain within an acceptable range, and the fuel cell would operate well within the rated output previously suggested.

5.7.2 Return from Redlands to LAUS

The simulation was then repeated for the more demanding journey from Redlands to LAUS. The track elevation profile for this route is illustrated in Figure 5-5, showing the significant drop in elevation towards LAUS (at approximately 110 km), and the corresponding climb back to Redlands for the return leg of the journey.

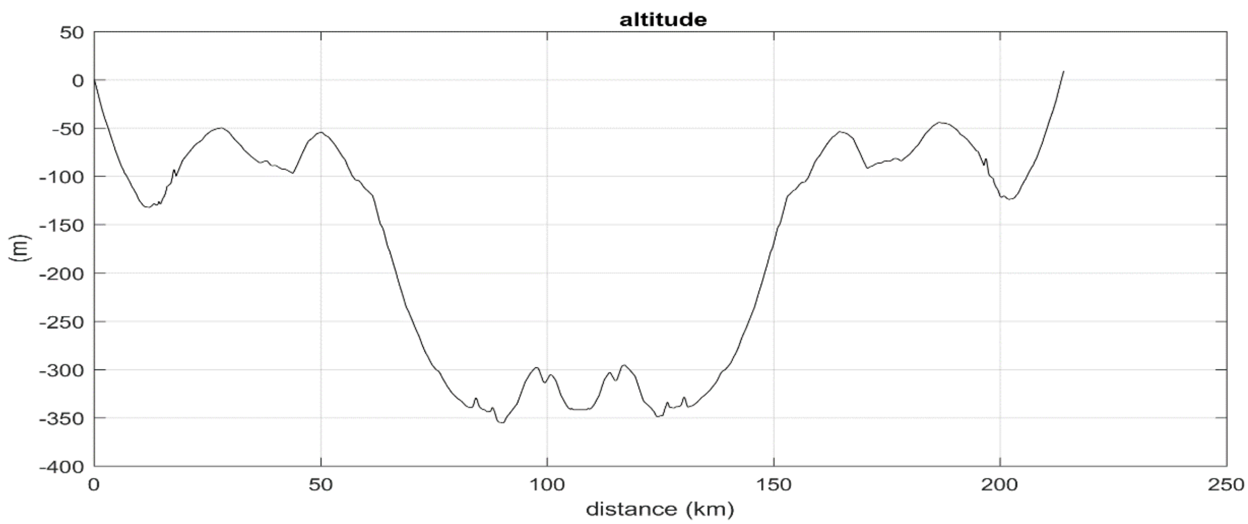


Figure 5-5: Altitude Profile for Roundtrip Route Redlands - LAUS

As the power required for the downhill and uphill directions are very different, the fuel cell output was set to meet the average power requirement for each direction separately, i.e. a lower average power for the downhill run to LAUS, and a higher power output for the uphill journey back to Redlands. The return leg was initially capped at 400 kW, i.e. the maximum rated output suggested previously.

The initial battery SoC was again set to 50% so that the train would benefit from energy recovery on the downhill run from Redlands to LAUS. But despite being fully recharged upon departure from LAUS, the battery was predicted to completely discharge at a number of points during the return, uphill, leg of the journey. Therefore the 'cap' on the fuel cell output was removed, which gave the results shown in Figure 5-6.

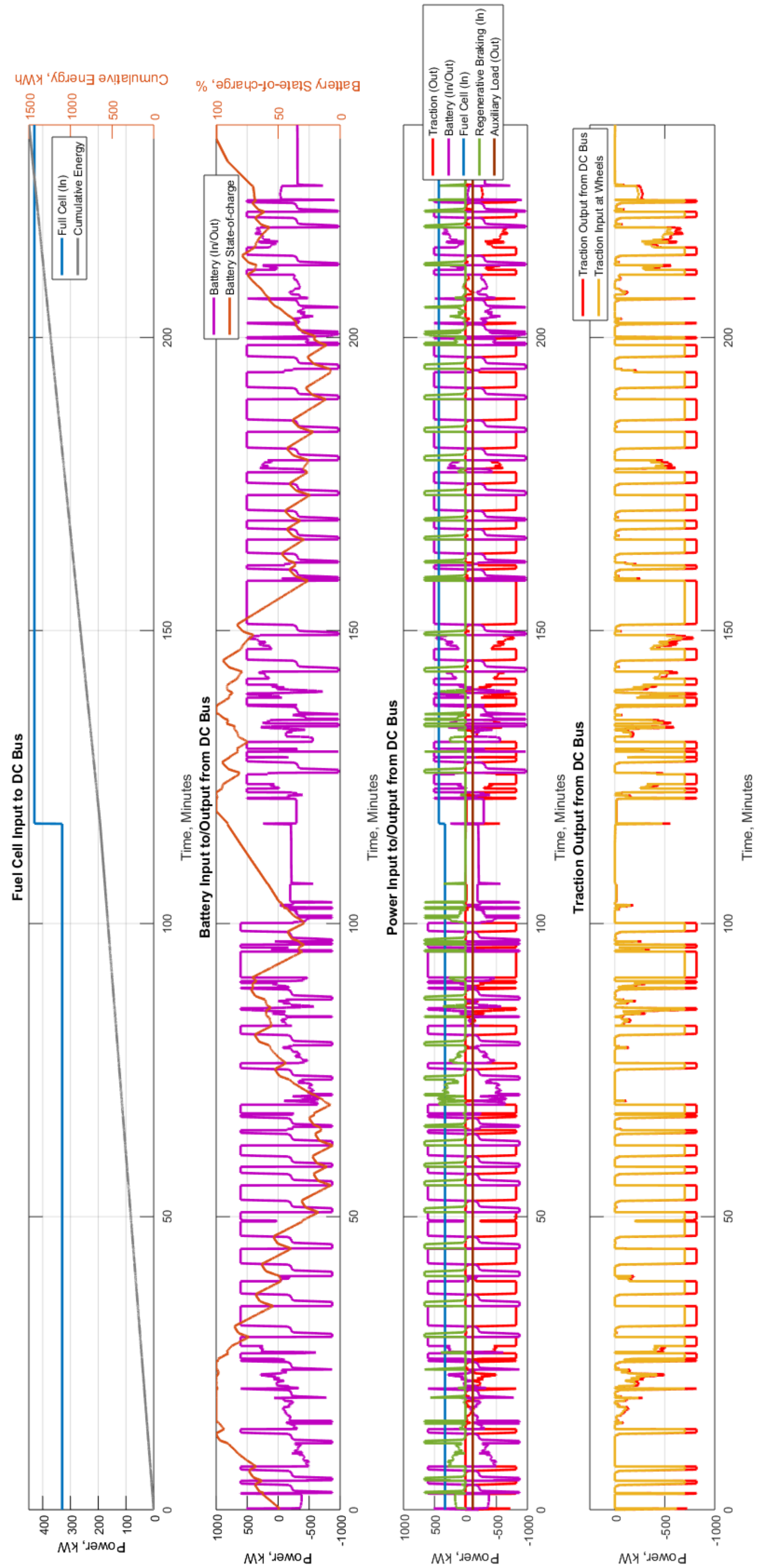


Figure 5-6: Predicted Power Flows at DC-Bus for a Roundtrip Journey Redlands - LAUS

Even with an initial SoC of 50%, it was noted that the battery was predicted to become fully charged at several points on the downhill journey, thereby limiting the amount of energy captured through regenerative braking. And even with the increased fuel cell output, the battery SoC was predicted to fall as low as 10% on the uphill leg, which is unacceptable in terms of achieving a reasonable battery life.

A option would be to retain the suggested component sizing and implement a control strategy that would turn off the fuel cell powerplant when the battery SoC reaches a particular high point and not utilize the battery when a particular low point is reached; these strategies would have an impact on energy consumption and journey time but would be suitable to demonstrate the capability of a hybrid FCEMU on a longer route.

A further option, preferable for regular service operation would be to install a larger battery pack to optimize for lifetime and energy recovery, and additional simulations were undertaken assuming that a 200kWh battery pack were fitted to the train.

Several further simulations were undertaken assuming different initial battery SoC levels, and it was found that even with an initial SoC of as high as 66%, the 200kWh battery pack was able to capture **all** of the energy from regenerative braking, as shown in Figure 5-7.

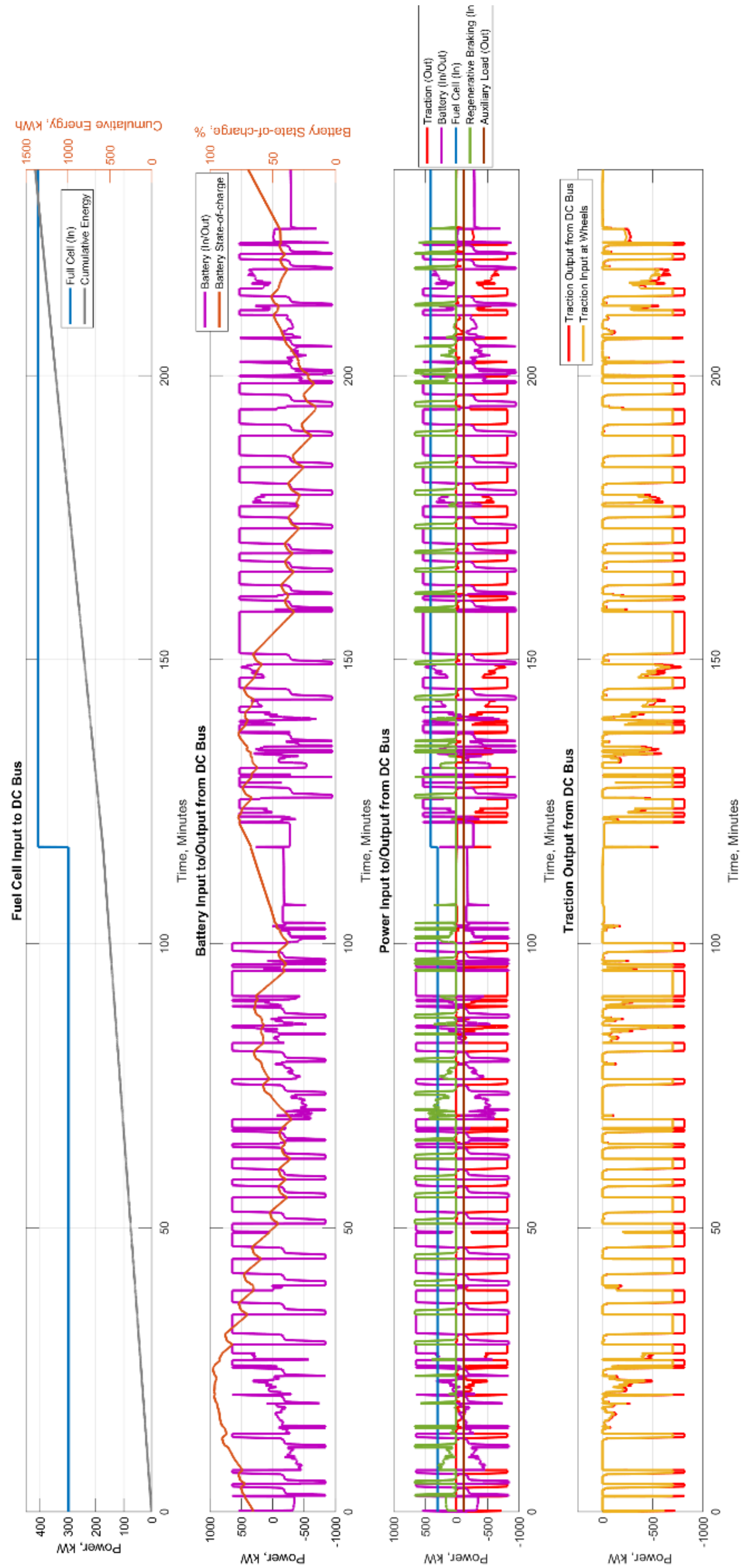


Figure 5-7: Power Flows for Roundtrip Redlands - SBTC with 200 kWh Battery Pack

The larger battery pack meant that the minimum predicted battery SoC for the return, uphill, journey remained above 20%, which is considered to be the limit of acceptable discharge, with the added benefit of reducing the average power required for the uphill journey to 400kW, i.e., the fuel cell rating previously proposed for the longer route, therefore an impact on journey time would be avoided while energy consumption reduced.

5.7.3 Summary

Modelling the power at the DC-Bus and battery SoC suggests that a 2-car FCEMU equipped with the proposed 300 kW fuel cell and 110 kWh end-of-life (EOL) battery pack would work well for the shorter route between Redlands and SBTC. However, for the more demanding roundtrip journey from Redlands to LAUS, a larger battery of at least 200 kWh EOL would be required to maximize the benefit of regenerative braking and achieve acceptable battery life. Furthermore, as fuel cells work at their most efficient when operated at less than their full rated power, it would be advisable to fit a fuel cell with a maximum rated output of greater than 400 kW so that it continues to operate at high efficiency for the more demanding uphill LAUS to Redlands journey. If extension to LAUS has a high priority, then it is recommended that these increased component sizes are specified for a train as a minimum.

6 INFRASTRUCTURE REQUIREMENTS FOR HYDRAIL

In this section, high-level infrastructure requirements for hydrogen options are presented. Hydrogen can be produced from several different sources and supply arrangements vary as already described. Three options where evaluated in more detail:

- Hydrogen delivered as a liquid. This option is the most similar to DMU operating practices where the fuel is delivered to a refueling site. It is assumed that the hydrogen would be produced from NG as this is currently the most common production option. This also the currently utilized option for the mobile refueling station for the Alstom iLINT in Germany.
- Hydrogen produce on-site from NG. This option is likely a cost-effective solution with limited infrastructure requirements and frequently used if a relatively high hydrogen demand exists at a location, for example for warehouses that operate with hydrogen-powered forklifts.
- Hydrogen produced on-site from electrolysis. This option offers a zero-emission on-site production solution and would benefit from continued decarbonization of the CA electricity mix. The current feedstock mix for CA has been considered and a 100% renewable option is presented, the latter an option through purchasing agreements.

6.1 Production and Transportation

There are several methods by which hydrogen can be produced and these are illustrated in Figure 2-10. For the SBCTA applications three hydrogen production methods have been investigated in more detail: on-site production via electrolysis, on-site production via steam methane reformation (SMR), and centralized production and delivery. These were selected based on an initial assessment of hydrogen availability in the region and emission reduction ambitions.

On-site hydrogen production would occur at a rail facility, e.g. a maintenance or refueling facility, which has the advantage of not relying on regular deliveries. On-site electrolysis refers to the production of hydrogen via electricity and water. Electrical charges in an electrolyzer separates water (H_2O) into hydrogen (H_2) and oxygen (O_2) gases; the reverse process of fuel cells (illustrated in Figure 2-11). This can be an environmentally superior method of producing hydrogen, with the benefit depending on the specifics of the power grid. It offers the potential to be completely zero-emission, well-to-wheel, if renewable electricity sources are used. And it can assist in the management of the supply and demand of the electricity grid system (see the discussion on the duck curve in 2.3 Renewables and Hydrogen) potentially offering attractive prices. It is, however, often a more expensive method to produce hydrogen than SMR, described below, due to the cost of electricity. An electrolyzer for low-volume production of hydrogen is illustrated in Figure 6-1.

Figure 6-1: Illustration of a Low-Production Volume Electrolyzer (Hoffrichter, 2019)

Hydrogen can be produced from fossil fuels and the generalized process is illustrated in Figure 6-2; production from the feedstock of natural gas is the most popular option currently. SMR is a process in which a gas, typically natural gas, i.e. mostly methane, is converted to hydrogen. Currently, SMR accounts for approximately 95% of hydrogen production in the US. Currently, it is estimated that it is the cheaper of the two main on-site production options due to relatively low cost of natural gas. However, when natural gas is used, this process might not be as environmentally beneficial as electrolysis of water, depending on the electricity mix, as GHG emissions are a result of the production process. There is the possibility of utilizing renewable biogas or landfill gas, which can lead to a zero-emission option.

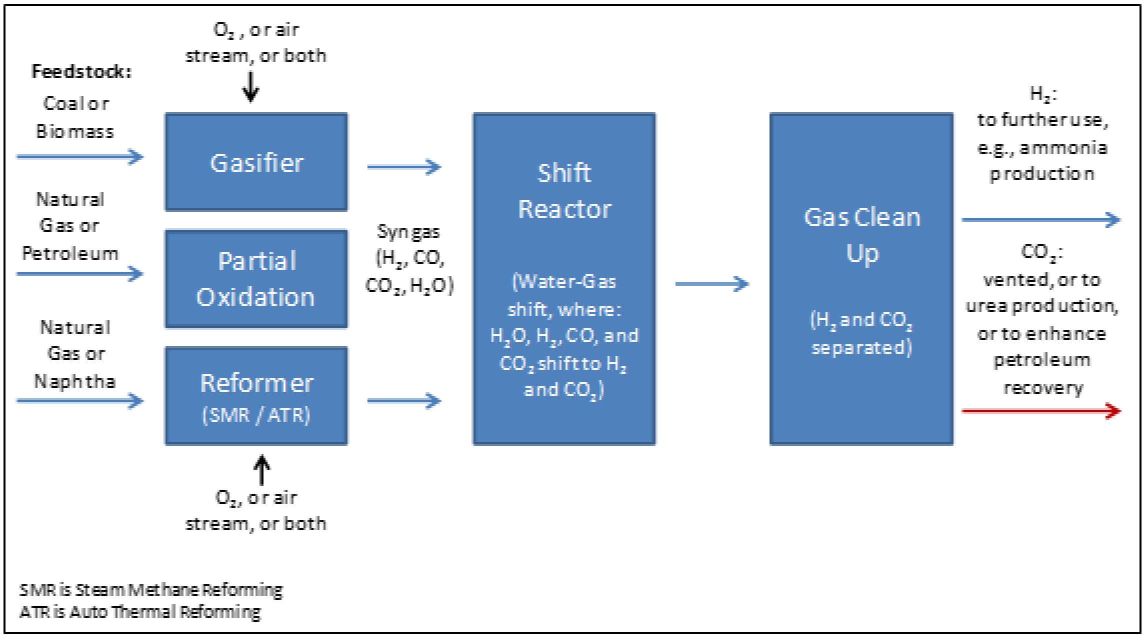


Figure 6-2: Generalized Hydrogen Production Process from Fossil Fuels (Hoffrichter, 2013)

The third investigated option is delivery of hydrogen, which could address potential space or capital cost concerns, particularly if a mobile refueling station would be employed. Hydrogen is produced at a central location, typically via SMR, and delivered to the refueling site. Often, the hydrogen is liquified for transportation in tanker trucks to minimize delivery frequency and cost. However, this leads to higher emissions and environmental impacts during the well-to-pump phase compared to on-site production due to emissions occurring during transportation and the significant energy requirement for hydrogen liquification. If relatively small quantities of hydrogen are required, a higher delivery frequency is possible, or on-site hydrogen storage with sufficient capacity for reasonable delivery frequencies, such as weekly, transportation as a gas with a tanker truck is an option. The delivery option with a mobile refueling station is a likely option for SBCTA during the demonstration phase of the project if hydrogen fuel cell trains would be chosen as an option. An illustration of a mobile refueling trailer that stores hydrogen as a gas is illustrated in Figure 6-3.

6.2 Fueling

The fueling infrastructure for hydrogen is more complex than for diesel. While it is similar to the one required for CNG/LNG, there are a few significant differences. For example, there are significantly higher pressures involved with hydrogen due to the differing energy densities of the two fuels (as illustrated in Figure 2-9). As a result, more powerful compressors, stronger tanks, and dispensers are required. This also, typically, implies different materials. Leak detection (e.g. from station storage tanks) of hydrogen is more technologically complex than it is with natural gas (Ogden, Jaffe, Scheitrum, McDonald, & Miller, 2018).

While the rate at which hydrogen enters the tank is significantly slower than diesel, similar refueling times can be achieved as less energy is stored on-board of a hydrogen train compared to a diesel variant. Estimated refueling times for the Arrow hydrogen-hybrid vehicle are 15 to 30 minutes. The Alstom Coradia iLINT hydrogen-hybrid has a refueling time of 15 minutes for estimated 180kg, for example, and that train is relatively similar to the vehicle required for the Arrow service. In Figure 6-4 a fueling nozzle connected to a railway vehicle is depicted. Figure 6-5 shows a mobile dispenser also used for train refueling while Figure 6-6 depicts a more permanent installation for buses.

With two vehicles, it would probably make sense to refuel one vehicle in the morning and one at night. This would help balance the power demand and on-site hydrogen storage, impacting cost.

Figure 6-3: Illustration of a Mobile Hydrogen Refuelling Trailer (Hoffrichter, 2019)

Figure 6-4: Hydrogen Refuelling Nozzle Connected to a Train (Hoffrichter, 2019)

Figure 6-5: Mobile Hydrogen Dispenser (Hoffrichter, 2019)

Figure 6-6: Permanent Hydrogen Refuelling Dispenser (Hoffrichter, 2019)

Re-fueling of the vehicle occurs in the gaseous state, both in the dispensing of the fuel as well as in its storage on the vehicle. Most likely the on-board storage would be at 350 bar pressure. 700 bar could also be accommodated, and would reduce the space required; however, it would also result in greater cost. This is because higher pressure of the hydrogen requires further equipment to maintain the pressure and the storage tanks need to be of higher strength to accommodate the pressure.

6.3 On-Site Storage

To operate a passenger rail service with hydrogen fuel cell or hydrogen fuel cell hybrid option, supporting infrastructure and services, including fuel storage and dispensing facilities will be required, even if hydrogen is not produced on-site, but delivered. This infrastructure is more complex than is the case with diesel, since hydrogen needs to be maintained at an appropriate pressure for storage and dispensing. The overall facilities sizes, including storage, have been estimated below:

- On-site hydrogen via electrolysis. This refueling facility would require ~1,300ft^2 (not including space for the vehicle), with a roof height of at least 20ft (to enable stackable hydrogen storage). Such a facility would produce enough hydrogen to meet the Arrow system's daily needs.
- On-site SMR. The station size required is similar, at ~1,400ft^2 (again, not including space for the vehicle), with a height of approximately 13ft.
- Hydrogen delivery option. Assuming liquid storage, the area required would be around 1,600-1,700ft^2.

6.4 Utilities

For on-site production of hydrogen, regardless of the method, an electricity supply would be necessary, as would access to significant amounts of water. Production via steam methane reformation would, however, require approximately five times the amount of water as electrolysis at ~100,000 gallons per month for a non-hybrid service, and would also require a connection to the natural gas supply line.

Hydrogen has characteristics that make it a good choice for storing energy. This is due to its very significant energy density per mass and due to its stability, which is the characteristic leading to its ability to provide storage for a longer time compared to other currently existing storage alternatives, with a storage time ranging from several months to years.

Generally speaking, taking advantage of this potential, for hydrogen could serve as a way to address the substantial problem of mismatched supply and demand on the grid that results from the operating characteristics of renewable energy powerplants, solar, in particular in the California case, as discussed in section 2.3. Renewables and Hydrogen

6.5 Maintenance and Storage Facility Modifications

Based on the infrastructure assessment completed in this section and the associated service provision estimated in section 5, it is assumed that no additional infrastructure is required within the RPRP corridor to implement a hydrogen ZEMU. Any additions and modifications that are required, such as hydrogen storage and fueling, could be incorporated into the footprint of the current Arrow Maintenance Facility (AMF). Should a hydrogen production facility also be constructed for operation of a hydrogen-based Arrow service, the additional production equipment could also be installed at the AMF.

In addition to the new infrastructure listed above, the maintenance facility building itself would also require upgrades in order to safely maintain the hydrogen trains. This would include hydrogen leak detectors and upgraded or new ventilation equipment. Considerations regarding ventilation is discussed in further detail in the safety section 6.9 of the hydrogen assessment. It was assumed that the necessary modifications and safety requirements could be retrofit into the existing building, and that a separate hydrogen maintenance facility would not be required.

6.6 Market Availability

The necessary equipment for hydrogen fuel cell (HFC) trains and supporting infrastructure is available. However, the majority of commercially available equipment has been designed for non-rail applications, such as buses, but the equipment can be adapted for rail use. Ballard, Hydrogenics, Plug Power, and Power Cell are examples of possible suppliers of heavy-duty FCS.

Air Liquide, Linde, and Trillium provide on-site SMR hydrogen production with associated storage, while Trillium also provides on-site electrolysis production of hydrogen along with storage. Millennium Reign, a firm in Ohio, also produces on-site electrolysis and storage systems, and its equipment has been utilized by TIG/m to supply its hydrogen-powered streetcars. Plug Power could provide refueling facilities where hydrogen is either delivered as a liquid or produced on-site through electrolysis.

Air Products, Air Liquide, and Linde also provide centralized production of hydrogen, along with liquefaction, e.g. for distributed delivery of H_2 as a liquid or delivery as a gas. In summary, refueling stations would be customized for the rail application but are relatively easily available.

There are also several suppliers of high-pressure hydrogen tanks suitable for on-board storage, examples are Hexagon, Worthington Industries, Luxfer, and Fuel Solutions. Market availability of suitable batteries was covered in the accompanying report provided by Mott MacDonald (MM et al., 2019).

Currently, the most limiting part of the supply chain is the integration of all the necessary hydrogen-related components to produce a train. Only Alstom offers an off-the-shelf regional train that would be suitable for the Arrow service. However, several other manufacturers offer HFC railway vehicles, for example TIG/m and CRRC offer streetcars. In addition, regional HFC trains, similar to the vehicles required for the RPRP corridor are currently under development, most notably by Siemens in collaboration with Ballard, and JREast in collaboration with Toyota. Stadler is also currently developing five HFC trains for the Zillertal Railway in Austria, which is expected to use hydrogen that is produced locally with electrolyzers.

6.7 Provider Dependency

The hydrogen market is steadily growing. There are a few different railway vehicle manufacturers that have either already manufactured or are committed to manufacturing hydrogen-powered trains as previously described. In addition, the heavy-duty sector for hydrogen fuel cells is growing in addition to the light duty sector.

Hexagon Lincoln and Worthington Industries are two major manufacturers of hydrogen tanks, and it is likely that there will soon be additional competitors to these, given the growth in fuel cell deployment seen in recent years, as illustrated in Figure 6-7.

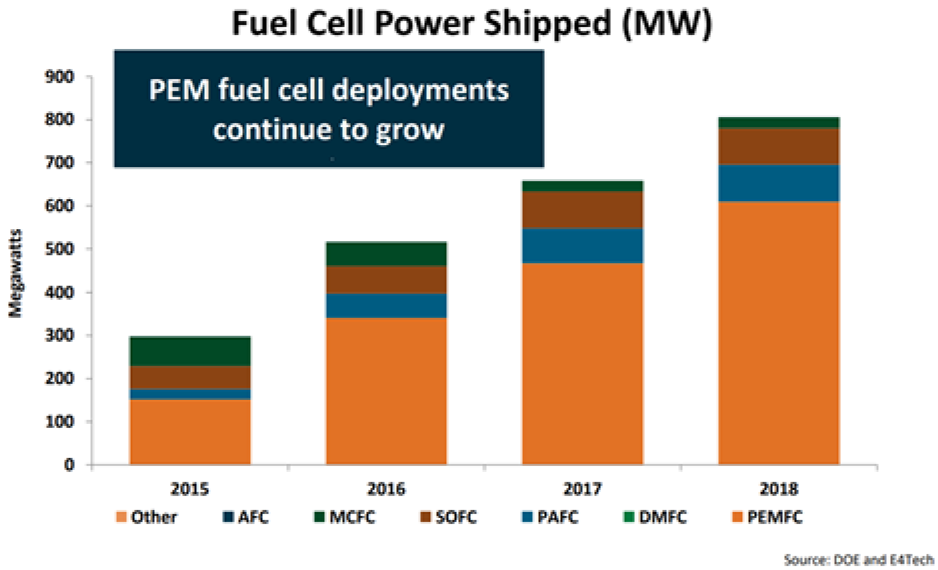


Figure 6-7: Growth in Fuel Cell Deployment (Satyapal, 2019b)

The remaining components can be sourced from a variety of manufacturers, as such equipment is common to most hydrogen fuel cell operations and even some other power applications, including pipes, fans, power electronics, gas regulators, etc. Hydrogen as a gas or the infrastructure necessary to produce it on-site is available from several suppliers (e.g. Air Liquide, Air Products, Trillium, and Linde, as noted earlier; also, Millennium Reign Energy, for on-site electrolysis equipment). Hydrogen is already used in large amounts by the oil refining sector and the agricultural sector, specifically in making ammonia for fertilizer, so the market for merchant hydrogen supply and production is mature.

6.8 Technology Obsolescence

Hydrogen is a fundamental building block of the universe, and the source of the sun's energy. It is also the most abundant element in the universe and plentiful on earth. As such, there will be no shortage of hydrogen, which sets it apart from fossil fuels and rare earth-based materials, the latter often serving as key components in battery production. While using hydrogen as a fuel has historically proven to present some challenges, there has been significant research and development enabling viability in road, rail, and stationary applications. Some of the remaining challenges are likely to be overcome as the U.S. government and commercial entities invest further into research and development, and this will only serve to increase its attractiveness as an energy carrier. In recent conversations with private utility companies, like SoCalGas (Sempra Energy), several are considering utilizing hydrogen technologies to capture surplus renewable electricity. This method would thus improve the supply chain for renewable hydrogen.

Combustion of fossil fuels leads to emissions as previously described, and California recently implemented the "Innovative Clean Transit" rule. Regulations such as these, in addition to helping to spur continued innovation within industry, also serve to make fossil fuel-based technologies progressively less advantageous as compared to alternatives such as hydrogen, which have not traditionally enjoyed the kinds of structural support and economic incentives that fossil fuels have received.

Natural gas has some benefit over diesel fuel in terms of its environmental effects; however, the benefits are likely not enough to compensate for the efforts that would be undertaken to change the vehicle and related refueling infrastructure. Moreover, with significant research and development focus on hydrogen and other zero-emission technologies, as noted above, NG technology, at least in a rail context, is also likely bound to become obsolete in the coming years.

Of course, any technology evolves over time and the pace of technology change in this century is especially rapid. Areas such as fuel cell design and method of and materials used for hydrogen storage are likely to change, changes that will enhance hydrogen's viability and overcome the previously alluded challenges. Examples of potential changes include a transition away from platinum-based catalysts, which are typically expensive, to materials that are cheaper. Similarly, storage may eventually evolve towards either a liquid organic-type carrier or otherwise a solid carrier, such as a metal hydride or metal organic framework, technologies that could potentially reduce the volume required for a given amount of hydrogen storage. Incorporating such future developments or others into vehicles whose components are reflective of the present technology should not be difficult, but rather require upgrades to the existing powertrain.

6.9 Safety

Hydrogen has a different chemical composition than diesel fuel; consisting of complex hydrocarbons. 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 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. In many cases, new methods of infrastructure protection will need to be employed, but these are not likely to be particularly costly nor are they 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.

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. That said, a fully enclosed area is likely not ideal for hydrogen refueling and maintenance work, while a partially enclosed area would be adequate. Such a partially enclosed solution has, in fact, been implemented in the case of a facility that is located in Orange County, where a new hydrogen fuel cell bus fleet has recently begun operations. If possible, a similar arrangement of a partially enclosed maintenance facility for the RPRP corridor is suggested, while locating hydrogen refueling and dispensing equipment outside.

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. 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. If hydrogen would be implemented as a solution, more detailed work would be required than presented in this report.

6.10 System Expansion to LAUS

One of the primary advantages of a hydrogen solution is the comparatively easy expansion of the service onto other routes as no right-of-way infrastructure for energy supply is required, as long as the train operates within the on-board energy storage range, which is substantial. Extension of the service to LA Union Station is possible with hydrogen options. The recommended 2-car hydrogen-hybrid train would be able to complete two roundtrips on the Redlands LAUS route, approximately a 10-hour shift before requiring refueling. More detail was provided in the previous section 5 and in Appendix 14.2 Simulation Results with Corresponding Emissions. Expansion of service would require additional hydrogen delivery or production and all investigated options can technically be scaled to increase provision. The easiest option is with hydrogen delivery as the only required adjustment would be an increase in the frequency of hydrogen delivery. The on-site production methods would require additional capital investment to increase production rates.

7 ENVIRONMENTAL IMPACT ASSESSMENT FOR A HYDRAIL SYSTEM

It is expected that the ZEMU and its supporting infrastructure will need to undergo environmental review with either the National Environmental Policy Act (NEPA) or the California Environmental Quality Act (CEQA) or both. Generally, the key environmental impacts the ZEMU and its supporting infrastructure could potentially affect are:

- Visual Quality and Aesthetics
- Noise
- Air Quality and GHGs
- Hazardous Waste and Materials
- Energy
- Socio-Economic / Environmental Justice impacts

The operation of the ZEMU vehicle is anticipated to provide positive effects by reducing air pollutants at the site of operation. The potential conversion of the rest of the Arrow service fleet to a low- or zero-emissions rail vehicle could further improve air quality. A high-level environmental assessment was conducted as part of the study to identify the feasible technologies for the Arrow service. However, a complete environmental assessment will be needed to determine the environmental effects of the chosen technology.

7.1 Visual Quality and Aesthetics

On-board energy storage options have limited impact on visual quality and aesthetics, some options will occasionally have visible emissions, such as in a diesel case, while for a battery option charging infrastructure might be required at relatively frequent intervals. All options, aside from the battery-only, require refueling infrastructure, which typically has an industrial appearance. Hydrogen does not result in any aesthetics or visual quality concerns along the right-of-way. Because it is zero-emissions at the point-of-use, usage of hydrogen as a fuel, especially in large amounts, would reduce smog levels. The primary visual impact would be at the refueling and potential hydrogen production facility, as additional equipment has to be installed.

7.2 Noise

HFC do not produce significant noise, possibly audible noise could be produced by air compressors and other balance-of-plant components, however, the noise level is similar to wayside-electric trains. Thus, switching to a hydrogen powertrain would result in a significant noise reduction with respect to combustion engine-based powertrains.

7.3 Energy, Air Quality and GHGs

Energy impact and emission occur throughout the fuel cycle for any vehicle. For some, such as diesel, the primary energy form change occurs on-board of the vehicle in the form of combustion of a chemical fuel ultimately resulting in motion of the train. The primary energy change for electric vehicles occurs at the power plant, e.g., NG power station and the electricity is then transmitted to the train, which leads to zero-emission during operation at the point-of-use. However, emissions are released in the extraction and transportation of the natural gas and its combustion in the power station. Two primary zero-emission during operation options have been identified as suitable for the Arrow service: battery-only and hydrogen. However, to provide a more complete assessment regarding emissions and energy consumption, a well-to-wheel analysis was conducted where the entire energy supply chain was considered. The 2018 version of the Greenhouse Gases, Regulated Emission, and Energy Use in Transportation (GREET) model authored by Michael Wang, developed by Argonne National Laboratory was employed to conduct the well-to-wheel assessments. Some modification of the model where necessary to account for the specific rail cases. Results for all options, aside the battery-only due to the relative incompatibly for extended service to LAUS, are presented in this section. An impact assessment of the battery option can be found in the accompanying report (MM et al., 2019).

Hydrogen-powered railway vehicles do not produce any harmful emission at the point-of-use and are considered zero-emission vehicles while also reducing energy consumption compared to diesel trains, as already described in section 5. However, hydrogen has to be produced and delivered to the vehicles, and consideration of the overall energy and emission impact on a well-to-wheel basis of several possible production pathways is described in this section. Emissions during operation have a significant weight in the Arrow application due to operation in air quality non-attainment areas, and emissions occurring in the supply chain might be a lower weight as production may occur in air quality attainment areas.

Figure 7-1, shows the results of the emissions analysis for the Arrow route, given a 2-car multiple unit vehicle. The presented results include energy and emissions during operations, which have a direct impact on the local community along the corridor, employees, and passengers. Some of the results have been presented previously (MM et al., 2019) but some adjustments updating combustion engine efficiencies have been incorporated in the calculations after discussion with a rail vehicle manufacturer that is active in the HFC and diesel MU market. This has an impact on energy consumption and emissions from operations as well as on well-to-wheel assessments for all options that utilize combustion engines.

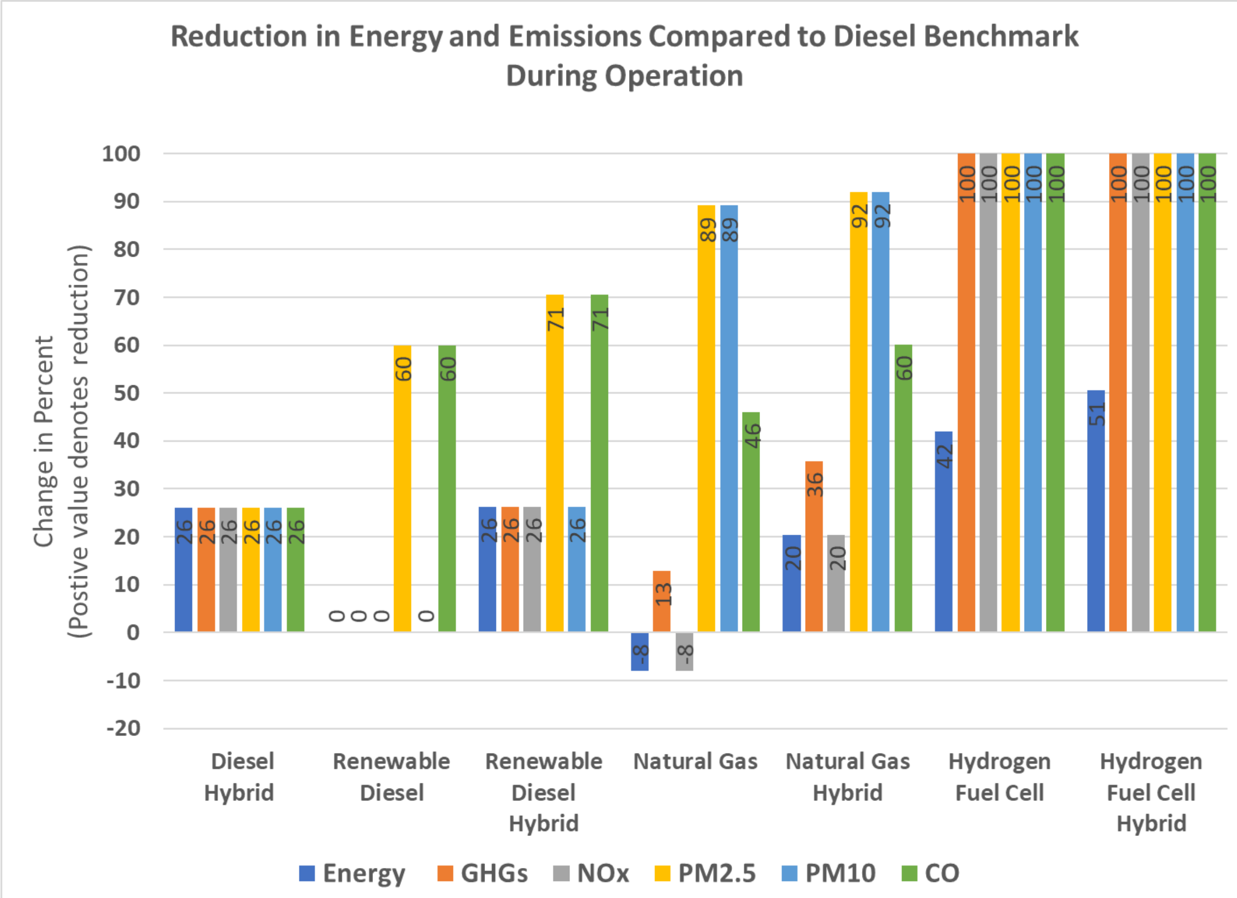


Figure 7-1: Energy and Emission Impact of Various Options from Operation

Most options have a direct positive impact on energy consumption and emissions during operation, with the top performance being the zero-emission hydrogen options as anticipated. In all cases, the hybrid options perform better than their counterpart non-hybrids. The biofuel, renewable diesel, has a positive impact regarding PM and CO but the other emissions remain the same while its hybrid version reduces all emissions and energy consumption from operations. NG is attractive from a PM and CO perspective with some improvement in GHG emissions. The NG hybrid offers reductions in all categories. More detailed results are presented in Appendix 14.2 Simulation Results with Corresponding Emissions.

In Figure 7-2, the energy and emissions impacts resulting from energy provision to the vehicles for operation are added, presenting the more complete well-to-wheel assessment.

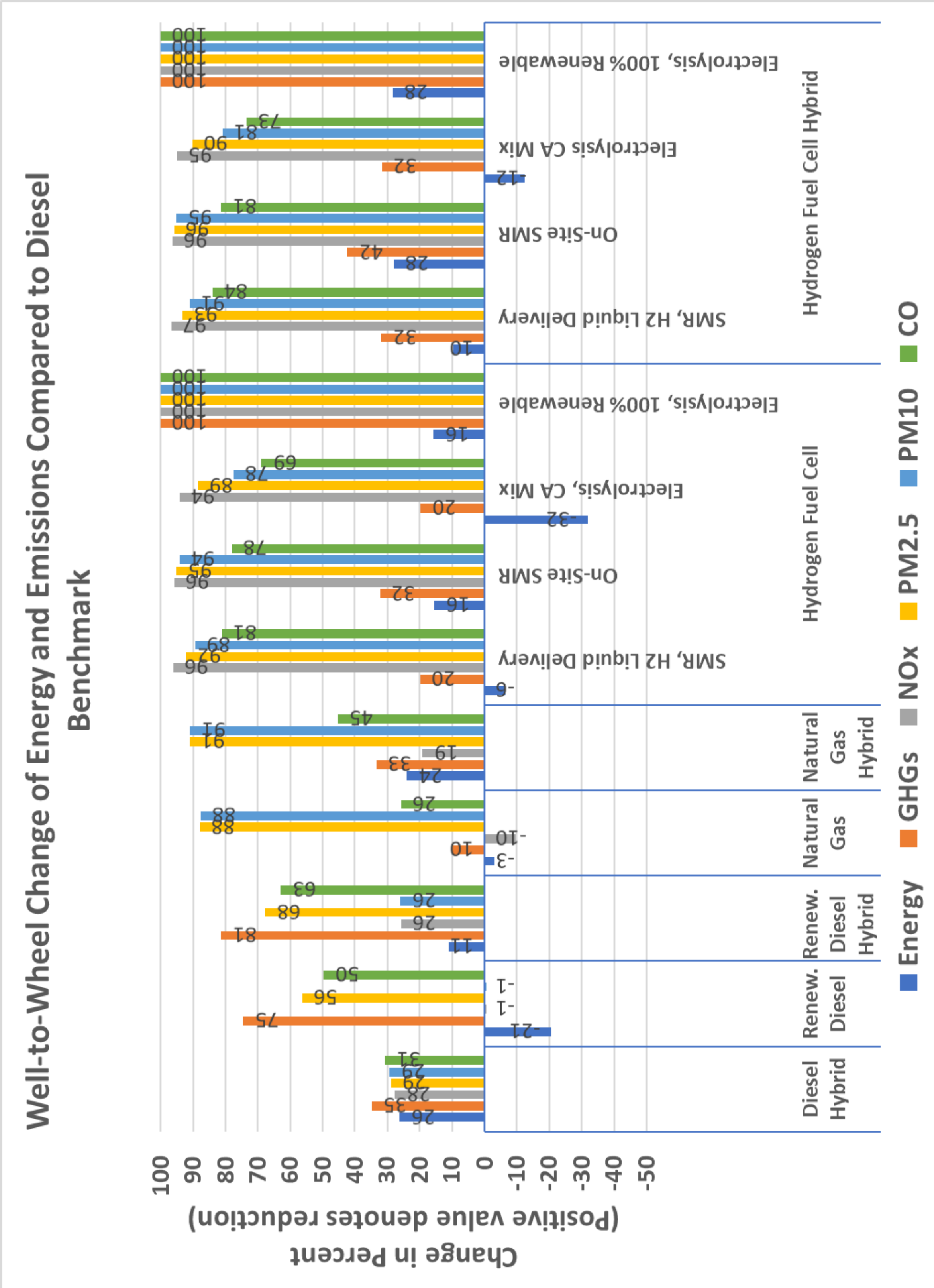


Figure 7-2: Well-to-Wheel Impact on Energy and Emissions of Various Options

General observations are that all options reduce GHGs and regulated emissions that impact air quality. Hybrids perform better than their conventional counterparts in all categories. Both hydrogen options offer the highest reduction on regulated emissions but the HFC hybrid performs better.

Examining the charts, beginning from the from left side:

- A diesel hybrid will significantly reduce energy consumption. It will also reduce GHG and regulated emissions by similar amounts in the region of ~26% - 35%. A diesel-hybrid offers an attractive solution based on energy consumption and GHG compared to several hydrogen and HFC hybrid options but does not reach the substantial regulated emission reductions of the two hydrogen cases.
- Renewable diesel has a substantial positive impact on GHG emissions due to the production nature of the fuel from biomass and in the hybrid case a positive impact on air quality regulated emissions are achieved.
- NG offers very attractive reduction potential for PM due to the lower carbon content in the fuel and the hybrid results in energy and GHG savings.
- The following description focuses on the hydrogen cases due to their substantial improvement potential for local air quality and zero-emissions at the point of use.

The results for a HFC, non-hybrid, are discussed next. In two cases, this option does not lead to the same reduction in either energy or greenhouse gases compared to a diesel hybrid, but regulated emissions would be significantly reduced compared to a diesel and diesel hybrid option. In the 100% renewable energy electric grid with hydrogen production by electrolysis, an energy reduction of 16% would be achieved accompanied by eliminating GHGs and regulated emissions.

The next part of the chart illustrates the results of the HFC hybrid option. This powertrain, like the HFC non-hybrid, offers a suitable option for achieving environmental and public health goals. SMR produced hydrogen with liquid delivery would some impact on the energy consumed with respect to the incumbent diesel technology while offering GHG reductions, however slightly less of a reduction than a diesel hybrid. Regulated emission would be reduced significantly compared to a diesel and diesel hybrid. On-site SMR appears to be an attractive option, as it reduces energy consumption by a similar but slightly higher amount as the diesel hybrid but reduces GHGs by a larger amount. As with all hydrogen cases, regulated emissions are considerably reduced.

Electrolysis given the current electricity production mix in California, would result in similar reductions of GHGs and regulated emissions as the central SMR hydrogen and liquid delivery, despite an increase in total energy consumed as compared to diesel. Pollutant levels would sharply decrease over both the diesel and a hybridized diesel powertrain, though just a bit less than with the liquid delivery.

Again, the 100% renewable electrolysis scenario of a hybrid HFC train is ideal from an emissions and energy perspective, with similar results to the HFC but accompanied by an even larger energy reduction. This is the best performing solution of all compared options considering emission and energy impacts.

Looking broadly at the results, SMR-produced, hydrogen delivered to the refueling site would be a good option to start with as less infrastructure is required, in particular a temporary/mobile refueling arrangement would be suitable. As described previously, less new infrastructure would be required, while GHGs would be reduced by 32%, and regulated emissions significantly reduced. As SBCTA gains confidence with the hydrogen solution, a transition could occur to one of the two on-site options or a switch to a renewable hydrogen supplier might be an option. The choice of on-site production options depends on the timeline and the accompanying improvements in the contribution of renewables to the California electricity mix. If the transition were to occur prior to 2025, SMR would likely be a suitable option. However, by 2025 or after, continued improvements in the renewables contribution to the electric grid would translate into electrolysis becoming a more attractive option. Agreements with the electricity supplier to operate the electrolyzer during high renewable production times, see Duck Curve, in section 2, would directly contribute to high energy efficiency and significant reduction in GHG and regulated emissions.

As noted previously, transitioning to a fuel like hydrogen (as with battery electricity) would greatly reduce the formation of smog, which depends on the high levels of pollutants (especially VOC, SO2, and NOx) in fossil fuels. Hydrogen is an odorless gas, also, and the only emission from a fuel cell is water. More detailed results regarding energy and emission impact are presented in Appendix 14.2 Simulation Results with Corresponding Emissions.

The difference between the HFC and he hydrogen-hybrid is also clear from the analysis, with the hybrid version performing better from an energy and emissions perspective and, therefore, it is suggested to be the preferred choice for the Arrow service with a possibility being a battery-only option if easy expansion to LAUS is not required.

7.4 Hazardous Waste and Materials

Hydrogen fuel cell systems do not contain any materials that qualify as true hazardous materials but handling of the hydrogen itself requires appropriate care. The majority of components used in fuel cells (95%+) can be recycled and so can the components of the tanks, albeit with more difficulty. In the hybrid case, the same provision to the battery apply as outline in the accompanying report (MM et al., 2019), battery section.

7.5 Socio-Economic Impacts

As is the case with batteries, a greater reliance on hydrogen as a transportation fuel would go a long way towards reducing emissions in areas and communities traditionally subjected to high pollution levels (e.g. areas near stations or railyards) since hydrogen has no operational emissions. With electrolysis and, especially, renewables-only electrolysis, there would be limited or no emissions anywhere in the fuel lifecycle, as was demonstrated in Figure 7-2. Reduced noise levels compared to a diesel train are a further benefit. Introduction of the new technology could have a positive impact on the local economy due to attraction of other possible implementers from around the country. Education, training, and knowledge transfer possibilities exist while additional demand from the project for the new components and associated infrastructure would stimulate that sector.

8 ECONOMIC FEASIBILITY FOR THE RPRP CORRIDOR

Estimate cost for a 2-car hydrogen fuel cell hybrid vehicle operating on the RPRP are presented in this section.

8.1 Cost

In this section, the estimated capital cost for a 2-car HFC hybrid vehicle and three hydrogen provision options are presented. Estimated operational cost, including expenses for fuel and major component overhaul for the vehicle powertrains and hydrogen provision infrastructure are also shown over a 30-year anticipated vehicle life. The cost information is the same as already included in the accompanying report (MM et al., 2019). First estimated capital costs are presented followed by estimated operational cost for the three hydrogen supply options. Estimated lifetime of the various major components that differ from a conventional DEMU, such as FCS and hydrogen tanks have been incorporated in this assessment. Costs have been determined by a combination of available data in literature, primarily published by the Department of Energy, and engagement of possible suppliers.

8.1.1 Capital Costs

The up-front capital costs associated with implementing a 2-car HFC hybrid vehicle for a ZEMU service are summarized in Table 5.3 to Table 5.5. Costs are broken down by major components and estimated values are presented. Further detail on the items were provided in accompanying report (MM et al., 2019).

Table 5.3: Capital Cost for Hydrogen Fuel Cell Hybrid ZEMU with On-Site Electrolysis

Item	Cost
HFC hybrid ZEMU vehicle, including: • Modified base vehicle designed to accept and integrate a HFC hybrid powertrain • PEM FCS power assumed 400 kW • Hydrogen storage assumed 220 kg • LTO battery system assumed 140 kWh	$11,200,000
ZEMU vehicle non-recurring costs, including: • Project and engineering management / overhead • Engineering and design • Testing and commissioning • FRA process approval	$10,000,000
HFC hybrid ZEMU specific capital spares	$1,000,000
Hydrogen production, storage and dispensing infrastructure, including: • Electrolyzer • Fuel storage & dispenser • Utility connections • AMF Retrofit	$3,300,000
General costs, including: • Environment and permitting • Project and construction management • Public outreach campaign	$3,300,000
Unallocated contingencies (20% of total)	$5,800,000
TOTAL – HFC hybrid and electrolysis option	**$34,600,000**

Table 5.4: Capital Cost for Hydrogen Fuel Cell Hybrid ZEMU with On-Site Steam Methane Reforming

Item	Cost
HFC hybrid ZEMU vehicle, including: • Modified base vehicle designed to accept and integrate a HFC hybrid powertrain • PEM FCS power assumed 400 kW • Hydrogen storage assumed 220 kg • LTO battery system assumed 140 kWh	$11,200,000
ZEMU vehicle non-recurring costs, including: • Project and engineering management / overhead • Engineering and design • Testing and commissioning • FRA process approval	$10,000,000
HFC hybrid ZEMU specific capital spares	$1,000,000
Hydrogen production, storage and dispensing infrastructure, including: • Steam Methane Reformer • Fuel storage & dispenser • Utility connections • AMF Retrofit	$2,800,000
General costs, including: • Environment and permitting • Project and construction management • Public outreach campaign	$3,200,000
Unallocated contingencies (20% of total)	$5,600,000
TOTAL – HFC hybrid and steam methane reforming option	**$33,800,000**

Table 5.5: Capital Cost for Hydrogen Fuel Cell Hybrid ZEMU with Hydrogen Delivery

Item	Cost
HFC hybrid ZEMU vehicle, including: • Modified base vehicle designed to accept and integrate a HFC hybrid powertrain • PEM FCS power assumed 400 kW • Hydrogen storage assumed 220 kg • LTO battery system assumed 140 kWh	$11,200,000
ZEMU vehicle non-recurring costs, including: • Project and engineering management / overhead • Engineering and design • Testing and commissioning • FRA process approval	$10,000,000
HFC hybrid ZEMU specific capital spares	$1,000,000
Hydrogen storage and dispensing infrastructure, including: • Fuel storage & dispenser • Utility connections • AMF Retrofit	$2,300,000
General costs, including: • Environment and permitting • Project and construction management • Public outreach campaign	$3,000,000
Unallocated contingencies (20% of total)	$5,500,000
TOTAL – HFC hybrid and hydrogen delivery option	**$33,000,000**

Cost for a 2-car HFC hybrid vehicle is $22.2 million and this cost does not change regardless of the hydrogen provision option. Overall, the highest capital cost is occurred with the on-site electrolysis option followed by on-site steam methane reforming while the cheapest is hydrogen delivery as a liquid.

8.1.2 Operational and Maintenance Cost

The on-going operation and maintenance costs associated with implementing a 2-car HFC hybrid ZEMU service are summarized in Table 5.6 to Table 5.8. These calculations assume that two 2-car trains are necessary for the proposed Arrow service. Operation costs are broken down by major components and estimated values are shown. As a point of comparison, the total annual estimated equivalent DMU vehicle for fuel, service and engine overhaul is $750,000 per year. Further details on these items were provided in the accompanying report (MM et al., 2019).

Table 5.6: HFC Hybrid ZEMU Operating and Maintenance Costs for On-Site Electrolysis

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Hydrogen fuel costs, including: • Electricity and water supply (~$4.30 per kg) • Compression costs • Dispensing costs	1	Annual	$520,000	$520,000
FCS and battery replacement / overhaul – ZEMU	2 ZEMUs	7.5 years	$980,000	$196,000
Hydrogen tank replacement – ZEMU	2 ZEMUs	15 years	$180,000	$12,000
Infrastructure maintenance, including: • Production equipment • Storage equipment • AMF equipment	1	Annual	$60,000	$60,000
Hydrogen production and storage facility overhaul	1	15 years	$2,000,000	$68,000
TOTAL ANNUAL ex contingency – Electrolysis Option				**$856,000**

Table 5.7: HFC Hybrid ZEMU Operating and Maintenance Cost for On-Site Steam Methane Reforming

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Hydrogen fuel costs, including: • Natural Gas, electricity and water supply (~$1.77 per kg) • Compression costs • Dispensing costs	1	Annual	$220,000	$220,000
FCS and battery replacement / overhaul – ZEMU	2 ZEMUs	7.5 years	$980,000	$196,000
Hydrogen tank replacement – ZEMU	2 ZEMUs	15 years	$180,000	$12,000
Infrastructure maintenance, including: • Production equipment • Storage equipment • AMF equipment	1	Annual	$60,000	$60,000
Hydrogen production and storage facility overhaul	1	20 years	$1,500,000	$52,000
TOTAL ANNUAL ex contingency – Steam Methane Reforming Option				**$540,000**

Table 5.8: HFC Hybrid ZEMU Operating and Maintenance Costs for Hydrogen Delivery

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Hydrogen fuel costs, including: • Hydrogen supply (~$7.50 per kg) • On-site liquid and compressed storage • Compression costs • Dispensing costs	1	Annual	$890,000	$890,000
FCS and battery replacement / overhaul – ZEMU	2 ZEMUs	7.5 years	$980,000	$196,000
Hydrogen tank replacement – ZEMU	2 ZEMUs	15 years	$180,000	$12,000
Infrastructure maintenance, including: • Storage equipment • AMF equipment	1	Annual	$29,000	$29,000
Hydrogen storage facility overhaul	1	15 years	$810,000	$27,000
TOTAL ANNUAL ex contingency – Hydrogen Delivery Option				**$1,154,000**

The lowest cost is realized with on-site SMR, which is primarily due to the relatively low cost of natural gas. Electrolysis offers the cost in the middle, similar to the diesel option, while hydrogen delivery is the most expensive option, due to the high cost of hydrogen. Cost with electrolysis can potentially be reduced if an agreement with the electricity supplier can be reached, for example, where assistance with the management of the duck curve challenge could be offered through a responsive electrolyzer.

SBCTA is eligible to receive low carbon fuel standard (LCFS) credits by either owning the finished hydrogen fuel at the time the finished fuel is created or acquiring ownership of the finished hydrogen fuel if a contract is agreed upon between transferor and recipient (MM et al., 2019). The credits will be generated for each metric ton of CO_2 emissions reduced through the use of hydrogen, which can be sold for monetary value through CARB's credit Report and Credit Bank & Transfer System.

8.2 Feasibility of HFC Hybrid for the RPRP Corridor

A hydrogen solution is feasible for the corridor. A 2-car hydrogen hybrid option with sufficient hydrogen storage to allow daily refueling (~220kg on-board hydrogen storage) is recommended to most closely match the operation of the conventional diesel trains.

From a hydrogen supply perspective, electrolysis offers the highest emission reduction potential through utilization of renewable electricity generation. However, currently this is a costlier alternative but has the potential for significantly reduced hydrogen cost if an agreement with the local utility can be arranged, through assistance of managing the duck curve effect. In addition, operational cost for the HFC hybrid option with electrolysis are similar to the conventional diesel. On-site SMR offers attractive regulated emission, GHG, and energy reductions while also being a commercially attractive option due to the low natural gas price, and in the HFC hybrid option reduces operating cost significantly compared to the conventional diesel. In the future, emissions could be further reduced through utilization of renewable gas. Hydrogen delivery as a liquid is an option with slightly reduced capital expenditure compared to SMR but significantly higher operating cost, which are due to the higher cost of hydrogen. This option offers the flexibility of hydrogen provider choice and 100% renewable hydrogen is likely to be available in the 2020 to 2025 timeframe at similar cost to centrally produced SMR hydrogen.

All options require construction of facilities, most likely located close to the maintenance facility for the vehicles. The choice of hydrogen production will primarily depend on the objectives of SBCTA and associated ability to cover capital and operating expenses. Electrolysis is the option for the highest emission reduction, while on-site SMR offers attractive operating costs and significant emission reductions, delivery would be the most flexible and least supplier dependent choice but has the highest hydrogen cost. To initially implement the technology, hydrogen delivery to a mobile refueling station would be an attractive option, due to the avoidance of significant infrastructure capital expenditure but this will be offset by a higher hydrogen cost, estimated at ~$10 to ~$20 per kilogram.

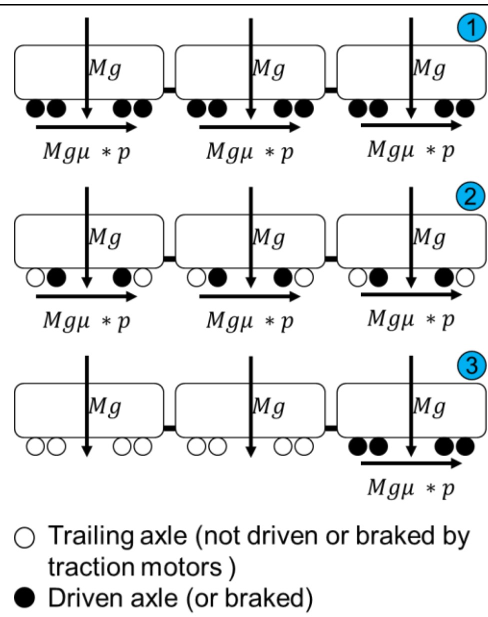
9 APPLICATION OF HYDRAIL MULTIPLE UNITS TO CALIFORNIA

The majority of railway services in California and the U.S. are provided by locomotive-hauled trains. All freight trains in the U.S., as far as the authors are aware of, are operated with locomotives. Passenger railways have more variety and multiple unit (MU) trains are popular for several applications, including rapid transit systems, such as BART, subway systems, such as the Los Angeles Metro subway, and in some commuter rail applications, such as the METRA electric district in Chicago, and soon Caltrain in the Bay Area.

9.1 Background to Multiple Unit Trains

MU trains are particularly useful if high acceleration rates are necessary, e.g., operating short headways such as a train every five minutes or more frequent, very large amounts of power are needed such as in very high speed trains operating at 200mph or higher, or relatively short train consists are operated, such as in the case with SBCTA's Arrow service. In MU trains, passenger space is available in the cars that also have traction equipment, whereas in locomotive-hauled trains all the equipment necessary for traction is concentrated in the locomotive and no space for passengers is present. The traction equipment necessary for motive power is distributed throughout the MU train, leading to many powered axels per train compared to typical locomotive-hauled trains. This has an impact on the traction and acceleration characteristics of the train, as illustrated in the theoretical examples in Table 9-1.

Table 9-1: Traction Characteristics of Multiple Unit Trains



Maximum possible acceleration or deceleration before wheels spin or slide:		
$a = g\mu p$		
Example:		
1	2	3
$g = 10\frac{m}{s^2}$ $\mu = 20\%$ $p = 1\ (100\%)$ $a = 2m/s^2$	$g = 10\frac{m}{s^2}$ $\mu = 20\%$ $p = 0.5\ (50\%)$ $a = 1m/s^2$	$g = 10\frac{m}{s^2}$ $\mu = 20\%$ $p = 1\ (100\%)$ $a = 2m/s^2$
Maximum possible tractive effort:		
$TE = Mg\mu p$		
Example:		
1	2	3
$M = 300'000\ kg$ $g = 10\frac{m}{s^2}$ $\mu = 20\%$ $p = 1\ (100\%)$ $TE = 600'000\ N$	$M = 300'000\ kg$ $g = 10\frac{m}{s^2}$ $\mu = 20\%$ $p = 0.5\ (50\%)$ $TE = 300'000\ N$	$M = 100'000\ kg$ $g = 10\frac{m}{s^2}$ $\mu = 20\%$ $p = 1\ (100\%)$ $TE = 200'000\ N$

Where:
a = acceleration
g = acceleration due to gravity
M = mass
μ = coefficient of adhesion between the rail and wheels
p = proportion of powered axles
TE = tractive effort

In Table 9-1, case 1 represents a MU train where all axels are powered, case 2 a MU train where 50% of the axles are powered, and case 3 a locomotive-hauled. In the examples, all vehicles are assumed to have the same weight. As can be seen, case 1 and 2 have the same maximum possible acceleration, i.e., before the wheels begin to spin, while case 2 has half of the maximum acceleration. However, the maximum tractive effort is the highest for case 1, followed by case 2, and the lowest is in case 3. Tractive effort is directly related to hauling ability of a motive power vehicle, which is the reason that locomotives are typically heavy, enabling haulage of long, heavy trains. This is often not a requirement for a MU so they can be constructed lighter. Tractive effort can also be a limiting factor for train acceleration, particularly when the resistance to motion is high, such as on lines with high grades. Traction equipment, such as motors and motor controllers, are expensive. All these characteristics, among others, result in the current preference for locomotive-hauled consist for freight operation while MU trains are preferred for high acceleration and maximum speed requirements such as in some passenger train applications. However, HFC technology could be applied to both technologies, and locomotive-hauled options are explored in section 11. HFC technology can be challenging for some MU applications as a significant volume for hydrogen storage is required and limited space is available in the cars without impacting the passenger salon. Therefore, the technology would present challenges for services that require high power and subsequent energy, such as very high-speed trains, and lines where space comes at a premium, such as subway systems.

Combinations, between MU and locomotive-hauled arrangements, such as the Stadler FLIRT vehicle platform, where a power module is employed for power generations but the traction motors are installed on the passenger coaches, could possibly overcome the volume challenge for several applications, such as regional trains and commuter operation where MU's would be preferred due to acceleration requirements.

9.2 DMU's in California

Currently, there are a few railway services that are provided with DMU trains in California, while many others are operated with locomotives. Most of MU's are powered with wayside electrification, such as LA metro and BART, and these are not considered in this section as they are already zero-emission at the point-of-use. DMU services that the authors are aware of in California are:

- East Contra Costa County BART extension (eBART)
- Sonoma–Marin Area Rail Transit (SMART)
- North County Transit District Sprinter (SPRINTER)

These systems have been considered in this and the following section 10 as they all have potential to be converted to hydrogen operation, more detail on the characteristics of these is provided in the next section 10.

9.3 Energy Consumption and Emission Impacts for MU Systems in California

Fuel consumption data for these systems was not available, so it was estimated based on the available timetable and simulated energy consumption for the Arrow service. Corresponding emissions, were calculated with the same method as for the Arrow service, based on the simulated annual energy consumption for all of the services. In Table 9-2 the estimate annual energy consumption for operation and point-of-use GHG and regulated emissions are presented. The zero-emission characteristics of the hydrogen options is apparent.

Table 9-2: Annual Estimated Energy Consumption and Emissions for MU Service in California from Operations

		Diesel	Hydrogen Fuel Cell	Hydrogen Fuel Cell Hybrid
Engery	kWh	41979745	24365575	20732365
Regulated Emissions in grams	GHGs	11307753115	0	0
	NOx	141639608	0	0
	PM2.5	4028967	0	0
	PM10	4153574	0	0
	CO	23399231	0	0

Based on the estimated energy consumption and a lower heating value of 33kWh/kg for hydrogen, conversion of these three MU systems would result in an additional annual hydrogen demand of 738,351kg or approximately two tonnes per day for the HFC options and for the HFC hybrid option 628,253kg annually or approximately 1.7 tonnes per day. The estimate displacement of diesel would be approximately one million gallons annually. It is likely that this amount of hydrogen demand could be provided by the existing central SMR facilities and delivered to the railways. This amount is sufficiently high to encourage renewable hydrogen production facilities, ideally if the railway services would be located in similar geographic areas. This would be the case for eBART and SMART in the Bay Area and for SPRINT and SBCTA in southern California (SBCTA was not considered in the provided numbers, so the Arrow service hydrogen demand would be in addition).

The energy supply chain for these MU services has subsequently been considered and the same three possible hydrogen production pathways as for the Arrow service were analyzed. In Table 9-3, the estimated annual energy consumption and corresponding emissions are presented.

Table 9-3: Annual Estimated WTW Energy and Emissions for MU services in California

		Diesel	Hydrogen Fuel Cell				Hydrogen Fuel Cell Hybrid			
			SMR H_2 Liquid Delivery	On-Site SMR	Electrolysis CA Mix	Electrolysis 100% Renewable	SMR H2 Liquid Delivery	On-Site SMR	Electrolysis CA Mix	Electrolysis 100% Renewable
Energy	kWh	50251330	53442211	42452129	66304332	42301345	45473313	36121989	56417533	35993689
	GHGs	13699259518	10975182576	9284430790	10989922862	0	9338646476	7900006790	9351188802	0
Regulated Emissions in grams	NOx	145756177	5647303	6102116	8501267	0	4805220	5192215	7233623	0
	PM2.5	4257004	331483	205113	486997	0	282055	174528	414380	0
	PM10	4423567	467629	254969	993053	0	397899	216950	844977	0
	CO	25371710	4088999	4773398	6765358	0	3479278	4061625	5756559	0

From Table 9-3, the superior performance of 100% renewable hydrogen compared to all other options is apparent and would be the preferred option for hydrogen generation.

Given the grid management difficulties resulting from additional solar power, i.e., the duck curve see section 2, an electrolyzer installation that would provide hydrogen to the respective two railways service, either in the north or south of California, could be an attractive proposition, fully decarbonizing these railway services.

More detail for the individual services is provided in the next section 10.

9.4 Hydrogen Safety

A report published by the Federal Transit Administration (Raj, 1997), classified hydrogen as a fuel for transit to have a safety advantage over conventional fuels, therefore with appropriate implementation, MU railway systems could potentially become safer. Hydrogen characteristics and safety implications have been covered in section 6 and the accompanying report (MM et al., 2019) for the Arrow service. Generally, these do not change when applied to other systems but specific consideration to the local case, such as refueling sites and maintenance facilities, would have to be considered on an individual basis. Any implementation of a hydrogen rail solution would provide a reference and learning case for other systems, and it is anticipated that the first adopter will be able to provide assistance to other early adopters, similar as in the bus case, for example SunLine. From a risk and safety perspective, implementation of hydrogen trains on several systems could provide benefits in terms of standardization, regulatory approval, and safety management systems. It would also be likely that the cost to an individual agency would be lower, as the same or very similar procedures could apply to all systems involved. If an individual agency decides to be the first adopter, e.g., SBCTA, it would be sensible to incorporate processes that could be adopted by others who may wish to transition to hydrogen-powered trains.

10 VALUE PROPOSITION FOR REGIONAL HYDRAIL MULTIPLE-UNITS IN CALIFORNIA

There are a few other DMU systems in California that could be good candidates for hydrogen-powered trains (hydrail). Initial estimates show similar requirements to the vehicles that the SBCTA is seeking to procure, more detail is provided in this section. First, some details about each route and operation is provided, followed by energy emission impacts for each system.

10.1.1eBART

The Bay Area Rapid Transit extension between Pittsburg Bay Point, CA and Antioch, CA often referred to as eBART, covers the 10-mile corridor between the termini, with an additional station, Pittsburg Center, between these endpoints, see Figure 10-1 for an illustration. BART procured eight GTW DMU's from Stadler for this service, see Figure 10-2, which began operations in May 2018. Each eBART vehicle contains two passenger coaches with a power module between them, similar to the Arrow DMUs but without articulation. The service runs approximately every 15 minutes and its Pittsburg station is located approximately 17 miles from a Martinez-based site of merchant hydrogen production.

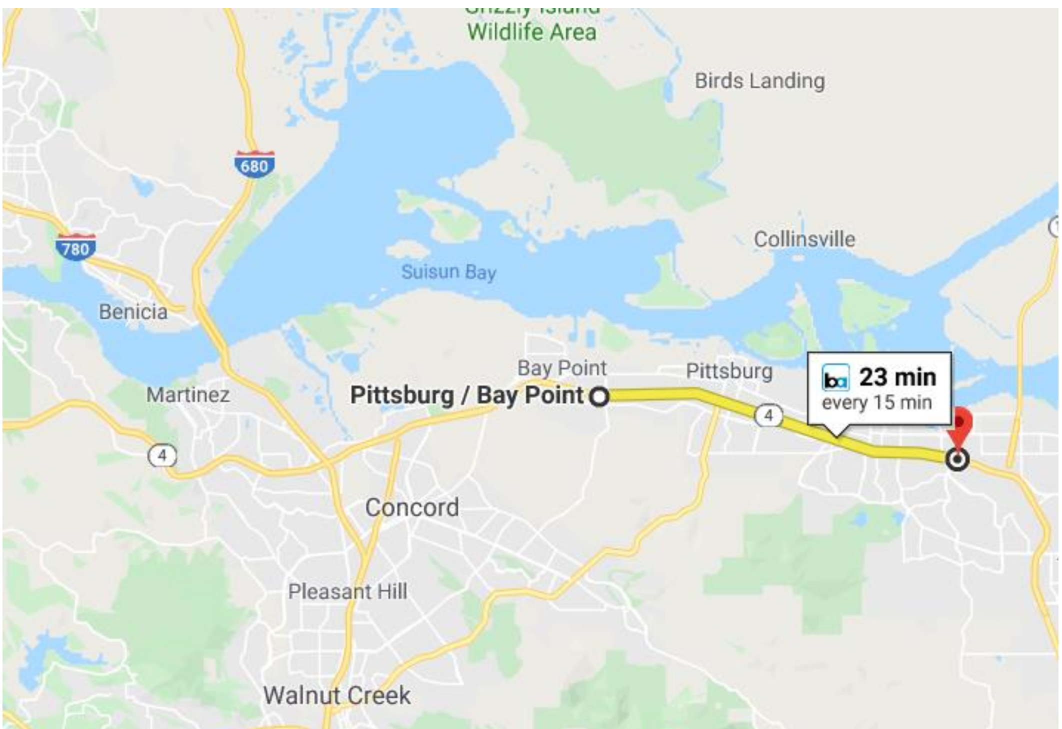


Figure 10-1: eBART Route
(Google Maps, 2019)

Figure 10-2: GTW Employed on eBART
(Wikipedia eBART, 2018)

10.1.2 SMART

The Sonoma-Marin Area Rail Transit (SMART) system offers 17 round trips a day on weekdays and five round trips per day on weekends. The route currently consists of ten stations between San Rafael, CA and the Sonoma County Airport, CA, see Figure 10-3, with another six planned, including one scheduled opening in Larkspur in December 2019. With the planned additions, the current 43-mile route would become a 70-mile route. As of mid-2019, SMART operates 14 2-car DMUs, see Figure 10-4 for an illustration, with four more on order. Service levels are variable and similar to planned SBCTA operations. The service is about 12 miles from a site of merchant hydrogen production, based in Richmond.

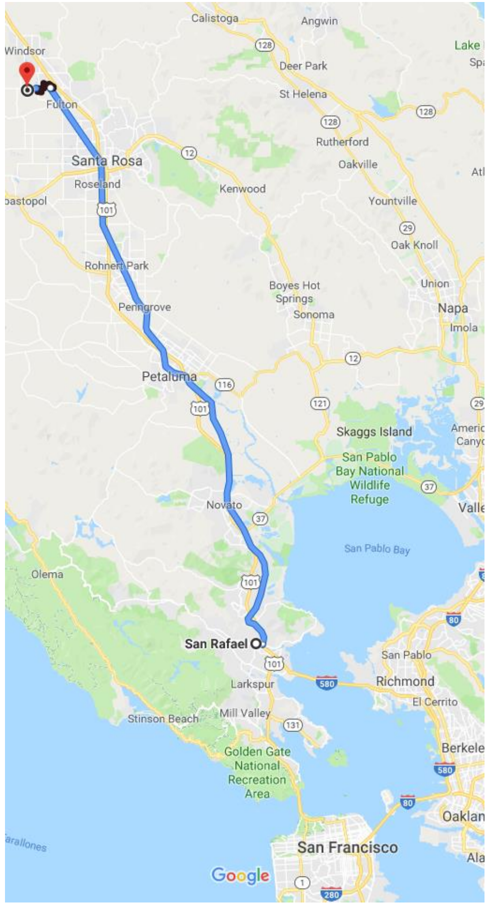


Figure 10-3: SMART Route
(Google Maps, 2019)

Figure 10-4: SMART DMU
(Perkins, rail-guru.com, 2017)

10.1.3 SPRINTER

North County Transit District's Sprinter (SPRINTER) service operates along a 22-mile corridor from Oceanside, CA to Escondido, CA, see Figure 10-5. The service currently utilizes 12 DMUs, with a top speed of 50 mph, stopping at 15 stations; Figure 10-6 depicts the train. Operating over 30 roundtrips a day on weekdays (with a slightly modified service on weekends), in FY 2018, SPRINTER service served 2.5 million riders. There are several merchant hydrogen suppliers within approximately 80 miles of SPRINTER operations in the greater Los Angeles area.

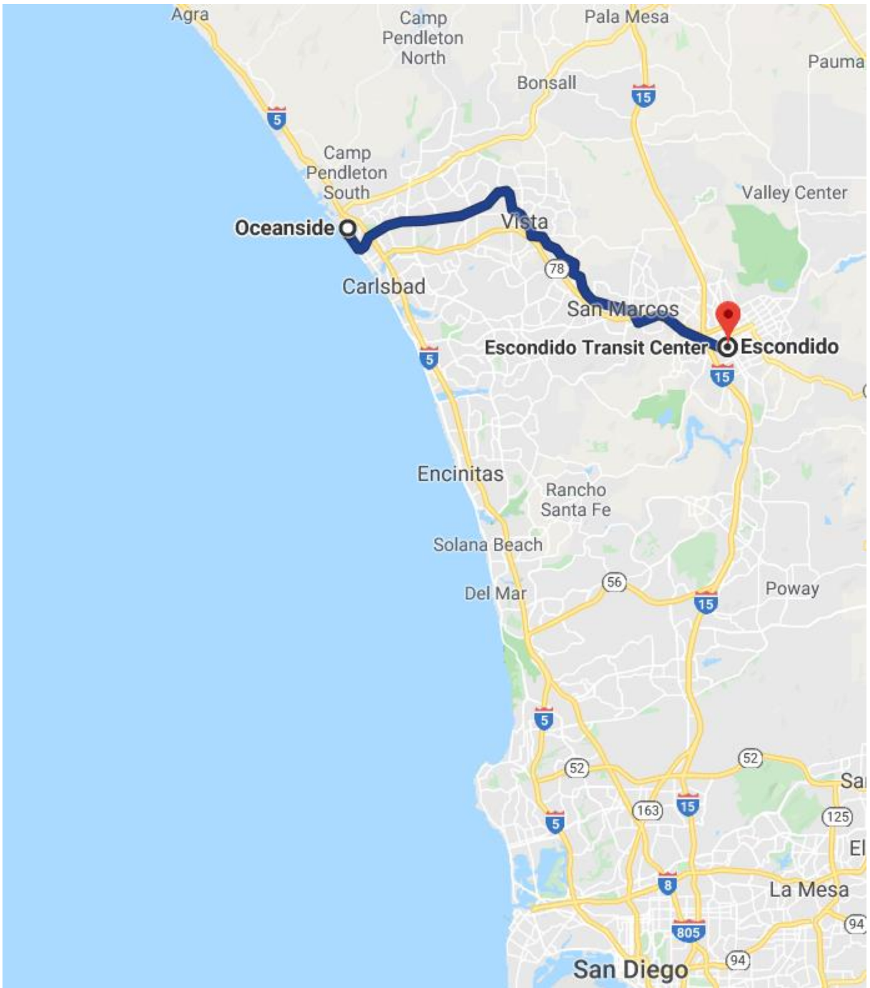


Figure 10-5: SPRINTER Route
(Google Maps, 2019)

Figure 10-6: SPRINTER DMU
(Vincent, rrpictureachrives.net, 2007)

10.1.4 Energy and Emission Reductions for MU Systems in California

In this subsection, the estimated energy and emission impacts for the three MU systems are presented. Energy consumption data for the systems was not available, so these were estimated with the following method: The daily miles and corresponding energy consumption for one vehicle on the Arrow service was determined. Average daily miles for the MU services was estimated based on the publicly available schedules and the ratio to the Arrow service calculated. This ratio was then applied to the energy consumption for the various powertrain configurations. Emissions where subsequently determined with the GREET model, same as for the SBCTA cases. It was assumed that all MU systems would be Tier 4 compliant. However, it is likely that the SPRINTER complies with Tier 2 emission standards, so air quality impacting emission results are conservative for that particular case. The relative reductions from operations, illustrated in Figure 10-7, and on well-to-wheel basis, illustrated in Figure 10-8, follow same pattern as for the Arrow service due to the methodology employed; nevertheless these will be approximately accurate as the vehicles employed on the routes have similar characteristics to the Arrow trains.

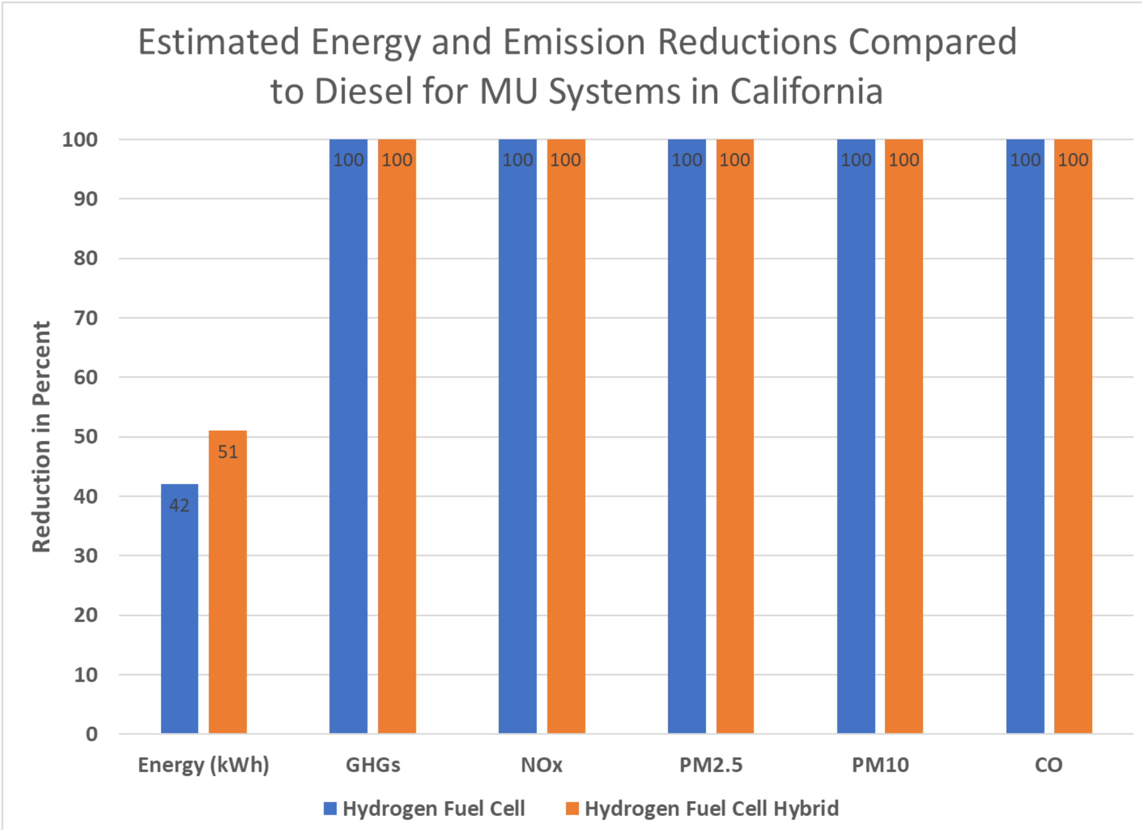


Figure 10-7: Estimated Energy and Emission Reductions Compared to Diesel for MU Systems in California

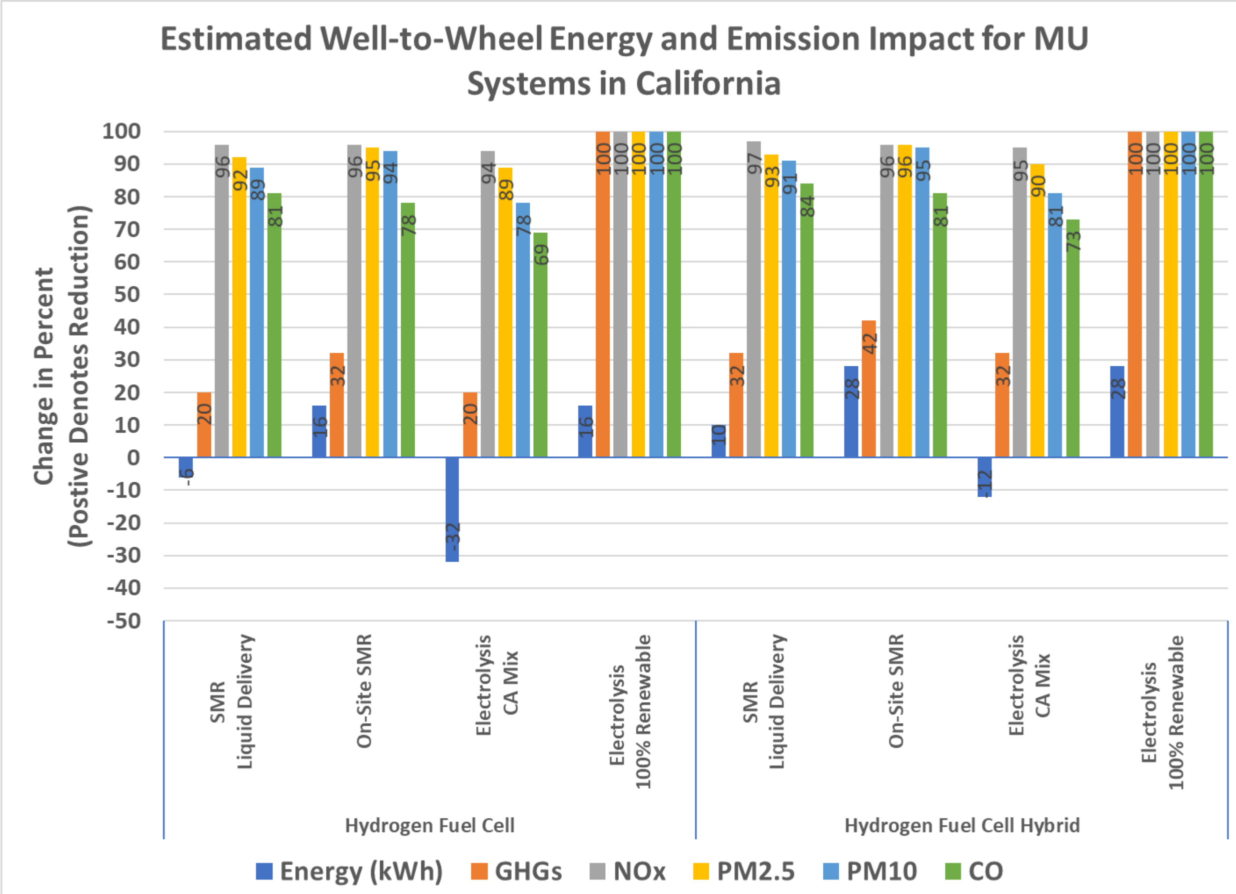


Figure 10-8: Estimated Well-to-Wheel Energy and Emission Impact for MU Systems in California

In Table 10-1, the estimated annual energy consumption and emissions resulting from operations for the three MU systems are presented. In Table 10-2, the estimated annual energy consumption and emissions on a well-to-wheel basis for the three MU systems are presented. As anticipated, the hydrogen options provide zero-emissions at the point of use with substantial energy reductions and are attractive from an emissions perspective for all evaluated hydrogen production cases and for some from an energy perspective.

Table 10-1: Estimated Annual Energy Consumption and Emission for the MU Systems in California From Operations

System			Diesel	Hydrogen Fuel Cell	Hydrogen Fuel Cell Hybrid
eBART	Energy	kWh	11994265	6961645	5923585
	Regulated Emissions in grams	GHGs	3230800650	0	0
		NOx	40468635	0	0
		PM2.5	1151138	0	0
		PM10	1186741	0	0
		CO	5637403	0	0
SMART	Energy	kWh	18490900	10732460	9131935
	Regulated Emissions in grams	GHGs	4980748027	0	0
		NOx	62388274	0	0
		PM2.5	1774647	0	0
		PM10	1829533	0	0
		CO	8690875	0	0
SPRINTER	Energy	kWh	11494580	6671470	5676845
	Regulated Emissions in grams	GHGs	3096204439	0	0
		NOx	38782699	0	0
		PM2.5	1103182	0	0
		PM10	1137301	0	0
		CO	9070953	0	0

Table 10-2: Estimate Annual WTW Energy Consumption and Emissions for MU Systems in California

System			Diesel	Hydrogen Fuel Cell				Hydrogen Fuel Cell Hybrid			
				SMR H_2 Liquid Delivery	On-Site SMR	Electrolysis CA Mix	Electrolysis 100% Renewable	SMR H2 Liquid Delivery	On-Site SMR	Electrolysis CA Mix	Electrolysis 100% Renewable
eBART	Energy	kWh	14357585	15269317	12129271	18944237	12086189	12992490	10320659	16119437	10284002
		GHGs	3914091164	3135789937	2652714380	3140001479	0	2668208195	2257164666	2671791748	0
	Regulated Emissions in grams	NOx	41644803	1613527	1743475	2428952	0	1372932	1483503	2066768	0
		PM2.5	1216292	94710	58604	139143	0	80588	49866	118395	0
		PM10	1263882	133609	72849	283732	0	113687	61986	241424	0
		CO	6200971	1168294	1363838	1932974	0	994088	1160475	1644746	0
SMART	Energy	kWh	22134301	23540031	18699160	29205492	18632743	20029521	15910566	24850095	15854054
		GHGs	6034139507	4834308568	4089572361	4840801316	0	4113371176	3479697010	4118895664	0
	Regulated Emissions in grams	NOx	64201507	2487503	2687838	3744607	0	2116544	2287002	3186176	0
		PM2.5	1875091	146010	90348	214511	0	124236	76874	182521	0
		PM10	1948457	205979	112308	437416	0	175262	95560	372185	0
		CO	9559697	1801107	2102569	2979981	0	1532509	1789014	2535578	0
SPRINTER	Energy	kWh	13759444	14632862	11623699	18154604	11582413	12451303	9890764	15448001	9855634
		GHGs	3751028847	3005084070	2542144049	3009120067	0	2557067105	2163145114	2560501390	0
	Regulated Emissions in grams	NOx	39909867	1546272	1670803	2327708	0	1315744	1421709	1980679	0
		PM2.5	1165621	90762	56161	133343	0	77231	47789	113464	0
		PM10	1211228	128040	69812	271905	0	108951	59404	231368	0
		CO	9611043	1119597	1306991	1852404	0	952681	1112136	1576236	0

10.1.5 SBCTA – LAUS Route

In addition to the Arrow service from SBTC to Redlands, SBCTA is also considering extension of their service to LAUS as already described. A more detailed analysis for this case has been performed, compared to the other MU services, and the results were already provided in section 5 and throughout this document. A 2-car and 4-car consist where simulated across the route and detailed simulation results are provided in Appendix 14.2 Simulation Results with Corresponding Emissions. HFC hybrids perform more favorable compared to the non-hybrid versions. The primary challenge will be accommodation of sufficient hydrogen on-board of the train to meet operation expectations. However, if an additional power module were to be employed than the on-board hydrogen requirement could be likely met. Alternatively, a longer power module car, possible with powered axles and a driver's cab, in that case effectively a locomotive could be employed. To obtain the favorable characteristic of a MU several of the other axles of the train could be powered.

10.1.6 Value Proposition

All three MU systems operate with similar vehicles as the proposed Arrow service and are in principle suitable to be operated with HFC options. Hybrids would be the preferable choice for all of them. Sizeable energy reductions are achieved from operations in addition to zero-emission operation. The costs of the various hydrogen systems are detailed in section 8 and can be considered indicative for the other MU systems. In general, the longer the route, the more suitable a hydrogen option is compared to a battery-only solution, so SMART and SPRINTER appear to be promising candidates. A zero-emission option for eBART could possibly be realized with a battery-only solution where charging at the termini would occur. The rationale is the similar length to the Arrow service and the accompanying report (MM et al., 2019) has established feasibility for such a short route. However, if extensions are planned, similar to the SBCTA LAUS case, then hydrogen would be more suitable.

From a cost perspective, a combined order of several trains for various agencies could lead to a more economical implementation across the state but would likely involve a more complex administration of funds and project management.

11 DIESEL-HYBRID AND HYDRAIL FEASIBILITY FOR RAILWAY PROPULSION IN CALIFORNIA

The previous sections in this report have focused on MU for regional train applications. There are several other types of trains that are operated in California, and the suitability of a hydrail powertrain for these is assessed from a high-level perspective in this section. No STS has been conducted and the assessment is based on the characteristics of the various train configurations.

11.1 Introduction to Hybridization

Railway motive power vehicles employ electric traction motors to provide power to the wheels to move the vehicle itself and the associated train. These traction motors, can provide a braking force while acting as generators, called dynamic braking, with the resulting electricity traditionally dissipated in the resistors as heat. With addition of an energy storage device, such as batteries part or all of this electricity can be captured and re-used for auxiliaries and traction power in the next acceleration or cruising phase. In addition, the powerplant can charge the batteries when not all generated power is required for traction. The concept is illustrated in Figure 11-1, where the red arrows show traction power flows and the green arrows braking power flows.

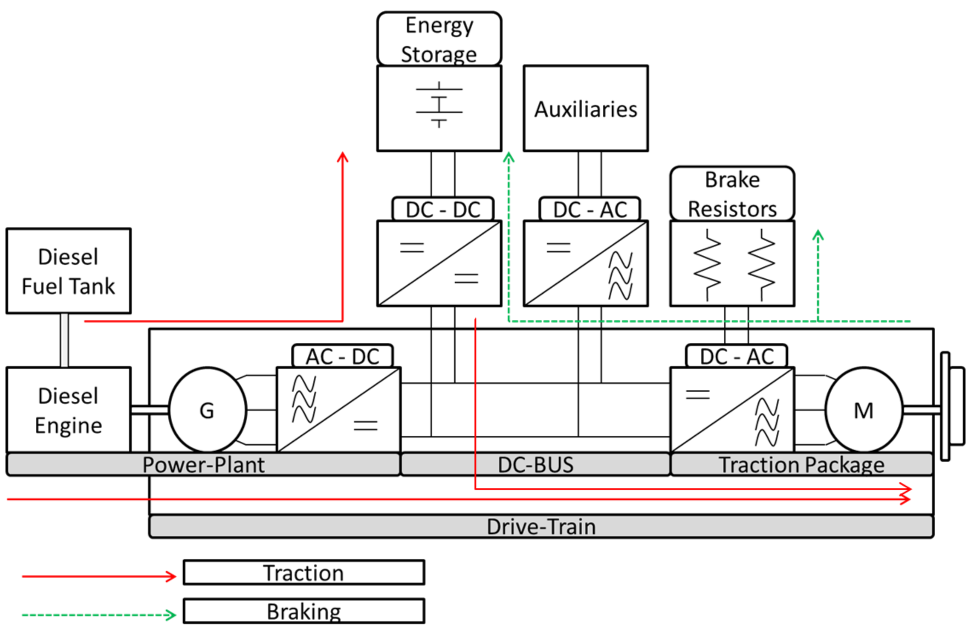


Figure 11-1: Block Diagram of a Diesel-Hybrid Powertrain (Hoffrichter, 2019)

The potential energy reduction that can be achieved through hybridization is directly dependent of the frequency and length of braking requirements. First, frequency is considered. In Figure 11-2, the impact of speed and stopping frequency on the hybridization potential is illustrated.

The x-axis shows speed in meters per second (m/s), the y-axis the distance between stops in kilometers (km), and the z-axis the hybridization potential, defined as the ratio of barking energy to traction energy at the wheels.

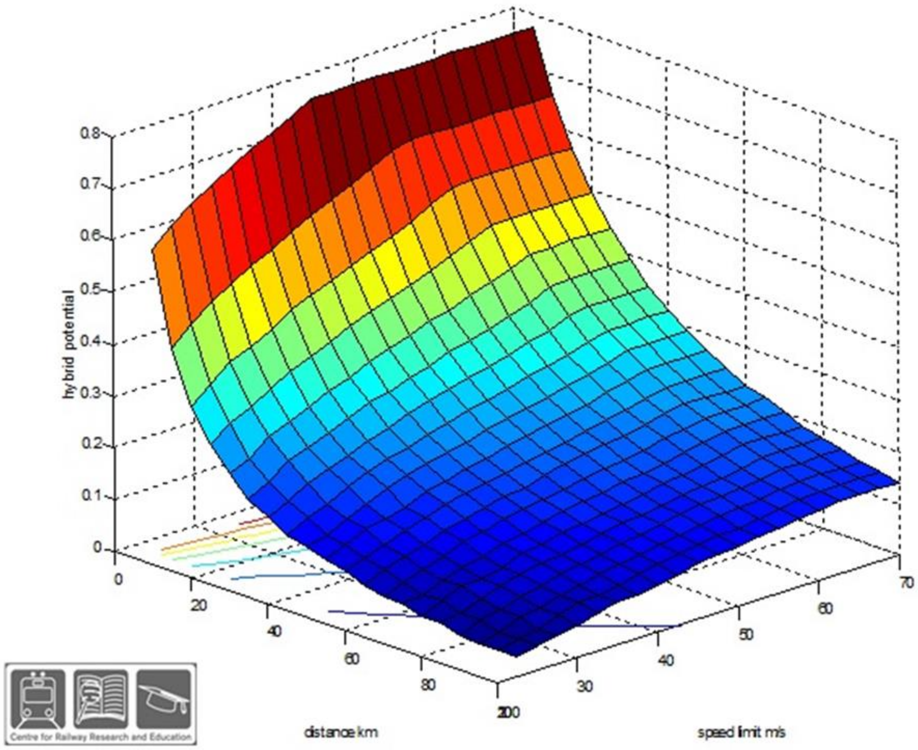


Figure 11-2: Hybridization Potential Related to Stop Frequency and Speed (Lu et al., 2008)

As can be seen from Figure 11-2, the speed of the train has a significantly lower impact compared to the stop frequency. Therefore, energy savings due to hybridization may justify the additional investment in energy storage devices if trains stop frequently, such as commuter and regional trains. The suitability for the latter has been demonstrated in the previous sections of this report. The difficulty with these installations is typically the rate of power that is provided to the energy storage systems due to the required braking rates. Battery chemistries with high C rates, such as LTO, are well-suited for such applications.

The other instance where long periods of braking occur, is on routes that have significant elevation changes. In this case, the relatively long, sustained braking application results in sizeable quantities of energy. An example of potential to utilize that braking energy is currently being explored by BNSF through the creation of a hybrid consist with the aid of a battery locomotive (BNSF Railway, 2019). The difficulty in these situations is the provision of a suitably large on-board energy storage system to recover the maximum practical amount of energy. In wayside electrified systems, often the braking energy is returned to the conductor wire for use of another uphill travelling train on the route.

The last primary instance where hybridization can offer potential benefits is where the average power demand is substantially different to the maximum power demand. In this case, the powerplant can be downsized from a power perspective with potential energy and emission benefits due to operation in a more efficient region, for example for diesel engines, and reduction of capital cost for the powerplant which may be beneficial if energy storage devices come at comparatively lower cost, such as in the HFC case, currently.

11.2 Switcher and Road-Switcher Services

Switcher locomotives operate in yards and assemble trains for longer-distance routes, for example, a switcher in a Los Angeles yard, would assemble trains from individual long-distance train destinations such as Chicago, New Orleans, or Phoenix. An example of a pair of switcher locomotive is depicted in Figure 11-3.

Figure 11-3: Switcher Locomotives in a Yard in Vancouver, BC (Hoffrichter, 2019)

Typically, switchers travel at relatively low speed as distances are not far and maximum speed limits in yards are low. The power demand for switchers is low compared to mainline locomotives but they have high demands for tractive effort. Most switchers have a maximum power of less than 1,500kW (2000HP) and many were used as line-haul locomotives in the past, therefore, the majority of switcher locomotives are more than 25 years old (Humphrey, 2019), i.e., Tier 0. There is significant potential to reduce emissions through upgrades to Tier 4 or better standards. It is very likely, that the most cost-effective way to achieve this is through retrofitting or rebuilding of the existing switcher fleet.

The operational reality for switchers, means that they remain idle for the majority of the duty cycle. A representative duty cycle for switcher locomotives is presented in Table 11-1, and the corresponding indicative power per notch is presented in Table 11-2.

Table 11-1: EPA Switcher Duty Cycle Data
(Isaac, 2019)

Notch	Idle	1	2	3	4	5	6	7	8
Percent of time	59.8	12.4	12.3	5.8	3.6	3.6	1.5	0.2	0.8

Table 11-2: Indicative Power for Switchers per Notch
(Isaac, 2019)

Notch	Idle	1	2	3	4	5	6	7	8
Power in kW	12.0	150	258.3	462.7	627.3	768.7	1034.7	1248.3	1402.7

There is some potential for regenerative braking due to the frequent stopping pattern, but the impact is limited resulting for the very low speed. Hybridization for switchers may be useful due to downsizing considerations for the powerplant.

Road-switchers are slightly more powerful locomotives that are utilized to make final delivery of cars to customers, typically within a relatively close vicinity of a yard. They operate at a somewhat higher speed than switchers but often not at the maximum allowable line speed limit. Sometimes, the same locomotives that are used for switching are also used for road-switching. Many shortline operations fall within this category. No data was available for road-switcher applications, but they are somewhere between line-haul and switcher operations, typically closer to switcher duty cycles.

Switchers and Road-Switchers tend to operate in a defined geographic area and frequently return to the same points on the network, e.g., assigned yard. This is an advantage for introducing hydrogen (or any alternative fuel) as refueling infrastructure and maintenance facilities do not have to be constructed all across the country, reducing implementation cost and significantly improving feasibility from an operational perspective.

In Figure 11-4, the impact of the different Tier standards on emissions from switchers is illustrated. In Figure 11-5, the WTW impact of the progressively stricter Tier standards along with hybridization of diesel switchers is illustrated. The benchmark relates to data measure and published by Hedrick, Fritz, and Plunkett (2012), while hybrid refers to addition of energy storage to the existing diesel engine, downsized to the lowest practical maximum power of a diesel engine, and ideal to a slightly higher power engine operating at its most efficient point.

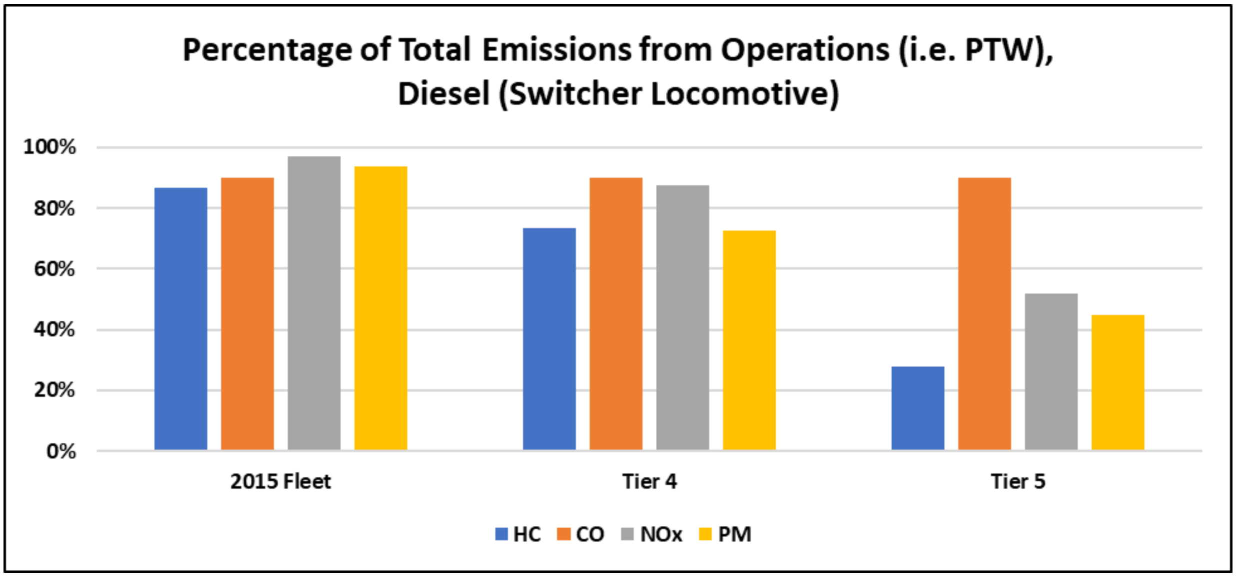


Figure 11-4: Percentage of Emissions for Various Tier Standards for Switcher Locomotives (Isaac, 2019)

In can be seen that the Tier standards affect air-quality impacting emissions, but these are not reduced to zero.

From Figure 11-5, it can be seen that many emissions are significantly reduced through hybridization compared to the benchmark, however zero-emissions are not achieved, and there is no potential to achieve zero-emissions due diesel being the primary fuel.

In Figure 11-6, the impact of different powertrain options, including hydrogen fuel cells and hybrids, as well as various hydrogen production pathways are illustrated.

In addition to being zero-emissions at the point-of-use, significantly surpassing even the proposed Tier 5 standards, it can be seen from Figure 11-6 that many hydrogen and hydrogen hybrid options would lead to further emissions reductions compared to Tier 5 diesel options. Zero-emissions WTW are achievable with 100% renewable hydrogen, but even with SMR and liquid delivery, emission levels are significantly reduced compare to Tier 4 and Tier 5.

The power and subsequent energy requirements for switchers and road-switchers are relatively low, and conversion to HFC technology is technically feasible while realizing an acceptable range and refueling frequency, for this high-level analysis. Hybridization does not have a significant impact on emissions for the HFC switcher case, due to the highest efficiencies occurring for fuel cells at partial load, see Figure 2-13, however hybridization would probably still occur due to the current price advantage of batteries over HFC.

A hydrogen-hybrid switcher project as a proof-of-concept has shown general feasibility of the technology for this application (Hess et al., 2010), but demonstrator vehicles would be necessary and implementation would likely require government funding.

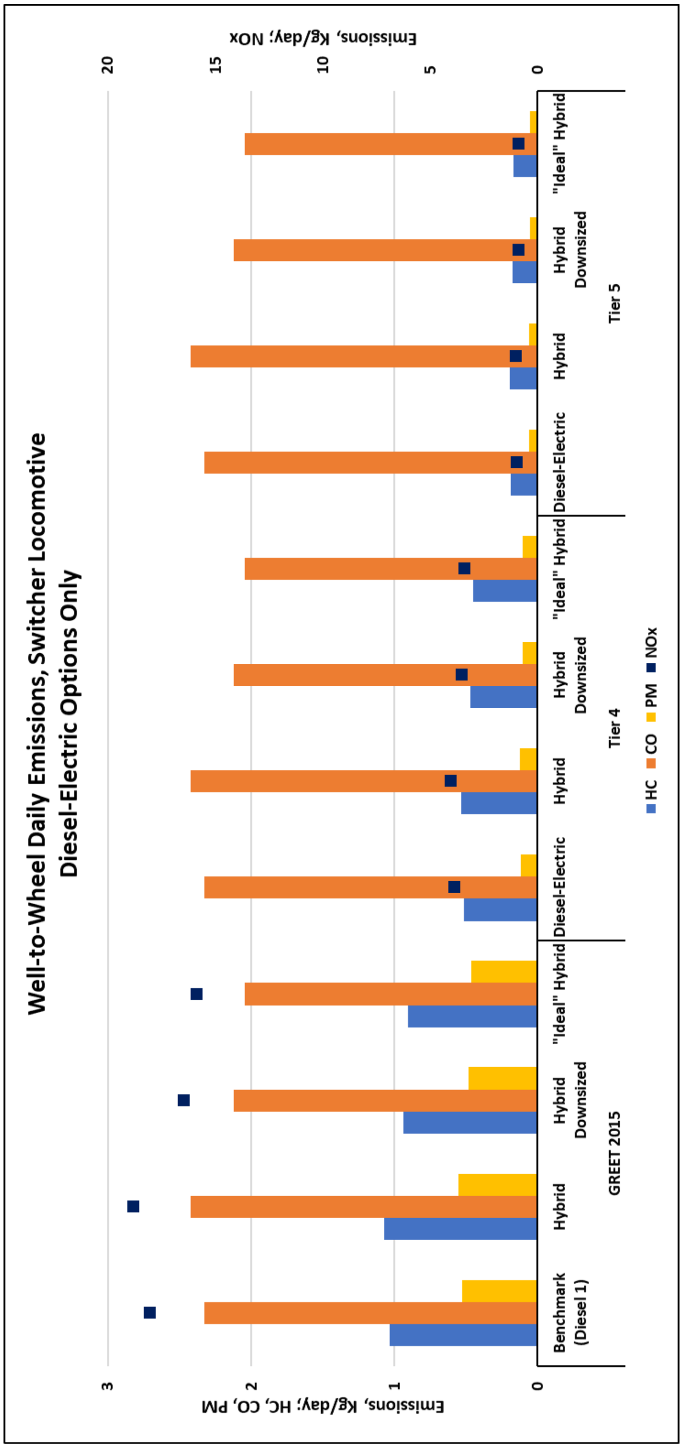


Figure 11-5: WTW Emissions for Diesel-Electric and Diesel-Hybrid Switchers for a 10 Hour Shift
(Isaac, 2019)

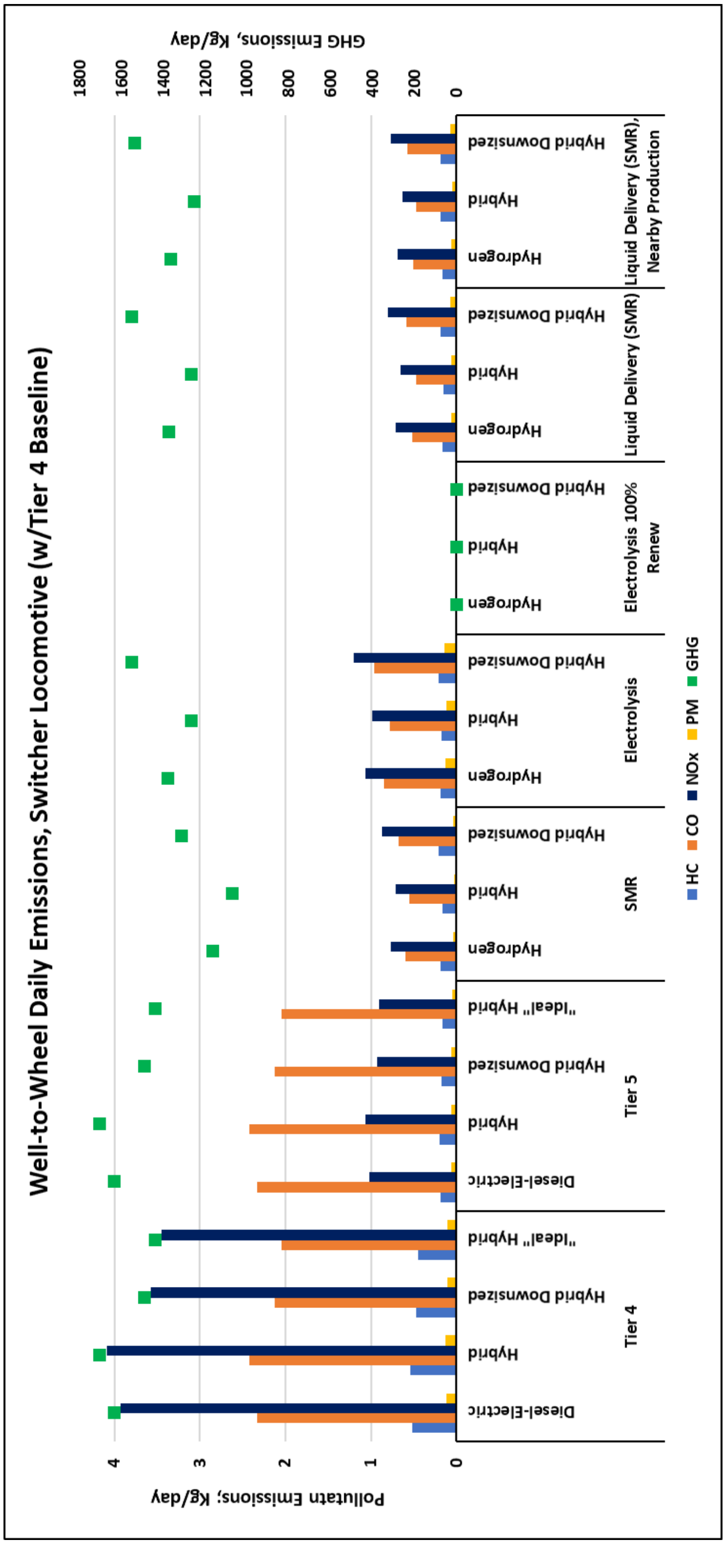


Figure 11-6: WTW Emissions for Various Switchers Including Hydrail Options for a 10 Hour Shift
(Isaac, 2019)

11.3 Light Rail and Streetcars

Most light rail and streetcar services are provided by MU trains. Often, they have lower power requirements than regional trains, stop more frequently, and cover shorter distances. Traditionally, these types of systems rely on wayside electrification, which requires significant capital investment in infrastructure. In general, HFC and HFC-hybrid technology is suitable for these applications, with hybrids likely out-performing the HFC only arrangement due to the duty cycle and high potential for regenerative braking. HFC-hybrid streetcars and light rail vehicles are commercially available from TIG/m and CRRE. Such vehicles are particularly useful if a new systems or line would be constructed as wayside electrification can be avoided while still providing a zero-emission option. For existing systems, where extensions are relatively short, a battery-only option might be more cost effective as it is likely that the wayside infrastructure could be utilized for charging with possible charging infrastructure added at certain stops, as described in the accompanying report (MM et al., 2019) and the example in Detroit mentioned in section 4.

11.4 Locomotive-Hauled Regional Trains

For the purposes of this report, the category includes systems that operate relatively frequent services, such as Metrolinks in the greater Los Angeles area, and systems such as Capitol Corridor and ACE. An example is illustrated in Figure 11-7.

Figure 11-7: Capitol Corridor Train
(Huddelston, Wiki Commons, 2011)

Commuter rail systems operate at relatively high speed and have a relatively frequent stopping pattern; therefore, they are typically well-suited for hybridization regardless of the primary powerplant choice, often achieving energy reductions in the 30% to 40% range, with a subsequent direct impact on emissions. Often the maximum power of such systems is similar to line-haul freight locomotives, at approximately 3.3MW (4,400 HP), which can be achieved with HFC due to the modular nature, similar to batteries, or a combination with HFC and batteries could provide the required power, having the benefit of lower energy consumption and likely lower implementation cost. The primary challenge, is hydrogen storage quantity due to the lower density compared to diesel, see Figure 2-9, which renders this option not practical for battery-only operation. While locomotives require higher power levels than MUs they also have additional space in which to place the equipment. Nonetheless, quite a significant re-design of the current locomotive layout would be required and, in some cases, it might even make sense to increase the height of the vehicle (to the maximum typically allowable loading gauge for such vehicles) so as to increase the available space. Again, rooftop space should be taken full advantage of for placement of hydrogen tanks, as necessary. A further option would be the addition of a tender car for hydrogen storage either with compressed gas or liquified hydrogen, similar to LNG vehicles, see Figure 3-1, to increase on-board energy storage. Alternatively, more frequent refueling than daily might be an option.

Results for a case study on the Capitol Corridor route determined with STS, have indicated feasibility for daily refueling without necessitating a tender car. A diesel-hybrid would reduce energy consumption by approximately 20%, while an HFC-hybrid locomotive-hauled train would reduce energy consumption from operations by up to 50%, with a hydrogen demand of approximately 300kg per roundtrip, while a downsized HFC-hybrid version would reduce energy consumption by approximately 38% with a roundtrip demand of approximately 380kg, and a WTW GHG emission reduction of approximately 40%. These results are indicative of similar services.

11.5 Long-Distance Locomotive-Hauled Trains

The most challenging conversion of service that are currently operated with diesel locomotive, are long-distance line-haul services, such as from Los Angeles to Chicago. These services are predominately provided by Class I freight railroads or Amtrak in the U.S. Long distance-type trains are depicted in Figure 11-8 and Figure 11-9.

Figure 11-8: Line-Haul Long-Distance Intermodal Train (Hoffrichter, 2016)

Figure 11-9: Amtrak Southwest Chief Long-Distance Passenger Train Locomotives (Hoffrichter, 2019

There is limited potential for hybridization as the trains do not stop frequently and the promising parts for hybridization, such as large elevation changes, are geographically constraint. A hybrid consist with a battery locomotive, such as under development by Wabtec and BNSF might offer a suitable option as the energy storage vehicle can be added for the elevation sections of the route increasing asset utilization, requiring fewer conversions of locomotives, and reducing total cost. In California, this could be useful for the mountainous sections of the state, such as leaving the Los Angeles basin or crossing the Sierra Nevada.

HFC can be applied from a power perspective due to their modularity, the primary technical challenge being accommodation of sufficient hydrogen on the vehicle. Early investigations have determined that a tender car would be required (Zenith et al., 2019) if locomotives could not be refueled along the route. However, in a California specific context it may be possible to redesign locomotives to operate within the state or crossing into a neighboring state without necessitating a tender car. A more detailed analysis would be required.

From an operational perspective, these services are challenging as locomotives frequently cross half the country and then may interchange with another railroad traversing the rest. In addition, locomotives often operated on various routes rather than on a fixed corridor. These characteristics would require addition of many refueling points throughout the U.S. in addition to suitable maintenance facilities. All these factors lead to high implementation cost. Therefore, it is recommended to begin introduction of a new technology in more geographically confined areas, such as regional MU systems, commuter rail, switchers, and road-switchers. Once a network of required facilities is established across a wider geographic region, change of line-haul locomotives would be easier. In case line-haul is a priority, it is suggested that specific corridors would be selected for implementation so that the new technology locomotives could be confined to that corridor, initially.

12 CONCLUSION

The purpose of the work presented in this report was to evaluate low- and zero-emission technologies that are suitable for railway applications, with emphasis on the MU Arrow service and possible extension to LAUS. Further, HFC technology and its application was to be investigated in more detail due to its zero-emission characteristics.

Feasibility was assessed through review of existing literature and heavy-duty HFC applications, STS of various powertrains along the RPRP and extension to LAUS, emission and energy modelling including possible hydrogen supply chains, a cost analysis, followed by broader possible MU and other railway applications in California.

12.1 Directly SBCTA Relevant Findings and Recommendations

While hydrogen technologies are not new to the transportation industry, it is relatively new to passenger rail. There is only one example of a regional train, similar to what would be required for the Arrow service, in revenue operation today (Coradia iLint in Germany), but there are several other projects under development in North America and Europe, and light rail/streetcar trains operate in China. The work presented in this report found that a zero-emission solution can be realized with a hydrogen-hybrid powertrain for both the initial 9-mile Arrow service and having the capability to expand to LAUS if desired with less significant additional investment compared to a battery-only train.

The tradeoffs with the hydrogen hybrid propulsion option is that it carries additional upfront capital cost and has uncertainties and risks around the technology, especially compared to a DMU implementation. Several hydrogen supply options were examined, with various characteristics and the preferred choice will depend on capital and operating cost as well as emission reduction potential. It is relatively likely that hydrogen would be delivered to SBCTA and dispensed via a mobile refueling station for initial implementation, if the agency decides to move forward with a hydrogen option.

While the upfront vehicle costs, when compared to a battery ZEMU, are not significant relative to the overall cost for the project, the initial operating costs will likely be more expensive than batteries, depending on the method by which SBCTA obtains its hydrogen. A commercially attractive option that would have lower operating cost than diesel is on-site SMR; it also offers substantial reductions in emissions, but this option does not allow for zero-emission well-to-wheel operation due to the utilization of low-cost natural gas. On-site electrolysis has similar operational cost to diesel, but more than SMR, while offering significant emission reductions with the possibility of a 100% zero-emission option well-to-wheel. SMR is better regarding cost while electrolysis has the potential to be much better from an environmental perspective.

Hydrogen as a transportation fuel is currently not readily available near the Arrow service but significant merchant hydrogen production occurs within the greater Los Angeles area. While there are plans to develop hydrogen production facilities by private companies, unless a new hydrogen production plant is included in the project, there is no certainty that the fuel will be available at a reasonable price.

As with all alternative fuels, there is a risk that the price to purchase hydrogen will remain expensive, ultimately resulting in significant operating cost to SBCTA for the life of the Arrow

Service operations. Based on the evaluation completed in this report, and should a hydrogen ZEMU vehicle be procured, it is likely recommended to operate the pilot project with a temporary hydrogen fueling station which would receive deliveries of hydrogen from an offsite production facility (there are a few in Southern California) with the intent to eventually construct a hydrogen production facility once the vehicle is approved to go into full passenger service operations (this temporary option to obtain approval is not a possibility with a battery train as the charging infrastructure has to be constructed for operation). Should a production facility not be able to be constructed, SBCTA should consider partnerships with 3rd party agencies who are producing or supplying hydrogen in the area in order to mitigate the risk of elevating hydrogen prices.

Another important risk to consider in the evaluation of this technology is the fact that few hydrogen railway vehicles are in operation and these projects are not within the United States. It is likely that the approval process for a hydrogen hybrid ZEMU will be more onerous as both the hydrogen propulsion system and the use of batteries on-board a passenger vehicle will need to be assessed. With that in mind, the FRA has been engaged to date on the advancement of this technology and has indicated that the approval process may be similar to that of natural gas.

The final consideration for SBCTA will be the reliability of the technology. Given there is limited data available on the operation of a hydrogen rail vehicle, the analyses completed in this report has had to rely on the assessment of the few vehicles considered, with the primary focus on the Alstom train as it most closely matches the requirements of the Arrow service. The ZEMU project has entered into a partnership with Stadler to procure the ZEMU vehicle, and therefore some uncertainty exists surrounding the timeline for the development of a hydrogen hybrid ZEMU, ability to convert the existing fleet to match this design and the reliability of this technology when placed into testing and operations.

One of the primary advantages of a hydrogen-hybrid solution is that the service can be expanded easily. The vehicles do not rely on frequent wayside infrastructure to recharge and could also provide service extension to LA Union Station. The primary required change would be additional hydrogen production to refuel more trains.

In conclusion, if there is a desire to extend the Arrow service beyond the planned 9-mile corridor, capital funding is available, and the additional risks as described above are acceptable, then the recommendation is to move forward with the hydrogen hybrid propulsion option.

12.2 Broader Assessment Relevant to California

HFC technology is feasible for MU applications and hybrids are preferable from an energy, emission, and cost perspective for these applications. The train that SBCTA may procure would be similar to vehicles needed that currently operate with DMUs in the state. Zero-emissions at the point-of-use are accompanied by energy reductions in operations, somewhat counteracting the higher hydrogen cost compared to diesel for some procurement pathways. If the three evaluated MU service were to be converted, daily hydrogen demand would be approximately two tonnes, sufficiently high to encourage investment in renewable hydrogen production facilities. SBCTA could be a demonstrator agency and knowledge gained from implementation is encouraged to be shared with other agency seeking to reduce or eliminate emissions.

Suitable railway services for hydrogen fuel cell technology are streetcars, light rail, regional MU’s, commuter on the passenger side and switcher, road-switcher, and shortline services on the freight side. Very high speed rail cannot be practically realized with current HFC technology due to high energy requirements and volumetric energy storage density of hydrogen. Line-haul, long-distance passenger and freight service could potentially be converted but technical, operational, and economical challenges exist most of these related to hydrogen storage requirements rather than to possible power provision from FCS. It is likely that a tender car would be required if refueling on the route is limited, refueling infrastructure would have to be established across the railway network and accompanying changes to maintenance facilities, both hindering easy interchange with other railroads. All these challenges can be overcome but implementation of other services is likely faster and more cost effective, and the know-how as well as facilities could then the expanded to enable long-distance services. If the intent is to operate with zero-emissions in California only, this could potentially be realized with HFC technology but with impact on national rail operations as locomotives would have to be exchanged before entering the state.

In general, HFC technology can already be applied to many railway services, eliminating harmful exhaust emissions, reducing energy consumption, and offering the potential for fully zero-emission energy supply chain. It is recommended that further research and investigation are conducted into potential applications followed by demonstrator projects. For MU services, a successful SBCTA implementation could lead the way for state-wide adoption and encourage exploration with possible implementation in other railway services. In addition, a HFC or HFC-hybrid railway implementation is likely to encourage scale-up of renewable hydrogen production and growth in other zero-emission transportation applications, such as buses, trucks, and private vehicles.

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14 APPENDICES

14.1 Alternative Propulsion Options

Case 1 – Alstom Coradia iLINT Regional Passenger Train (Germany)	
Sponsors: Alstom / the Lower Saxony Transport Provider (LNVG)	Year Introduced: 2018
Sector: Rail (passenger)	Technology: Hybrid hydrogen fuel cell traction
Description: The world’s first hydrogen fuel cell powered passenger train to enter service. Two are in daily service in northern Germany, with the full fleet of 14 trains to follow into service in 2021. The prototype has a top speed of 140km/h (approx. 90mph) and an operating range in excess of 800km. Key points to note: The design is based on a converted Diesel Multiple Unit (DMU) designed for operation on regional lines. It has fuel cells from Hydrogenics, and is a hybrid, using lithium based battery packs from Akasol with an MNC chemistry. Alstom are taking responsibility for the delivery of the trains and also the supply of hydrogen fuel. The trains are being introduced initially in areas where there is a local large-scale supply of hydrogen used for industrial purposes. It is understood that the production versions will have an operating range of 1000km (approx. 650 miles).	 Source: Wikipedia “Hydrail” page (2019)
https://en.wikipedia.org/wiki/Alstom_Coradia_LINT	

Case 2 – "Breeze" Regional Passenger Train Conversion (UK)	
Sponsors: Alstom / Eversholt Leasing	Year Introduced: 2022
Sector: Rail (passenger)	Technology: Hybrid hydrogen fuel cell traction
Description: A mid-life electric multiple unit (Class 321) that is being retro-fitted with hydrogen fuel cell traction intended for use in regional and branch line services in the UK. The train is intended to have a 600 mile range with a top speed of 90mph. The project is at the design stage, with a prototype expected on 2020/21. Key points to note: A proportion of the leading and trailing passenger salon is being used to accommodate the hydrogen tanks. This is likely to be driven (at least in part) by the restrictive loading gauge in the UK, which leaves insufficient space to accommodate storage tanks on the roof. The conversion will draw upon the experience that Alstom has gained through the development of the iLint multiple unit.	 Source: Alstom website 2019
https://www.telegraph.co.uk/cars/news/hydrogen-fuel-cell-trains-run-british-railways-2022/amp/ https://www.cnbc.com/amp/2019/01/07/designs-unveiled-for-new-hydrogen-powered-trains-in-the-uk.html	

Case 3 – HydroFlex Regional Passenger Train Demonstrator (UK)	
Sponsors:	Year Introduced: 2018
Sector: Rail (passenger)	Technology: Bi-mode hybrid hydrogen fuel cell traction
Description: A bi-mode fuel cell train, based on a mid-life Electric Multiple unit, the Class 319. The design is based on Porterbrook's recently launched Class 319 "Flex" bi-mode. This is a 4-car electric multiple unit that has been equipped with diesel generator sets mounted to the underframe of the leading and trailing vehicle. This enables it to run on both electrified and non-electrified lines. The new design is for a bi-mode hydrogen fuel cell hybrid, capable of drawing power from overhead lines wherever available, and swapping over to hydrogen elsewhere. Key points to note: The University of Birmingham is supporting the introduction of these units and a demonstrator started to operate in summer 2019 on private test track. The fuel cells for the prototype are being supplied by Ballard and the lithium-based traction batteries are being provided by Denchi (UK). The traction power available when running on overhead electric wires is 1000kW with a top speed of 100mph. When running on non-electrified lines, the traction power is expected to be lower, but appropriate for regional and branch line operation.	 Source: Porterbrook Leasing (2018)
https://masstransit.network/mass-transit-news/smartrail-world/porterbrookballard-signal-arrival-of-uks-1st-hydrogen-powered-train https://www.porterbrook.co.uk/innovation/case-studies/the-flex-family	

<table>
<tr><td colspan="2">Case 4 – Siemens Mireo Regional Train (Europe)</td></tr>
<tr><td>Sponsors: Siemens</td><td>Year Introduced: 2021</td></tr>
<tr><td>Sector: Rail (passenger)</td><td>Technology: Hybrid hydrogen fuel cell traction</td></tr>
<tr><td>Description:
Siemens are developing a hybrid hydrogen fuel cell version of their Mireo regional train in conjunction with Ballard. The train will be equipped with a 200kW fuel cells based on the next generation of Ballard fuel cell technology.
The train is expected to enter service around 2021.
Key points to note:
The next generation of Ballard fuel cell stacks will be marginally more efficient, will have a longer service life predicted to be in excess of 30,000 hours, and will no longer require a shore supply for overnight stabling.</td><td>
Source: Wikipedia “Siemens Mireo” page (2019)</td></tr>
<tr><td colspan="2">https://www.electrans.co.uk/siemens-ballard-fuel-cell-mireo-funded-germany/
https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/fuel-cell-mireo-multiple-unit-to-be-developed.html</td></tr>
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<table>
<tr><td colspan="2">Case 5 – CRRC Hydrogen Trams (China)</td></tr>
<tr><td>Sponsors: CRRC</td><td>Year Introduced: 2016 & 2019</td></tr>
<tr><td>Sector: Light Rail (passenger)</td><td>Technology: Hydrogen fuel cell traction</td></tr>
<tr><td>Description:
A fleet of eight hydrogen fuel cell-powered trams have been ordered from CRRC, the world’s largest train manufacturer. These will operate in the city of Foshan. The design is based on the Skoda ForCity 15T, and the fuel cell system is from Ballard. The trams will operate the 17km line at speeds of up to 70km/h.
A similar fleet of 7 trams area already in service on a partly electrified 9km line in Qingdao.
Findings:
Hydrogen fuel cells enable trams to operate without overhead wires, which can be particularly important for congested city centers.</td><td>
Source: Wikipedia “Skoda 15 T” page (2018)</td></tr>
<tr><td colspan="2">https://www.metro-report.com/news/single-view/view/foshan-hydrogen-fuel-cell-tram-contract-signed.html
https://www.railwaygazette.com/news/single-view/view/qingdao-opens-fuel-cell-tram-route.html</td></tr>
</table>

Case 6 – Zillertalbahn Narrow Gauge Train (Austria)	
Sponsors: ZVB (operator) & Stadler	Year Introduced: 2022
Sector: Narrow Gauge Rail (passenger)	Technology: Hydrogen fuel cell traction
Description: A fleet of five hydrogen fuel cell powered narrow-gauge trains have been ordered from Stadler for use on a 32km scenic rail network in Austria. The hydrogen will be produced locally using hydropower (i.e. hydroelectricity) and transported by tube trailers to the railway. Key points to note: Hydrogen was selected in preference to electrification due largely to the visual impact that overhead electrification equipment would have on the line.	 Source: Wikipedia "Zillertal Railway" page (2019)
https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/zillertalbahn-selects-hydrogen-train-supplier.html	

Case 7 - Aberdeen Fuel Cell Bus Fleet (UK)	
Sponsors: Aberdeen City Council / EU	Year Introduced: 2015
Sector: Road (Passenger)	Technology: Hybrid hydrogen fuel cell traction
Description: A fleet of 10 hydrogen fuel cell powered buses that are in daily service, running on hydrogen produced locally using Hydrogenics electrolysers. The buses are made by Van Hool, and are equipped with Ballard fuel cells, with an electric drive system from Siemens. The fleet is part of the European-wide project called JIVE, deploying 144 fuel cell buses and seven large hydrogen refuelling stations across five European cities Key points to note: Hydrogen production is limited to periods when the local wind farm is generating electricity. The hydrogen production & refuelling facilities are located adjacent to a residential area. The hydrogen production facilities have achieved very high levels of availability, and the fleet is due to double in size later this year. The local council have been highly supportive, with the buses owned by Aberdeen City Council and leased to Stagecoach and First Group (the local bus operators). Aberdeen is investing heavily in alternative power, and Scotland as a whole is close to sourcing 100% of its electricity from renewable sources. Aberdeen is the centre of the oil industry in the UK, servicing the numerous oil fields in the North Sea. The fleet has now done over a million miles in service.	   Source: Stephen Kent (2015)
https://news.aberdeencity.gov.uk/aberdeens-pioneering-hydrogen-bus-project-arrives-at-major-milestone/	

Case 8 - Los Angeles ‘Project Portal’ Semi (US)	
Sponsors: Toyota / Kenworth / Shell	Year Introduced: 2018/19
Sector: Road (Heavy Goods Vehicle)	Technology: Hybrid hydrogen fuel cell traction
Description: A prototype fuel cell semi (truck) designed to carry containers from Californian ports to distribution centres inland. The two fuel cell stacks based on those in Toyota’s Mirai car (just over 200kW in total) are combined with a 12 kWh battery to give the truck 670 horsepower and 1,325 foot-pounds of torque. This enables it to easily out-accelerate a conventional diesel semi, albeit with a much lower range of 300 miles for the second generation truck (first generation shown right). Key points to note: The combination of battery and modest fuel cell output is sufficient to out-accelerate a comparable diesel semi, albeit with a shorter range between refuelling. Toyota have previously been reluctant to apply their advanced fuel cell and hydrogen tank technology to non-car applications. But this development suggests that they are now looking seriously to engage with applications in the heavy duty transport market. With the first generation having done 10,000 miles or real world service, 10 trucks of the second generation design are now to be built.	 Source: Toyota (2018) – with permission
https://www.greencarreports.com/news/1118877_toyota-enters-82-million-partnership-to-roll-out-hydrogen-trucks-in-los-angeles-port	

<table>
<tr><td colspan="2">Case 9 – Nikola Semi (US)</td></tr>
<tr><td>Sponsors: Nikola Motor Company</td><td>Year Introduced: 2020/21</td></tr>
<tr><td>Sector: Road (Heavy Goods Vehicle)</td><td>Technology: Hybrid hydrogen fuel cell traction</td></tr>
<tr><td>Description:
Nikola are developing a hydrogen fuel cell powered semi (truck), with a number of prototype vehicles already in operation. It incorporates a 320kWh battery and 300kW fuel cell to generate 1000 horsepower and 2000 foot-pounds of torque, which enables the truck to comfortable out-accelerate conventional diesel semis.
Each truck carries 100kg of hydrogen – sufficient to give a range of 1200 miles.
Anheuser-Busch have ordered 800 for operation in the USA.
Key points to note:
Nikola plans to initially have 56 refuelling stations in operation by 2019/2020, with the intention to expand this to 700 by 2028. They are partnering with NEL, one of the world's main electrolyser companies to deliver this.
The operating costs are expected to be considerably lower than for comparable diesel trucks.</td><td>

Source: Wikipedia "Nikola Motor Company" page (2019)</td></tr>
<tr><td colspan="2">https://en.wikipedia.org/wiki/Nikola_Motor_Company
https://www.trucks.com/2016/12/01/nikola-one-hydrogen-fuel-cell-electric-semi-truck-debuts/
https://www.theverge.com/2018/5/3/17314606/anheuser-busch-budweiser-hydrogen-trucks-zero-emission-startup-nikola</td></tr>
</table>

Case 10 – Fuel Cell Delivery Lorries (Switzerland)	
Sponsors: ESORO / Hyundai	Year Introduced: 2018 / 2019-23
Sector: Road (Heavy Goods Vehicle)	Technology: Hydrogen fuel cell traction
Description: The Swiss COOP currently operates a fleet of hybrid hydrogen fuel cell powered delivery trucks. These use a 100kW fuel cell from PowerCell of Sweden in conjunction with a 120kWh Lithium battery to drive 250kW motor mated to a four-speed automatic gearbox. Hyundai have recently signed a contract to deliver 1,600 fuel cell trucks for operation across Switzerland. They will feature a 190kW fuel cell system and will have a range of 400km. These are to be introduced into service starting 2019, with the full fleet in the mid/end 2020s. Key points to note: Switzerland has a plentiful supply of renewable energy, so hydrogen fuel cell trucks are a natural fit. Bosch has recently signed an agreement with PowerCell to mass produce fuel cells for heavy-duty transport applications.	 Source: H2 Energy
https://www.sciencedirect.com/science/article/pii/S1464285916303674 https://www.telegraph.co.uk/cars/news/hyundai-supply-1000-hydrogen-fuel-cell-lorries-switzerland/ https://www.hyundai.co.nz/hyundai-motor-and-h2-energy-to-bring-the-world-s-first-fleet-of-fuel-cell-electric-trucks-into-commercial-operation- https://uk.reuters.com/article/us-bosch-electric-fuelcell/bosch-signs-pact-with-swedens-powercell-to-mass-produce-fuel-cells-idUKKCN1S50LE	

Case 11 – Fast Charging Blues (Geneva, Switzerland)	
Sponsors: ABB & TPG	Year Introduced: 2018
Sector: Road Transport (Bus)	Technology: Fast Charging Batteries
Description: ABB were asked to construct a fleet of rapid charging buses for operation in Geneva, Switzerland. The 12km route features a number of rapid charging stations which repeatedly 'top up' the batteries while the buses are stationery via a roof mounted catenary system. This delivers charge at a rate of 600kW, with the LTO battery packs rated at up to 8C for flash charging and 6C for continuous charging. ABB published a helpful paper detailing specifics about the battery pack, including Beginning Of Life and End Of Life values for the battery packs. It is this data that has been used as the basis for the battery packs in this study.	 Source: ABB Review 4|16
https://new.abb.com/substations/references-selector/tosa-flash-charging-e-bus-geneva-switzerland https://library.e.abb.com/public/25aadd82a8f14d88b1813157db771d61/08-12%204m6069_EN_72dpi.pdf	

14.2 Simulation Results with Corresponding Emissions

14.2.1 Diesel Multiple Unit

DEMU (Diesel Electric Multiple Unit)						
CONFIGURATION & ASSUMPTIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target round trip journey time including terminal dwells	60	60	240	240	minutes	MSU for Redlands, estimate for LAUS
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Engine	8,000	12,000	8,000	12,000	kg	Stadler mass data sheet (2 x engines for 2 car, 3 x engines for 4 car)
Fuel	2,000	2,000	2,000	2,000	kg	
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	134,000	201,000	134,000	201,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen limit at wheel	1800	1800	1800	1800	kW	Stadler brochure for TEX Rail FLIRT (assume rated rheostatic fitted)
Resistance A	1.624	2.408	1.624	2.408		
Resistance B	0.0442	0.0651	0.0442	0.0651		Equivalent to CN resistance formula with streamlining = 19
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	119	174	940	1338	kWh	Results from STS model
Braking energy at wheel for return journey	84	119	534	668	kWh	Results from STS model
Return journey time excluding dwell at terminals	**40**	**40**	**177**	**177**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Traction package efficiency	86%	86%	86%	86%		
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Max auxiliary power demand at DC bus	117.5	200	117.5	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
Alternator and DC:DC converter efficiency	92%	92%	92%	92%		
Required engine output (max)	1016	1486	1016	1486	kW	
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	139	203	1099	1563	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus per return journey	257	403	1569	2363	kWh	
Diesel Genset Efficiency	30%	30%	30%	30%		
Fuel energy required per journey	844	1326	5162	7775	kWh	
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy per unit of fuel	9.94	9.94	9.94	9.94	kWh / litre	
Units of fuel require per journey	**85**	**133**	**519**	**782**	**litres**	
Number of journeys per day	1	1	1	1		
Energy required for all journeys	844	1326	5162	7775	kWh	
Total volume fuel required	**85**	**133**	**519**	**782**	**litres**	
Fuel specific mass	0.832	0.832	0.832	0.832	kg/litre	
Total mass of fuel required	71	111	432	650	kg	

Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC	
Configuration - DEMU	2-Car	4-Car	2-Car	4-Car
ENERGY CONSUMPTION - BENCHMARK, POINT-OF-USE				
	844	1326	5162	7775
POINT-OF-USE-EMISSIONS				
	Total Emissions In Grams			
GHGs	227474	357268	1390361	2094191
NOx: Total	2849	4475	17416	26232
PM2.5: Total	81	127	495	746
PM10: Total	84	131	511	769
CO: Total	397	623	2426	3654
VOC: Total	118	186	723	1089
SOx: Total	2	2	10	14
CH4	20	31	120	181
N2O	6	10	38	57
CO2 (w/ C in VOC & CO)	224264	352226	1370740	2064637
BC: Total	7	11	42	63
OC: Total	72	113	439	661

Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC	
Configuration	2-Car	4-Car	2-Car	4-Car
ENERGY CONSUMPTION - BENCHMARK, WELL-TO-PUMP				
Energy Requirements (in kWh)	166	261	1017	1532
WELL-TO-PUMP EMISSIONS				
	Total Emissions, in Grams			
GHGs	48109	75560	294051	442906
NOx: Total	83	130	506	762
PM2.5: Total	5	7	28	42
PM10: Total	5	9	33	50
CO: Total	40	62	243	365
VOC: Total	23	36	140	211
SOx: Total	34	54	210	316
CH4	324	510	1983	2987
N2O	1	1	4	6
CO2 (w/ C in VOC & CO)	38064	59783	232656	350431
BC: Total	1	1	5	7
OC: Total	1	2	9	13

Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC	
Configuration	2-Car	4-Car	2-Car	4-Car
ENERGY CONSUMPTION - BENCHMARK, WELL-TO-WHEEL				
Energy Requirements (in kWh)	1011	1588	6179	9307
WELL-TO-WHEEL EMISSIONS				
	Total Emissions, In Grams			
GHGs	275583	432828	1684413	2537097
NOx: Total	2932	4605	17922	26994
PM2.5: Total	86	135	523	788
PM10: Total	89	140	544	819
CO: Total	437	686	2669	4019
VOC: Total	141	222	863	1300
SOx: Total	36	56	219	330
CH4	344	541	2104	3168
N2O	7	11	42	63
CO2 (w/ C in VOC & CO)	262328	412010	1603396	2415068
BC: Total	8	12	46	70
OC: Total	73	115	448	674

14.2.2 Hybrid Diesel-Electric Multiple Unit

Hybrid DEMU (Diesel Electric Multiple Unit)						
CONFIGURATION & ASSUMPTIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target journey time	60	60	240	240	minutes	Round-trip including dwell at terminal stations
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Engines	4,000	4,000	4,000	8,000	kg	1 / 1 / 1 / 2 x Deutz diesel engines
Batteries	4,000	6,000	4,000	2,000	kg	2 / 3 / 2 / 1 x ABB LTO battery packs
Fuel	2,000	2,000	2,000	2,000	kg	Estimate
MAX REGEN LIMITATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max regen limit of battery pack	660	660	660	660	kW	See "Battery Calcs" sheet
Traction package efficiency	86%	86%	86%	86%		See "Efficiency Calcs" sheet
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	134,000	199,000	134,000	199,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen at wheel	771	771	771	771	kW	
Resistance A	1.624	2.408	1.624	2.408		
Resistance B	0.0442	0.0651	0.0442	0.0651		Equivalent to CN resistance formula with streamlining = 19
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	119	173	940	1330	kWh	Results from STS model
Braking energy at wheel for return journey	66	85	327	385	kWh	Results from STS model
Return journey time (excluding dwell at terminals)	**40**	**40**	**177**	**177**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Auxiliary power demand (worst case)	118	200	118	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	139	202	1099	1555	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus before regen	257	402	1569	2355	kWh	
Regen efficiency wheel to DC bus	74%	74%	74%	74%		
Energy stored and released by battery pack	49	63	242	285	kWh	
Total energy for return journey including regen	**208**	**339**	**1327**	**2070**	**kWh**	
ENGINE SIZE CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Average power that needs generating	208	339	332	518	kW	
Alternator & DC:DC converter efficiency	92%	92%	92%	92%		
Absolute minimum engine rated output	226	368	360	562	kW	
Suggested minimum engine rated output	**271**	**441**	**432**	**674**	**kW**	Guidance from MSU (minimum + 20%)
Actual likely engine output	520	520	520	1040	kW	Assume multiples of Deutz 520kW
BATTERY SIZE CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max power to be supplied by battery at DC bus	416	849	416	329	kW	Maximum power minus likely engine output
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Hybrid Diesel genset efficiency	33%	33%	33%	33%		See "Efficiency Calcs" sheet - Generator and associated alternator efficiences already included
Fuel energy required per journey	627	1022	4002	6242	kWh	
Energy per unit of fuel	9.94	9.94	9.94	9.94	kWh / litre	See "Fuel Data" sheet
Units of fuel require per journey	**63**	**103**	**402**	**628**	**litres**	
Number of journeys per day	1	1	1	1		
Energy required for all journeys	627	1022	4002	6242	kWh	
Total volume fuel required	**63**	**103**	**402**	**628**	**litres**	
Fuel specific mass	0.832	0.832	0.832	0.832	kg/litre	
Total mass of fuel required	52	85	335	522	kg	

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration Hybrid DEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	627		1022		4002		6242	
Energy Reduction	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*
	218	*26*	305	*23*	1160	*22*	1533	*20*
POINT-OF-USE EMISSIONS								
	Total Emissions		Total Emissions		Total Emissions		Total Emissions	
	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*
GHGs	**168884**	***26***	**275243**	***23***	**1078002**	***22***	**1681373**	***20***
NOx: Total	2115	***26***	3448	***23***	13503	***22***	21061	***20***
PM2.5: Total	60	***26***	98	***23***	384	***22***	599	***20***
PM10: Total	62	***26***	101	***23***	396	***22***	618	***20***
CO: Total	295	***26***	480	***23***	1881	***22***	2934	***20***
VOC: Total	88	***26***	143	***23***	561	***22***	874	***20***
SOx: Total	1	***26***	2	***23***	7	***22***	12	***20***
CH4	15	***26***	24	***23***	93	***22***	145	***20***
N2O	5	***26***	7	***23***	29	***22***	45	***20***
CO2 (w/ C in VOC & CO)	166501	***26***	271358	***23***	1062789	***22***	1657645	***20***
BC: Total	5	***26***	8	***23***	32	***22***	50	***20***
OC: Total	53	***26***	87	***23***	340	***22***	531	***20***

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid DEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, WELL-TO-PUMP								
Energy Requirements (in kWh)	124		201		789		1230	
Energy Reduction	*In %*		*In %*		*In %*		*In %*	
	26		*23*		*22*		*20*	
WELL-TO-PUMP EMISSIONS								
	Total Emissions		Total Emissions		Total Emissions		Total Emissions	
	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*
GHGs	**11845**	***75***	**19305**	***74***	**18902**	***94***	**29482**	***93***
NOx: Total	20	***75***	33	***74***	33	***94***	51	***93***
PM2.5: Total	1	***75***	2	***74***	2	***94***	3	***93***
PM10: Total	1	***75***	2	***74***	2	***94***	3	***93***
CO: Total	10	***75***	16	***74***	16	***94***	24	***93***
VOC: Total	6	***75***	9	***74***	9	***94***	14	***93***
SOx: Total	8	***75***	14	***74***	13	***94***	21	***93***
CH4	80	***75***	130	***74***	127	***94***	199	***93***
N2O	0	***75***	0	***74***	0	***94***	0	***93***
CO2 (w/ C in VOC & CO)	9372	***75***	15274	***74***	14956	***94***	23326	***93***
BC: Total	0	***75***	0	***74***	0	***94***	0	***93***
OC: Total	0	***75***	1	***74***	1	***94***	1	***93***

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, WELL-TO-WHEEL								
Energy Requirements (in kWh)	751		1223		4791		7472	
Energy Reduction	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*
	260	*26*	365	*0*	6179	*0*	9307	*0*
WELL-TO-WHEEL EMISSIONS								
	Total Emissions		Total Emissions		Total Emissions		Total Emissions	
	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*
GHGs	**180730**	***34***	**294548**	***32***	**1096904**	***35***	**1710855**	***33***
NOx: Total	2136	***27***	3481	***24***	13535	***24***	21111	***22***
PM2.5: Total	61	***28***	100	***26***	386	***26***	602	***24***
PM10: Total	63	***29***	103	***26***	398	***27***	621	***24***
CO: Total	304	***30***	496	***28***	1897	***29***	2958	***26***
VOC: Total	93	***34***	152	***31***	570	***34***	888	***32***
SOx: Total	10	***73***	16	***72***	21	***90***	33	***90***
CH4	94	***73***	154	***72***	221	***90***	344	***89***
N2O	5	***31***	8	***28***	29	***29***	46	***27***
CO2 (w/ C in VOC & CO)	175873	***33***	286632	***30***	1077744	***33***	1680971	***30***
BC: Total	5	***31***	9	***28***	33	***30***	51	***27***
OC: Total	54	***27***	87	***24***	341	***24***	532	***21***

14.2.3 Hydrogen Fuel Cell Multiple Unit

FCEMU (Fuel Cell Electric Multiple Unit)						
CONFIGURATION & ASSUMPTIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target journey time	60	60	240	240	minutes	Round-trip including dwell at terminal stations
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Fuel cell & BoP	5,000	7,000	5,000	7,000	kg	10 x fuel cell modules for 2 car, 14 for 4 car @ 500kg per module
Tanks	3,500	5,500	5,500	8,000	kg	35 / 55 / 55 / 80 x Hexagon Composites @ 100kg per tank
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	132,500	199,500	134,500	202,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen at wheel	1800	1800	1800	1800	kW	Assume fully rated rheostat
Resistance A	1.624	2.408	1.624	2.408		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0651	0.0442	0.0651		
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	118	173	942	1341	kWh	Results from STS model
Braking energy at wheel for return journey	83	118	535	669	kWh	Results from STS model
Return journey time (excluding dwell at terminals)	**40**	**40**	**177**	**177**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Traction package efficiency	86%	86%	86%	86%		
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Auxiliary power demand (worst case)	118	200	118	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
DC: DC converter efficiency	98%	98%	98%	98%		
Required fuel cell output rating	**955**	**1397**	**955**	**1397**	**kW**	**2 car needs 10 x fuel cell modules, 4 car needs 14 x fuel cell modules**
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	138	202	1101	1568	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus	**256**	**402**	**1571**	**2368**	**kWh**	
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Fuel cell efficiency	51%	51%	51%	51%		
Fuel energy required per journey	497	781	3054	4602	kWh	
Energy per unit of fuel	0.022	0.022	0.022	0.022	kWh/litre	
Hydrogen fuel required per journey	22,576	35,517	138,815	209,185	litres	
Fuel specific mass	0.00067	0.00067	0.00067	0.00067	kg/litre	
Total mass of fuel required per journey	15	24	93	140	kg	
Number of journeys per day	1	1	1	1		
Hydrogen fuel energy required for all journeys	497	781	3054	4602	kWh	
Total hydrogen fuel required per day	**15**	**24**	**93**	**140**	**kg**	
FUEL VOLUME CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Volume per kg of stored hydrogen	0.0750	0.0750	0.0750	0.0750	m3/kg	
Total fuel storage volume required	**1.1**	**1.8**	**7.0**	**10.5**	**m3**	
Approx number of tanks	**2**	**3**	**12**	**18**		**Integer value only**

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU - 1/3	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	497		781		3054		4602	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	348	*41*	545	*41*	2108	*41*	3173	*41*
POINT-OF-USE EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**0**	*100*	**0**	*100*	**0**	*100*	**0**	*100*
NOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM2.5: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM10: Total	0	*100*	0	*100*	0	*100*	0	*100*
CO: Total	0	*100*	0	*100*	0	*100*	0	*100*
VOC: Total	0	*100*	0	*100*	0	*100*	0	*100*
SOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
CH4	0	*100*	0	*100*	0	*100*	0	*100*
N2O	0	*100*	0	*100*	0	*100*	0	*100*
CO2 (w/ C in VOC & CO)	0	*100*	0	*100*	0	*100*	0	*100*
BC: Total	0	*100*	0	*100*	0	*100*	0	*100*
OC: Total	0	*100*	0	*100*	0	*100*	0	*100*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, WELL-TO-PUMP (CA ONSITE SMR)								
Energy Requirements (in kWh)	369		580		2267		3416	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-202	*-122*	-319	*-122*	-1250	*-123*	-1884	*-123*
WELL-TO-PUMP (CA ONSITE SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**189258**	***-293***	**297737**	***-294***	**1163690**	***-296***	**1753609**	***-296***
NOx: Total	124	*-50*	196	*-50*	765	*-51*	1153	*-51*
PM2.5: Total	4	*9*	7	*9*	26	*8*	39	*8*
PM10: Total	5	*4*	8	*4*	32	*4*	48	*4*
CO: Total	97	*-145*	153	*-146*	598	*-147*	902	*-147*
VOC: Total	29	*-27*	46	*-27*	179	*-28*	270	*-28*
SOx: Total	40	*-18*	63	*-18*	248	*-18*	374	*-18*
CH4	618	*-90*	972	*-91*	3798	*-91*	5723	*-92*
N2O	4	*-494*	6	*-495*	24	*-498*	37	*-498*
CO2 (w/ C in VOC & CO)	169684	*-346*	266943	*-347*	1043333	*-348*	1572237	*-349*
BC: Total	1	*34*	1	*34*	3	*33*	5	*33*
OC: Total	1	*36*	1	*36*	6	*36*	8	*36*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, WELL-TO-WHEEL (CA ONSITE SMR)								
Energy Requirements (in kWh)	865		1361		5321		8018	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	146	*14*	226	*14*	858	*14*	1288	*14*
WELL-TO-WHEEL (CA ONSITE SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**189258**	***31***	**297737**	***31***	**1163690**	***31***	**1753609**	***31***
NOx: Total	124	*96*	196	*96*	765	*96*	1153	*96*
PM2.5: Total	4	*95*	7	*95*	26	*95*	39	*95*
PM10: Total	5	*94*	8	*94*	32	*94*	48	*94*
CO: Total	97	*78*	153	*78*	598	*78*	902	*78*
VOC: Total	29	*79*	46	*79*	179	*79*	270	*79*
SOx: Total	40	*-12*	63	*-13*	248	*-13*	374	*-13*
CH4	618	*-79*	972	*-80*	3798	*-81*	5723	*-81*
N2O	4	*42*	6	*42*	24	*42*	37	*42*
CO2 (w/ C in VOC & CO)	169684	*35*	266943	*35*	1043333	*35*	1572237	*35*
BC: Total	1	*93*	1	*93*	3	*93*	5	*93*
OC: Total	1	*99*	1	*99*	6	*99*	8	*99*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU - 2/3	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (CA ONSITE ELECTROLYSIS)								
Energy Requirements (in kWh)	855		1345		5257		7921	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-689	*-414*	-1084	*-415*	-4239	*-417*	-6389	*-417*
WELL-TO-PUMP EMISSIONS (CA ONSITE ELECTROLYSIS)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	224024	*-366*	352430	*-366*	1377453	*-368*	2075736	-369
NOx: Total	173	*-109*	273	*-110*	1066	*-111*	1606	-111
PM2.5: Total	10	*-116*	16	*-117*	61	*-118*	92	-118
PM10: Total	20	*-273*	32	*-273*	124	*-275*	188	-275
CO: Total	138	*-248*	217	*-248*	848	*-250*	1278	-250
VOC: Total	30	*-31*	47	*-31*	185	*-32*	279	-32
CH4	533	*-64*	838	*-64*	3275	*-65*	4935	-65
N2O	3	*-380*	5	*-381*	20	*-383*	30	-383
CO2 (w/ C in VOC & CO)	207201	*-444*	325964	*-445*	1274014	*-448*	1919860	-448
SOx: Total	163	*-375*	256	*-375*	1001	*-377*	1508	-378
BC: Total	1	*-65*	2	*-65*	8	*-66*	12	-66
OC: Total	3	*-128*	5	*-128*	20	*-129*	30	-129

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (CA ONSITE ELECTROLYSIS)								
Energy Requirements (in kWh)	1352		2126		8310		12523	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-341	*-34*	-539	*-34*	-2132	*-35*	-3217	*-35*
WELL-TO-WHEEL (CA ONSITE ELECTROLYSIS)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	224024	*19*	352430	*19*	1377453	*18*	2075736	*18*
NOx: Total	173	*94*	273	*94*	1066	*94*	1606	*94*
PM2.5: Total	10	*88*	16	*88*	61	*88*	92	*88*
PM10: Total	20	*77*	32	*77*	124	*77*	188	*77*
CO: Total	138	*68*	217	*68*	848	*68*	1278	*68*
VOC: Total	30	*79*	47	*79*	185	*79*	279	*79*
SOx: Total	163	*-354*	256	*-355*	1001	*-357*	1508	*-357*
CH4	533	*-55*	838	*-55*	3275	*-56*	4935	*-56*
N2O	3	*53*	5	*53*	20	*53*	30	*53*
CO2 (w/ C in VOC & CO)	207201	*21*	325964	*21*	1274014	*21*	1919860	*21*
BC: Total	1	*83*	2	*83*	8	*83*	12	*83*
OC: Total	3	*96*	5	*96*	20	*96*	30	*96*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (100% RENEWABLE)								
Energy Requirements (in kWh)	366		575		2248		3388	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-199	*-120*	-314	*-120*	-1231	*-121*	-1856	*-121*

WELL-TO-PUMP EMISSIONS (100% RENEWABLE)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	0	*100*	0	*100*	0	*100*	0	*100*
NOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM10: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM2.5: Total	0	*100*	0	*100*	0	*100*	0	*100*
CO: Total	0	*100*	0	*100*	0	*100*	0	*100*
VOC: Total	0	*100*	0	*100*	0	*100*	0	*100*
CH4	0	*100*	0	*100*	0	*100*	0	*100*
N2O	0	*100*	0	*100*	0	*100*	0	*100*
CO2 (w/ C in VOC & CO)	0	*100*	0	*100*	0	*100*	0	*100*
SOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
BC: Total	0	*100*	0	*100*	0	*100*	0	*100*
OC: Total	0	*100*	0	*100*	0	*100*	0	*100*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU - 3/3	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (100% RENEWABLE - H2 ELECTROLYSIS)								
Energy Requirements (in kWh)	**862**		**1357**		**5302**		**7990**	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	149	15	231	15	877	14	1317	14
WELL-TO-WHEEL EMISSIONS (100% RENEWABLE - H2 ELECTROLYSIS)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**0**	***100***	**0**	***100***	**0**	***100***	**0**	***100***
NOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM2.5: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM10: Total	0	*100*	0	*100*	0	*100*	0	*100*
CO: Total	0	*100*	0	*100*	0	*100*	0	*100*
VOC: Total	0	*100*	0	*100*	0	*100*	0	*100*
CH4	0	*100*	0	*100*	0	*100*	0	*100*
N2O	0	*100*	0	*100*	0	*100*	0	*100*
CO2 (w/ C in VOC & CO)	0	*100*	0	*100*	0	*100*	0	*100*
SOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
BC: Total	0	*100*	0	*100*	0	*100*	0	*100*
OC: Total	0	*100*	0	*100*	0	*100*	0	*100*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (CA LIQUID H2 DELIVERY, SMR)								
Energy Requirements (in kWh)	593		932		3644		5492	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-426	*-256*	-671	*-257*	-2627	*-258*	-3960	*-259*
WELL-TO-PUMP (CA LIQUID H2 DELIVERY, SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**223723**	***-365***	351957	***-366***	1375605	***-368***	2072952	***-368***
NOx: Total	115	*-39*	181	*-39*	708	*-40*	1067	*-40*
PM2.5: Total	7	*-47*	11	*-48*	42	*-48*	63	*-48*
PM10: Total	10	*-76*	15	*-76*	59	*-77*	88	*-77*
CO: Total	83	*-110*	131	*-110*	513	*-111*	772	*-111*
VOC: Total	27	*-18*	43	*-18*	167	*-19*	251	*-19*
SOx: Total	68	*-99*	107	*-99*	419	*-100*	631	*-100*
CH4	538	*-66*	846	*-66*	3306	*-67*	4983	*-67*
N2O	2	*-153*	3	*-154*	10	*-155*	16	*-155*
CO2 (w/ C in VOC & CO)	206930	*-444*	325538	*-445*	1272349	*-447*	1917351	*-447*
BC: Total	1	*-11*	1	*-11*	5	*-12*	8	*-12*
OC: Total	2	*-29*	3	*-29*	11	*-30*	17	*-30*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (CA LIQUID H2 DELIVERY, SMR)								
Energy Requirements (in kWh)	1089		1714		6698		10094	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-79	*-8*	-126	*-8*	-520	*-8*	-787	*-8*
WELL-TO-WHEEL (CA LIQUID H2 DELIVERY, SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**223723**	***19***	**351957**	***19***	**1375605**	***18***	**2072952**	***18***
NOx: Total	115	*96*	181	*96*	708	*96*	1067	*96*
PM2.5: Total	7	*92*	11	*92*	42	*92*	63	*92*
PM10: Total	10	*89*	15	*89*	59	*89*	88	*89*
CO: Total	83	*81*	131	*81*	513	*81*	772	*81*
VOC: Total	27	*81*	43	*81*	167	*81*	251	*81*
SOx: Total	68	*-90*	107	*-90*	419	*-91*	631	*-91*
CH4	538	*-56*	846	*-57*	3306	*-57*	4983	*-57*
N2O	2	*75*	3	*75*	10	*75*	16	*75*
CO2 (w/ C in VOC & CO)	206930	*21*	325538	*21*	1272349	*21*	1917351	*21*
BC: Total	1	*88*	1	*88*	5	*88*	8	*88*
OC: Total	2	*98*	3	*98*	11	*97*	17	*97*

14.2.4 Hydrogen Fuel Cell Hybrid

Hybrid FCEMU (Fuel Cell Electric Multiple Unit)

CONFIGURATION & ASSUMPTIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target journey time	60	60	240	240	minutes	Round-trip including dwell at terminal stations
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Fuel cell & BoP	1,500	2,000	2,000	3,000	kg	3 / 4 / 4 / 6 x 100kW fuel cell modules @ 500kg per module
Batteries	4,000	6,000	4,000	6,000	kg	2 x ABB LTO battery packs for 32 car, 3 x for 4 car
Tanks	2,500	4,000	4,000	6,500	kg	25 / 40 / 40 / 65 x Hexagon Composites @ 100kg per tank
MAX REGEN LIMITATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max regen limit of battery pack	660	660	660	660	kW	
Traction package efficiency	86%	86%	86%	86%		
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	132,000	199,000	134,000	202,500	kg	Assume similar mass to DEMU (single diesel engine + 2 battery packs)
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen at wheel	771	771	771	771	kW	
Resistance A	1.624	2.408	1.624	2.408		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0651	0.0442	0.0651		
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	118	173	940	1343	kWh	Results from STS model
Braking energy at wheel for return journey	65	85	327	387	kWh	Results from STS model
Return journey time (excluding dwell at terminals)	**40**	**40**	**177**	**178**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Auxiliary power demand (worst case)	118	200	118	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	138	202	1099	1570	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus before regen	255	402	1569	2370	kWh	
Regen efficiency wheel to DC bus	74%	74%	74%	74%		
Energy stored and released by battery pack	48	63	242	286	kWh	
Total energy for return journey including regen	**207**	**339**	**1327**	**2084**	**kWh**	
ENGINE SIZE CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Average power that needs generating at DC bus	206.8	338.9	331.8	521.0	kW	
DC: DC converter efficiency	98%	98%	98%	98%		
Absolute minimum fuel cell rated ouput	211.0	345.8	338.6	531.6	kW	
Suggested fuel cell rated output	**253**	**415**	**406**	**638**	**kW**	Guidance from MSU (minimum + 20%)
Actual likely fuel cell output	300	400	400	600	kW	
BATTERY SIZE CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max power to be supplied by battery at DC bus	636	969	536	769	kW	Maximum power minus likely fuel cell output
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Hybrid Fuel cell genset efficiency	49%	49%	49%	49%		
Fuel energy required per journey	422	692	2709	4253	kWh	
Energy per unit of fuel	0.022	0.022	0.022	0.022	kWh/litre	
Hydrogen fuel require per journey	19,186	31,435	123,118	193,304	litres	
Fuel specific mass	0.00067	0.00067	0.00067	0.00067	kg/litre	
Total mass of fuel required per journey	**13**	**21**	**82**	**130**	**kg**	
Number of journeys per day	1	1	1	1		
Hydrogen fuel energy required for all journeys	422	692	2709	4253	kWh	
Total hydrogen fuel required per day	**13**	**21**	**82**	**130**	**kg**	
FUEL VOLUME CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Volume per kg of stored hydrogen	0.0750	0.0750	0.0750	0.0750	m3/kg	
Total fuel storage volume required	**1.0**	**1.6**	**6.2**	**9.7**	**m3**	
Approx number of tanks	**1**	**2**	**10**	**17**		

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid FCEMU - 1/3	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	422		692		2709		4253	
Energy Reduction	**In kWh**	***Reduc. In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	422	*50*	635	*48*	2453	*48*	3522	*45*
POINT-OF-USE EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**0**	*100*	**0**	*100*	**0**	*100*	**0**	*100*
NOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM2.5: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM10: Total	0	*100*	0	*100*	0	*100*	0	*100*
CO: Total	0	*100*	0	*100*	0	*100*	0	*100*
VOC: Total	0	*100*	0	*100*	0	*100*	0	*100*
SOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
CH4	0	*100*	0	*100*	0	*100*	0	*100*
N2O	0	*100*	0	*100*	0	*100*	0	*100*
CO2 (w/ C in VOC & CO)	0	*100*	0	*100*	0	*100*	0	*100*
BC: Total	0	*100*	0	*100*	0	*100*	0	*100*
OC: Total	0	*100*	0	*100*	0	*100*	0	*100*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
CConfiguration - Hybrid FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (CA ONSITE SMR)								
Energy Requirements (in kWh)	313		513		2011		3157	
Energy Reduction	***In %***		***In %***		***In %***		***In %***	
	-88		*-96*		*-98*		*-106*	
WELL-TO-PUMP EMISSIONS (CA ONSITE SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**160835**	***-234***	**263523**	***-249***	**1032101**	***-251***	**1620474**	***-266***
NOx: Total	106	*-28*	173	*-33*	678	*-34*	1065	*-40*
PM2.5: Total	4	*23*	6	*19*	23	*19*	36	*15*
PM10: Total	4	*19*	7	*15*	28	*15*	45	*11*
CO: Total	83	*-108*	135	*-117*	531	*-119*	833	*-128*
VOC: Total	25	*-8*	41	*-13*	159	*-13*	250	*-18*
SOx: Total	34	*0*	56	*-4*	220	*-5*	345	*-9*
CH4	525	*-62*	860	*-69*	3368	*-70*	5289	*-77*
N2O	3	*-405*	5	*-427*	22	*-430*	34	*-453*
CO2 (w/ C in VOC & CO)	144200	*-279*	236267	*-295*	925353	*-298*	1452872	*-315*
BC: Total	0	*44*	1	*41*	3	*41*	4	*38*
OC: Total	1	*46*	1	*43*	5	*43*	8	*41*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (CA ONSITE SMR)								
Energy Requirements (in kWh)	735		1205		4719		7409	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	275	*27*	383	*24*	1460	*24*	1897	*20*
WELL-TO-WHEEL EMISSIONS (CA ONSITE SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**160835**	***42***	**263523**	***39***	**1032101**	***39***	**1620474**	***36***
NOx: Total	106	*96*	173	*96*	678	*96*	1065	*96*
PM2.5: Total	4	*96*	6	*96*	23	*96*	36	*95*
PM10: Total	4	*95*	7	*95*	28	*95*	45	*95*
CO: Total	83	*81*	135	*80*	531	*80*	833	*79*
VOC: Total	25	*82*	41	*82*	159	*82*	250	*81*
SOx: Total	34	*4*	56	*0*	220	*0*	345	*-5*
CH4	525	*-53*	860	*-59*	3368	*-60*	5289	*-67*
N2O	3	*51*	5	*49*	22	*48*	34	*46*
CO2 (w/ C in VOC & CO)	144200	*45*	236267	*43*	925353	*42*	1452872	*40*
BC: Total	0	*94*	1	*94*	3	*94*	4	*94*
OC: Total	1	*99*	1	*99*	5	*99*	8	*99*

Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - Hybrid FCEMU - 2/3	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (CA ONSITE ELECTROLYSIS)								
Energy Requirements (in kWh)	727		1190		4662		7320	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-560	*-337*	-929	*-355*	-3645	*-358*	-5788	*-378*

WELL-TO-PUMP EMISSIONS (CA ONSITE ELECTROLYSIS)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**190379**	***-296***	**311930**	***-313***	**1221691**	***-315***	**1918145**	***-333***
NOx: Total	147	*-78*	241	*-86*	945	*-87*	1484	*-95*
PM2.5: Total	8	*-84*	14	*-92*	54	*-93*	85	*-101*
PM10: Total	17	*-217*	28	*-230*	110	*-233*	173	*-247*
CO: Total	117	*-195*	192	*-208*	752	*-210*	1181	*-223*
VOC: Total	26	*-11*	42	*-16*	164	*-17*	258	*-22*
SOx: Total	138	*-303*	227	*-321*	888	*-323*	1394	*-341*
CH4	453	*-39*	742	*-46*	2905	*-46*	4561	*-53*
N2O	3	*-308*	4	*-325*	17	*-328*	27	*-346*
CO2 (w/ C in VOC & CO)	176083	*-363*	288506	*-383*	1129949	*-386*	1774103	*-406*
BC: Total	1	*-40*	2	*-46*	7	*-47*	11	*-53*
OC: Total	3	*-94*	4	*-102*	18	*-103*	28	*-112*

Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - Hybrid FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (CA ONSITE ELECTROLYSIS)								
Energy Requirements (in kWh)	1149		1882		7371		11573	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-138	*-14*	-294	*-19*	-1192	*-19*	-2266	*-24*

WELL-TO-WHEEL EMISSIONS (CA ONSITE ELECTROLYSIS)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**190379**	***31***	**311930**	***28***	**1221691**	***27***	**1918145**	***24***
NOx: Total	147	*95*	241	*95*	945	*95*	1484	*95*
PM2.5: Total	8	*90*	14	*90*	54	*90*	85	*89*
PM10: Total	17	*81*	28	*80*	110	*80*	173	*79*
CO: Total	117	*73*	192	*72*	752	*72*	1181	*71*
VOC: Total	26	*82*	42	*81*	164	*81*	258	*80*
SOx: Total	138	*-286*	227	*-302*	888	*-305*	1394	*-322*
CH4	453	*-32*	742	*-37*	2905	*-38*	4561	*-44*
N2O	3	*60*	4	*59*	17	*58*	27	*56*
CO2 (w/ C in VOC & CO)	176083	*33*	288506	*30*	1129949	*30*	1774103	*27*
BC: Total	1	*85*	2	*85*	7	*85*	11	*84*
OC: Total	3	*96*	4	*96*	18	*96*	28	*96*

Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - Hybrid FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (100% RENEWABLE)								
Energy Requirements (in kWh)	311		509		1994		3130	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-144	*-87*	-248	*-95*	-977	*-96*	-1599	*-104*

WELL-TO-PUMP EMISSIONS (100% RENEWABLE)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**0**	***100***	**0**	***100***	**0**	***100***	**0**	***100***
NOx: Total	0	*100*	0	***100***	0	***100***	0	***100***
PM10: Total	0	*100*	0	***100***	0	***100***	0	***100***
PM2.5: Total	0	*100*	0	***100***	0	***100***	0	***100***
CO: Total	0	*100*	0	***100***	0	***100***	0	***100***
VOC: Total	0	*100*	0	***100***	0	***100***	0	***100***
CH4	0	*100*	0	***100***	0	***100***	0	***100***
N2O	0	*100*	0	***100***	0	***100***	0	***100***
CO2 (w/ C in VOC & CO)	0	*100*	0	***100***	0	***100***	0	***100***
SOx: Total	0	*100*	0	***100***	0	***100***	0	***100***
BC: Total	0	*100*	0	***100***	0	***100***	0	***100***
OC: Total	0	***100***	0	***100***	0	***100***	0	***100***

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid FCEMU - 3/3	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (100% RENEWABLE)								
Energy Requirements (in kWh)	733		1201		4702		7383	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	278	*28*	387	*24*	1476	*0*	1923	*21*

WELL-TO-WHEEL EMISSIONS (100% RENEWABLE)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***In %***	**In grams**	***In %***	**In grams**	***In %***	**In grams**	***In %***
GHGs	**0**	***100***	**0**	***100***	**0**	***100***	**0**	***100***
NOx: Total	0	***100***	0	***100***	0	***100***	0	***100***
PM2.5: Total	0	***100***	0	***100***	0	***100***	0	***100***
PM10: Total	0	***100***	0	***100***	0	***100***	0	***100***
CO: Total	0	***100***	0	***100***	0	***100***	0	***100***
VOC: Total	0	***100***	0	***100***	0	***100***	0	***100***
CH4	0	***100***	0	***100***	0	***100***	0	***100***
N2O	0	***100***	0	***100***	0	***100***	0	***100***
CO2 (w/ C in VOC & CO)	0	***100***	0	***100***	0	***100***	0	***100***
SOx: Total	0	***100***	0	***100***	0	***100***	0	***100***
BC: Total	0	***100***	0	***100***	0	***100***	0	***100***
OC: Total	0	***100***	0	***100***	0	***100***	0	***100***

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (CA LIQUID H2 DELIVERY, SMR)								
Energy Requirements (in kWh)	504		825		3232		5075	
Energy Reduction	***In %***		***In %***		***In %***		***In %***	
	-223		*-224*		*-225*		*#REF!*	

WELL-TO-PUMP (CA LIQUID H2 DELIVERY, SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**190124**	***-295***	**311512**	***-312***	**1220052**	***-315***	**1915572**	***-333***
NOx: Total	98	*-18*	160	*-23*	628	*-24*	986	*-29*
PM2.5: Total	6	*-25*	9	*-31*	37	*-31*	58	*-37*
PM10: Total	8	*-49*	13	*-56*	52	*-57*	82	*-63*
CO: Total	71	*-79*	116	*-86*	455	*-87*	714	*-95*
VOC: Total	23	*0*	38	*-5*	148	*-5*	232	*-10*
SOx: Total	58	*-69*	95	*-76*	371	*-77*	583	*-85*
CH4	457	*-41*	749	*-47*	2933	*-48*	4604	*-54*
N2O	1	*-115*	2	*-124*	9	*-126*	14	*-135*
CO2 (w/ C in VOC & CO)	175852	*-362*	288129	*-382*	1128472	*-385*	1771785	*-406*
BC: Total	1	*6*	1	*2*	5	*1*	8	*-3*
OC: Total	2	*-10*	3	*-15*	10	*-15*	16	*-20*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid FCEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL (CA LIQUID H2 DELIVERY, SMR)								
Energy Requirements (in kWh)	926		1517		5941		9328	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	85	*8*	-834	*-6989*	-3260	*-7019*	#REF!	*#REF!*

WELL-TO-WHEEL (CA LIQUID H2 DELIVERY, SMR)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**190124**	***31***	**311512**	***28***	**1220052**	***28***	**1915572**	***24***
NOx: Total	98	*97*	160	*97*	628	*96*	986	*96*
PM2.5: Total	6	*93*	9	*93*	37	*93*	58	*93*
PM10: Total	8	*91*	13	*91*	52	*90*	82	*90*
CO: Total	71	*84*	116	*83*	455	*83*	714	*82*
VOC: Total	23	*84*	38	*83*	148	*83*	232	*82*
SOx: Total	58	*-61*	95	*-68*	371	*-69*	583	*-77*
CH4	457	*-33*	749	*-39*	2933	*-39*	4604	*-45*
N2O	1	*79*	2	*78*	9	*78*	14	*77*
CO2 (w/ C in VOC & CO)	175852	*33*	288129	*30*	1128472	*30*	1771785	*27*
BC: Total	1	*90*	1	*90*	5	*90*	8	*89*
OC: Total	2	*98*	3	*98*	10	*98*	16	*98*

14.2.5 Battery-Only Multiple Unit

BEMU (Battery Electric Multiple Unit)										
CONFIGURATION & ASSUMPTIONS										
Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC					
	out	back	out	back	out	back	out	back		
Target SINGLE journey time including dwell	30	30	30	30	120	120	120	120	minutes	Round-trip including layover at terminal stations
COMPONENT MASSES	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	124,000	187,000	187,000	124,000	124,000	187,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Batteries	8,000	8,000	8,000	8,000	40,000	40,000	50,000	50,000	kg	
MAX REGEN LIMITATIONS	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Max regen limit of battery	1320	1320	1320	1320	>>motor		>>motor		kW	Regen limited by battery pack for Redlands, but not for LAUS
Traction package efficiency	86%	86%	86%	86%	86%	86%	86%	86%		
INPUTS TO SIMULATION	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Train mass	132,000	132,000	195,000	195,000	164,000	164,000	237,000	237,000	kg	Redlands BEMU=DEMU, LAUS BEMU=DEMU+32000 (2-car) +42000 (4-car)
Installed power at wheel	700	700	100	1000	700	700	1000	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen at wheel	1543	1543	1543	1543	1800	1800	1800	1800	kW	Regen limited by battery pack for Redlands, but not for LAUS
Resistance A	1.624	1.624	2.408	2.408	1.845	1.845	2.701	2.701		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0442	0.0651	0.0651	0.0542	0.0542	0.0783	0.0783		
Resistance C	0.0055	0.0055	0.0055	0.0055	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Mechanical energy at wheel for SINGLE journey	86.74	31.03	124.89	44.94	586.34	469.15	821.96	659.22	kWh	Results from STS model
Braking energy at wheel for SINGLE journey	24.33	56.65	33.97	76.93	262.04	313.72	313.12	381.53	kWh	Results from STS model
SINGLE journey time (excluding dwell at terminal)	**20**	**20**	**20**	**20**	**92**	**89**	**92**	**89**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Power supplied to traction package (max) at DC bus	818	818	1169	1169	818	818	1169	1169	kW	
Auxiliary power demand (worst case) at DC bus	118	118	200	200	118	118	200	200	kW	Stadler data for 2-car, estimate 4-car
Total power to be generated at DC bus (= min battery rated output)	**936**	**936**	**1369**	**1369**	**936**	**936**	**1369**	**1369**	**kW**	
Likely battery pack rated power	1320		1320		6600		8250		kW	
ENERGY CALCULATIONS	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Energy consumed by traction package at DC bus	101	36	146	53	685	548	961	771	kWh	
Energy consumed by auxiliaries (excludes dwell at terminals)	39	38	33	35	54	60	93	103	kWh	Assume auxiliaries powered by shore supply while at terminal stations
Total energy consumed per return journey before regen	140	75	179	87	740	609	1053	873	kWh	
Regen efficiency wheel to DC bus	74%	74%	74%	74%	74%	74%	74%	74%		
Energy stored and released by battery pack	18	42	25	57	194	232	232	282	kWh	
Total energy for single journey including regen	**122**	**33**	**154**	**30**	**546**	**376**	**822**	**591**	**kWh**	
Total energy for return journey including regen	155		184		922		1412		kWh	
Minimum battery pack rated capacity (max 50%	**245**	**65**	**308**	**60**	**1092**	**753**	**1643**	**1182**	**kWh**	
Likely battery pack rated capacity (max 50% discharge)	220		220		1100		1375		kWh	
ENERGY SUPPLY CALCULATIONS	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Battery pack storage efficiency	86%	86%	86%	86%	86%	86%	86%	86%		
Energy from shore supply to charge batteries at terminal stations	142	38	179	35	635	438	955	687	kWh	
Energy provided to auxiliaries while at terminals	20	20	33	35	54	60	93	103	kWh	
Total energy provided by shore supply per single journey	162	58	213	70	689	498	1048	790	kWh	
Number of SINGLE journeys per day	1	1	1	1	1	1	1	1		
Total energy provided by shore supply for all (daily) journeys	162	58	213	70	689	498	1048	790	kWh	
Total energy supplied by shore supply at terminals per day	**162**	**58**	**213**	**70**	**689**	**498**	**1048**	**790**	**kWh**	
CHARGING AT TERMINAL STATIONS	**2-Car**		**4-Car**		**2-Car**		**4-Car**		**Units**	**Source / Notes**
Battery max charge rate	1320	1320	1320	1320	6600	6600	8250	8250	kW	
Time at charging station	10	10	10	10	28	31	28	31	minutes	
Max energy delivered to battery pack during dwell at terminal	**222**	**229**	**220**	**228**	**3057**	**3378**	**3820**	**4232**	**kWh**	

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - BEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	220		282		1227		1838	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	624	74	1044	79	3934	76	5937	76
POINT-OF-USE EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**0**	***100***	**0**	***100***	**0**	***100***	**0**	***100***
NOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM2.5: Total	0	*100*	0	*100*	0	*100*	0	*100*
PM10: Total	0	*100*	0	*100*	0	*100*	0	*100*
CO: Total	0	*100*	0	*100*	0	*100*	0	*100*
VOC: Total	0	*100*	0	*100*	0	*100*	0	*100*
SOx: Total	0	*100*	0	*100*	0	*100*	0	*100*
CH4	0	*100*	0	*100*	0	*100*	0	*100*
N2O	0	*100*	0	*100*	0	*100*	0	*100*
CO2 (w/ C in VOC & CO)	0	*100*	0	*100*	0	*100*	0	*100*
BC: Total	0	*100*	0	*100*	0	*100*	0	*100*
OC: Total	0	*100*	0	*100*	0	*100*	0	*100*
Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - BEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP (CA ELECTRICITY)								
Energy Requirements (in kWh)	163		209		907		1357	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	4	*2*	53	*20*	111	*11*	175	*11*
WELL-TO-PUMP EMISSIONS (CA ELECTRICITY)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**65459**	***-36***	**83818**	***-11***	**364348**	***-24***	**545554**	***-23***
NOx: Total	51	*39*	65	*50*	282	*44*	422	*45*
PM2.5: Total	3	*37*	4	*48*	16	*42*	24	*43*
PM10: Total	6	*-9*	8	*11*	33	*1*	49	*1*
CO: Total	40	*-2*	52	*17*	224	*8*	336	*8*
VOC: Total	9	*62*	11	*69*	49	*65*	73	*65*
SOx: Total	48	*-39*	61	*-13*	265	*-26*	396	*-26*
CH4	156	*52*	199	*61*	866	*56*	1297	*57*
N2O	1	*-40*	1	*-14*	5	*-28*	8	*-27*
CO2 (w/ C in VOC & CO)	60543	*-59*	77524	*-30*	336987	*-45*	504586	*-44*
BC: Total	0	*52*	0	*61*	2	*56*	3	*56*
OC: Total	1	*33*	1	*46*	5	*39*	8	*40*
Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - BEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL								
Energy Requirements (in kWh)	383		491		2134		3195	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	628	*62*	1097	*69*	4045	*65*	6112	*66*
WELL-TO-WHEEL EMISSIONS (CA ELECTRICITY)								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	65459	*76*	83818	*81*	364348	*78*	545554	*78*
NOx: Total	51	*98*	65	*99*	282	*98*	422	*98*
PM2.5: Total	3	*97*	4	*97*	16	*97*	24	*97*
PM10: Total	6	*93*	8	*95*	33	*94*	49	*94*
CO: Total	40	*91*	52	*92*	224	*92*	336	*92*
VOC: Total	9	*94*	11	*95*	49	*94*	73	*94*
SOx: Total	48	*-33*	61	*-8*	265	*-21*	396	*-20*
CH4	156	*55*	199	*63*	866	*59*	1297	*59*
N2O	1	*86*	1	*89*	5	*88*	8	*88*
CO2 (w/ C in VOC & CO)	60543	*77*	77524	*81*	336987	*79*	504586	*79*
BC: Total	0	*95*	0	*96*	2	*95*	3	*95*
OC: Total	1	*99*	1	*99*	5	*99*	8	*99*

14.2.6 Natural Gas-Electric Multiple Unit

NGEMU (Natural Gas Electric Multiple Unit)						
CONFIGURATION & ASSUMPTIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target return journey time including terminal dwells	60	60	240	240	minutes	MSU for Redlands, estimate for LAUS
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading
Engine	8,000	12,000	8,000	12,000	kg	MSU
Fuel	2,000	2,000	2,000	2,000	kg	UoB Estimate
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	134,000	201,000	134,000	201,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen limit at wheel	1800	1800	1800	1800	kW	Stadler brochure for TEX Rail FLIRT
Resistance A	1.624	2.408	1.624	2.408		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0651	0.0442	0.0651		
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	119	174	940	1338	kWh	Results from STS model
Braking energy at wheel for return journey	84	119	534	668	kWh	Results from STS model
Return journey time excluding dwell at terminals	**40**	**40**	**177**	**177**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Traction package efficiency	86%	86%	86%	86%		
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Max auxiliary power demand at DC bus	118	200	118	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
Alternator and DC:DC converter efficiency	92%	92%	92%	92%		
Required engine output (max)	1016	1486	1016	1486	kW	
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	139	203	1099	1563	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus per return journey	257	403	1569	2363	kWh	
Diesel engine efficiency	30%	30%	30%	30%		
Fuel energy required per journey	912	1432	5575	8397	kWh	Multiplied by 1.08, based on GREET
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy per unit of fuel	2.64	2.64	2.64	2.64	kWh / litre	
Units of fuel require per journey	**345**	**543**	**2112**	**3181**	**litres**	
Number of journeys per day	1	1	1	1		Estimate
Energy required for all journeys	912	1432	5575	8397	kWh	
Total volume fuel required	**345**	**543**	**2112**	**3181**	**litres**	
Fuel specific mass	0.201	0.201	0.201	0.201	kg/litre	
Total mass of fuel required	69	109	424	639	kg	

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - NGEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	912		1432		5575		8397	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-68	*-8*	-106	*-8*	-413	*-8*	-622	*-8*
POINT-OF-USE EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**198209**	***13***	**311304**	***13***	**1211486**	***13***	**1824766**	***13***
NOx: Total	3077	*-8*	4833	*-8*	18809	*-8*	28330	*-8*
PM2.5: Total	9	*89*	14	*89*	54	*89*	81	*89*
PM10: Total	9	*89*	14	*89*	55	*89*	83	*89*
CO: Total	214	*46*	337	*46*	1310	*46*	1973	*46*
VOC: Total	128	*-8*	201	*-8*	781	*-8*	1176	*-8*
SOx: Total	1	*47*	1	*47*	5	*47*	8	*47*
CH4	425	*-2060*	667	*-2060*	2596	*-2060*	3910	*-2060*
N2O	7	*-8*	10	*-8*	41	*-8*	61	*-8*
CO2 (w/ C in VOC & CO)	182974	*18*	287377	*18*	1118369	*18*	1684510	*18*
BC: Total	1	*89*	1	*89*	4	*89*	7	*89*
OC: Total	8	*89*	12	*89*	47	*89*	71	*89*

Route	SBTC to Redlands to SBTC				TC to LAUS to SBTC			
Configuration - NGEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP								
Energy Requirements (in kWh)	131		206		800		1205	
Energy Reduction	***In %***		***In %***		***In %***		***In %***	
	21		*21*		*21*		*21*	
WELL-TO-PUMP EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	**50467**	**-5**	**79263**	**-5**	**308462**	**-5**	**464612**	**-5**
NOx: Total	136	*-65*	214	*-65*	834	*-65*	1255	*-65*
PM2.5: Total	2	*66*	2	*66*	10	*66*	14	*66*
PM10: Total	2	*64*	3	*64*	12	*64*	18	*64*
CO: Total	110	*-176*	172	*-176*	669	*-176*	1008	*-176*
VOC: Total	34	*-49*	54	*-49*	209	*-49*	314	*-49*
SOx: Total	39	*-15*	62	*-15*	240	*-15*	362	*-15*
CH4	817	*-152*	1284	*-152*	4995	*-152*	7524	*-152*
N2O	5	*-643*	8	*-643*	30	*-643*	45	*-643*
CO2 (w/ C in VOC & CO)	24644	*35*	38705	*35*	150626	*35*	226876	*35*
BC: Total	0	*44*	1	*44*	3	*44*	4	*44*
OC: Total	1	*61*	1	*61*	3	*61*	5	*61*

Route	SBTC to Redlands to SBTC				TC to LAUS to SBTC			
Configuration - NGEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL								
Energy Requirements (in kWh)	1043		1638		6375		9601	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-32	*-3*	-50	*-3*	-196	*-3*	-295	*-3*
WELL-TO-WHEEL EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	248675	*10*	390567	*10*	1519948	*10*	2289378	*10*
NOx: Total	3214	*-10*	5047	*-10*	19642	*-10*	29586	*-10*
PM2.5: Total	10	*88*	16	*88*	63	*88*	95	*88*
PM10: Total	11	*88*	17	*88*	67	*88*	101	*88*
CO: Total	324	*26*	509	*26*	1980	*26*	2982	*26*
VOC: Total	162	*-15*	254	*-15*	989	*-15*	1490	*-15*
SOx: Total	40	*-12*	63	*-12*	245	*-12*	370	*-12*
CH4	1242	*-261*	1951	*-261*	7591	*-261*	11434	*-261*
N2O	12	*-70*	18	*-70*	71	*-70*	106	*-70*
CO2 (w/ C in VOC & CO)	207617	*21*	326082	*21*	1268995	*21*	1911386	*21*
BC: Total	1	*84*	2	*84*	7	*84*	11	*84*
OC: Total	8	*89*	13	*89*	51	*89*	77	*89*

14.2.7 Natural Gas-Electric Hybrid Multiple Unit

Hybrid NGEMU (Natural Gas Hybrid Electric Multiple Unit)						
CONFIGURATION & ASSUMPTIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target journey time	60	60	240	240	minutes	Round-trip including dwell at terminal stations
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Engines	4,000	4,000	4,000	8,000	kg	2 x Deutz diesel engines
Batteries	4,000	6,000	4,000	2,000	kg	2 x ABB LTO battery packs
Fuel	2,000	2,000	2,000	2,000	kg	
MAX REGEN LIMITATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max regen limit of battery pack	660	660	660	660	kW	
Traction package efficiency	86%	86%	86%	86%		
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	134,000	199,000	134,000	199,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen at wheel	771	771	771	771	kW	
Resistance A	1.624	2.408	1.624	2.408		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0651	0.0442	0.0651		
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	119	173	940	1330	kWh	Results from STS model
Braking energy at wheel for return journey	66	85	327	385	kWh	Results from STS model
Return journey time (excluding dwell at terminals)	**40**	**40**	**177**	**177**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Auxiliary power demand (worst case)	118	200	118	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	139	202	1099	1555	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus before regen	257	402	1569	2355	kWh	
Regen efficiency wheel to DC bus	74%	74%	74%	74%		
Energy stored and released by battery pack	49	63	242	285	kWh	
Total energy for return journey including regen	**208**	**339**	**1327**	**2070**	**kWh**	
ENGINE SIZE CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Average power that needs generating	207.9	338.9	331.8	517.5	kW	
Alternator & DC:DC converter efficiency	92%	92%	92%	92%		
Absolute minimum engine rated output	226	368	360	562	kW	
Suggested minimum engine rated output	**271**	**441**	**432**	**674**	**kW**	Guidance from MSU (minimum + 20%)
Actual likely engine output	520	520	520	1040	kW	Assume multiples of Deutz 520kW
BATTERY SIZE CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Max power to be supplied by battery at DC bus	416	849	416	329	kW	Maximum power minus likely engine output
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Hybrid Diesel genset efficiency	33%	33%	33%	33%		
Fuel energy required per journey	677	1104	4322	6741	kWh	Multiplied by 1.08, according to GREET Model
Energy per unit of fuel	2.64	2.64	2.64	2.64	kWh / litre	
Units of fuel require per journey	**256**	**418**	**1637**	**2554**	**litres**	
Number of journeys per day	1	1	1	1		
Energy required for all journeys	677	1104	4322	6741	kWh	
Total volume fuel required	**256**	**418**	**1637**	**2554**	**litres**	
Fuel specific mass	0.201	0.201	0.201	0.201	kg/litre	
Total mass of fuel required	52	84	329	513	kg	

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid NGEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	677		1104		4322		6741	
Energy Reduction	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*
	167	*20*	223	*17*	839	*16*	1033	*13*

POINT-OF-USE EMISSIONS								
	Total Emissions		Total Emissions		Total Emissions		Total Emissions	
	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*
GHGs	**147157**	***35***	**239832**	***33***	**939313**	***32***	**1465058**	***30***
NOx: Total	2285	*20*	3723	*17*	14583	*16*	22746	*13*
PM2.5: Total	6	*92*	11	*92*	41	*92*	65	*91*
PM10: Total	7	*92*	11	*92*	43	*92*	67	*91*
CO: Total	159	*60*	259	*58*	1016	*58*	1584	*57*
VOC: Total	95	*20*	155	*17*	605	*16*	944	*13*
SOx: Total	1	*60*	1	*59*	4	*59*	6	*57*
CH4	315	*-1504*	514	*-1564*	2013	*-1575*	3139	*-1634*
N2O	5	*20*	8	*17*	31	*16*	49	*13*
CO2 (w/ C in VOC & CO)	135846	*39*	221398	*37*	867115	*37*	1352450	*34*
BC: Total	1	*92*	1	*92*	3	*92*	5	*91*
OC: Total	6	*92*	9	*92*	37	*92*	57	*91*

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - Hybrid NGEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, WELL-TO-PUMP								
Energy Requirements (in kWh)	97		158		620		967	
Energy Reduction	*In %*		*In %*		*In %*		*In %*	
	-391		*76*		*76*		*76*	

WELL-TO-PUMP EMISSIONS								
	Total Emissions		Total Emissions		Total Emissions		Total Emissions	
	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*
GHGs	**37468**	***22***	**61065**	***19***	**239163**	***19***	**373025**	***16***
NOx: Total	101	*-22*	165	*-27*	646	*-28*	1008	*-32*
PM2.5: Total	1	*75*	2	*74*	7	*74*	12	*73*
PM10: Total	1	*73*	2	*72*	9	*72*	14	*71*
CO: Total	81	*-105*	133	*-113*	519	*-114*	810	*-122*
VOC: Total	25	*-10*	41	*-15*	162	*-15*	252	*-19*
SOx: Total	29	*15*	48	*12*	186	*11*	291	*8*
CH4	607	*-87*	989	*-94*	3873	*-95*	6041	*-102*
N2O	4	*-451*	6	*-472*	23	*-476*	36	*-496*
CO2 (w/ C in VOC & CO)	18296	*52*	29819	*50*	116786	*50*	182153	*48*
BC: Total	0	*58*	1	*57*	2	*56*	3	*55*
OC: Total	0	*71*	1	*70*	3	*69*	4	*68*

Route	SBTC to Redlands to SBTC				TC to LAUS to SBTC			
Configuration - Hybrid NGEMU	2-Car		4-Car		2-Car		4-Car	
ENERGY COMPARISON, WELL-TO-WHEEL								
Energy Requirements (in kWh)	774		1262		4942		7709	
Energy Reduction	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*	In kWh	*In %*
	237	*23*	326	*21*	1236	*20*	1598	*17*

WELL-TO-WHEEL EMISSIONS								
	Total Emissions		Total Emissions		Total Emissions		Total Emissions	
	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*	In grams	*Reduc. In %*
GHGs	**184625**	***33***	**300896**	***30***	**1178476**	***30***	**1838083**	***28***
NOx: Total	2386	*19*	3888	*16*	15229	*15*	23754	*12*
PM2.5: Total	8	*91*	12	*91*	49	*91*	76	*90*
PM10: Total	8	*91*	13	*91*	52	*90*	81	*90*
CO: Total	240	*45*	392	*43*	1535	*42*	2394	*40*
VOC: Total	120	*15*	196	*12*	767	*11*	1196	*8*
SOx: Total	30	*17*	49	*14*	190	*13*	297	*10*
CH4	922	*-168*	1503	*-178*	5886	*-180*	9180	*-190*
N2O	9	*-26*	14	*-31*	55	*-32*	85	*-36*
CO2 (w/ C in VOC & CO)	154142	*41*	251216	*39*	983902	*39*	1534604	*36*
BC: Total	1	*88*	1	*88*	6	*88*	9	*88*
OC: Total	6	*92*	10	*91*	39	*91*	61	*91*

14.2.8 Renewable Diesel-Electric Multiple Unit

RDEMU (Renewable Diesel Electric Multiple Unit)						
CONFIGURATION & ASSUMPTIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target return journey time including terminal dwells	60	60	240	240	minutes	
COMPONENT MASSES	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition, less engine & fuel
Engine	8,000	12,000	8,000	12,000	kg	
Fuel	2,000	2,000	2,000	2,000	kg	
INPUTS TO SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Train mass	134,000	201,000	134,000	201,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen limit at wheel	1800	1800	1800	1800	kW	Stadler brochure for TEX Rail FLIRT (assume rated rheostatic fitted)
Resistance A	1.624	2.408	1.624	2.408		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0651	0.0442	0.0651		
Resistance C	0.0055	0.0055	0.0055	0.0055		
OUTPUTS OF SIMULATION	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Mechanical energy at wheel for return journey	119.11	173.85	940.35	1337.6	kWh	Results from STS model
Braking energy at wheel for return journey	83.62	118.86	533.85	668.15	kWh	Results from STS model
Return journey time excluding dwell at terminals	**39.55**	**39.67**	**176.76**	**177.36**	**min**	**Results from STS model**
POWER CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Traction package efficiency	86%	86%	86%	86%		
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Max auxiliary power demand at DC bus	117.5	200	117.5	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	
Alternator and DC:DC converter efficiency	92%	92%	92%	92%		
Required engine output (max)	1016	1486	1016	1486	kW	
ENERGY CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy consumed by traction package	139	203	1099	1563	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus per round-trip	257	403	1569	2363	kWh	
Diesel genset efficiency	30%	30%	30%	30%		
Fuel energy required per journey	844	1326	5162	7775	kWh	
FUEL CALCULATIONS	**2-Car**	**4-Car**	**2-Car**	**4-Car**	**Units**	**Source / Notes**
Energy per unit of fuel	9.94	9.94	9.94	9.94	kWh / litre	
Units of fuel require per journey	**85**	**133**	**519**	**782**	**litres**	
Number of journeys per day	1	1	1	1		
Energy required for all journeys	844	1326	5162	7775	kWh	
Total volume fuel required	**85**	**133**	**519**	**782**	**litres**	
Fuel specific mass	0.832	0.832	0.832	0.832	kg/litre	
Total mass of fuel required	71	111	432	650	kg	

Route	SBTC to Redlands to SBTC				SBTC to LAUS to SBTC			
Configuration - RDEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	844		1326		5162		7775	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	0	*0*	0	*0*	0	*0*	0	*0*

POINT-OF-USE EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	227474	*0*	357268	*0*	1390361	*0*	2094191	*0*
NOx: Total	2849	*0*	4475	*0*	17416	*0*	26232	*0*
PM2.5: Total	32	*60*	51	*60*	198	*60*	298	*60*
PM10: Total	84	*0*	131	*0*	511	*0*	769	*0*
CO: Total	159	*60*	249	*60*	970	*60*	1462	*60*
VOC: Total	118	*0*	186	*0*	723	*0*	1089	*0*
SOx: Total	2	*0*	2	*0*	10	*0*	14	*0*
CH4	20	*0*	31	*0*	120	*0*	181	*0*
N2O	6	*0*	10	*0*	38	*0*	57	*0*
CO2 (w/ C in VOC & CO)	224264	*0*	352226	*0*	1370740	*0*	2064637	*0*
BC: Total	7	*0*	11	*0*	42	*0*	63	*0*
OC: Total	72	*0*	113	*0*	439	*0*	661	*0*

Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC	
Configuration - RDEMU	**2-Car**	**4-Car**	**2-Car**	**4-Car**
ENERGY COMPARISON, WELL-TO-PUMP				
Energy Requirements (in kWh)	374	588	2286	3444
Energy Reduction	***In %***	***In %***	***In %***	***In %***
	-125	*-125*	*-125*	*-125*

WELL-TO-PUMP EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	-157403	*427*	-247216	*427*	-962075	*427*	-1449097	*427*
NOx: Total	100	*-20*	156	*-20*	609	*-20*	917	*-20*
PM2.5: Total	5	*-9*	8	*-9*	31	*-9*	46	*-9*
PM10: Total	6	*-9*	9	*-9*	36	*-9*	54	*-9*
CO: Total	61	*-53*	95	*-53*	371	*-53*	559	*-53*
VOC: Total	57	*-150*	90	*-150*	350	*-150*	528	*-150*
SOx: Total	68	*-99*	107	*-99*	418	*-99*	630	*-99*
CH4	103	*68*	162	*68*	631	*68*	951	*68*
N2O	63	*-9356*	99	*-9356*	384	*-9356*	578	*-9356*
CO2 (w/ C in VOC & CO)	-177132	*565*	-278201	*565*	-1082660	*565*	-1630726	*565*
BC: Total	2	*-146*	3	*-146*	12	*-146*	18	*-146*
OC: Total	1	*8*	2	*8*	8	*8*	12	*8*

Route	SBTC to Redlands to SBTC			BTC to LAUS to SBTC				
Configuration - RDEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL								
Energy Requirements (in kWh)	1219		1914		7448		11219	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	-208	*-21*	-326	*-21*	-1269	*-21*	-1912	*-21*

WELL-TO-WHEEL EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	70071	*75*	110053	*75*	428286	*75*	645094	*75*
NOx: Total	2949	*-1*	4632	*-1*	18024	*-1*	27149	*-1*
PM2.5: Total	37	*56*	59	*56*	229	*56*	345	*56*
PM10: Total	89	*-1*	141	*-1*	547	*-1*	824	*-1*
CO: Total	220	*50*	345	*50*	1342	*50*	2021	*50*
VOC: Total	176	*-24*	276	*-24*	1073	*-24*	1617	*-24*
SOx: Total	70	*-95*	110	*-95*	428	*-95*	644	*-95*
CH4	123	*64*	193	*64*	751	*64*	1132	*64*
N2O	69	*-912*	108	*-912*	421	*-912*	634	*-912*
CO2 (w/ C in VOC & CO)	47132	*82*	74025	*82*	288080	*82*	433912	*82*
BC: Total	9	*-15*	14	*-15*	53	*-15*	81	*-15*
OC: Total	73	*0*	115	*0*	447	*0*	673	*0*

14.2.9 Renewable Diesel-Electric Hybrid Multiple Unit

Hybrid RDEMU (Renewable Diesel Hybrid Electric Multiple Unit)

CONFIGURATION & ASSUMPTIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Route	SBTC to Redlands to SBTC		SBTC to LAUS to SBTC			
Target journey time	60	60	240	240	minutes	Round-trip including dwell at terminal

COMPONENT MASSES	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Train (without engine & fuel)	124,000	187,000	124,000	187,000	kg	Stadler data for AW3 loading condition,
Engines	4,000	4,000	4,000	4,000	kg	2 x Deutz diesel engines
Batteries	4,000	4,000	4,000	4,000	kg	2 x ABB LTO battery packs
Fuel	2,000	2,000	2,000	2,000	kg	

MAX REGEN LIMITATIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Max regen limit of battery pack	660	660	660	660	kW	
Traction package efficiency	86%	86%	86%	86%		

INPUTS TO SIMULATION	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Train mass	134,000	197,000	134,000	197,000	kg	
Installed power at wheel	700	1000	700	1000	kW	Stadler brochure for TEX Rail FLIRT
Max regen at wheel	771	771	771	771	kW	
Resistance A	1.624	2.408	1.624	2.408		Equivalent to CN resistance formula with streamlining = 19
Resistance B	0.0442	0.0651	0.0442	0.0651		
Resistance C	0.0055	0.0055	0.0055	0.0055		

OUTPUTS OF SIMULATION	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Mechanical energy at wheel for return journey	119	173	940	1330	kWh	Results from STS model
Braking energy at wheel for return journey	66	85	327	385	kWh	Results from STS model
Return journey time (excluding dwell at terminals)	**40**	**40**	**177**	**177**	**min**	**Results from STS model**

POWER CALCULATIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Max power supplied to traction package at DC bus	818	1169	818	1169	kW	
Auxiliary power demand (worst case)	118	200	118	200	kW	Stadler data for 2-car, estimate for 4-car
Total power to be generated at DC bus	936	1369	936	1369	kW	

ENERGY CALCULATIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Energy consumed by traction package	139	202	1099	1555	kWh	
Energy consumed by auxiliaries	118	200	470	800	kWh	
Total energy consumed at DC bus before regen	257	402	1569	2355	kWh	
Regen efficiency wheel to DC bus	74%	74%	74%	74%		
Energy stored and released by battery pack	49	63	242	285	kWh	
Total energy for return journey including regen	**208**	**339**	**1327**	**2070**	**kWh**	

ENGINE SIZE CALCULATIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Average power that needs generating	207.9	338.9	331.8	517.5	kW	
Alternator & DC:DC converter efficiency	92%	92%	92%	92%		
Absolute minimum engine rated output	225.7	367.9	360.2	561.8		
Suggested minimum engine rated output	**271**	**441**	**432**	**674**	**kW**	Guidance from MSU (minimum + 20%)
Actual likely engine output	520	520	520	1040	kW	Assume multiples of Deutz 520kW

BATTERY SIZE CALCULATIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Max power to be supplied by battery at DC bus	416	849	416	329	kW	Maximum power minus likely engine

FUEL CALCULATIONS	2-Car	4-Car	2-Car	4-Car	Units	Source / Notes
Hybrid Diesel genset efficiency	33%	33%	33%	33%		
Fuel energy required per journey	627	1022	4002	6242	kWh	
Energy per unit of fuel	9.94	9.94	9.94	9.94	kWh / litre	
Units of fuel require per journey	**63**	**103**	**402**	**628**	**litres**	
Number of journeys per day	1	1	1	1		
Energy required for all journeys	627	1022	4002	6242	kWh	
Total volume fuel required	**63**	**103**	**402**	**628**	**litres**	
Fuel specific mass	0.832	0.832	0.832	0.832	kg/litre	
Total mass of fuel required	52	85	335	522	kg	

Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - Hybrid RDEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, POINT-OF-USE								
Energy Requirements (in kWh)	627		1022		4002		6242	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	218	*26*	305	*23*	1160	*22*	1533	*20*
POINT-OF-USE EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	168884	*26*	275243	*23*	1078002	*22*	1681373	*20*
NOx: Total	2115	*26*	3448	*23*	13503	*22*	21061	*20*
PM2.5: Total	24	*70*	39	*69*	154	*69*	240	*68*
PM10: Total	62	*26*	101	*23*	396	*22*	618	*20*
CO: Total	118	*70*	192	*69*	752	*69*	1174	*68*
VOC: Total	88	*26*	143	*23*	561	*22*	874	*20*
SOx: Total	1	*26*	2	*23*	7	*22*	12	*20*
CH4	15	*26*	24	*23*	93	*22*	145	*20*
N2O	5	*26*	7	*23*	29	*22*	45	*20*
CO2 (w/ C in VOC & CO)	166501	*26*	271358	*23*	1062789	*22*	1657645	*20*
BC: Total	5	*26*	8	*23*	32	*22*	50	*20*
OC: Total	53	*26*	87	*23*	340	*22*	531	*20*

Route	**SBTC to Redlands to SBTC**		**BTC to LAUS to SBTC**					
Configuration - Hybrid RDEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-PUMP								
Energy Requirements (in kWh)	278		453		1773		2765	
Energy Reduction	***In %***		***In %***		***In %***		***In %***	
	-391		*-391*		*-391*		*-391*	
WELL-TO-PUMP EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	-116861	*343*	-190457	*352*	-745935	*354*	-1163443	*363*
NOx: Total	74	*11*	121	*7*	472	*7*	736	*3*
PM2.5: Total	4	*19*	6	*16*	24	*15*	37	*12*
PM10: Total	4	*19*	7	*16*	28	*16*	44	*13*
CO: Total	45	*-14*	73	*-18*	288	*-19*	449	*-23*
VOC: Total	43	*-85*	69	*-92*	272	*-94*	424	*-100*
SOx: Total	51	*-48*	83	*-54*	324	*-55*	506	*-60*
CH4	77	*76*	125	*75*	489	*75*	763	*74*
N2O	47	*-6921*	76	*-7185*	297	*-7232*	464	*-7492*
CO2 (w/ C in VOC & CO)	-131509	*445*	-214329	*459*	-839429	*461*	-1309268	*474*
BC: Total	1	*-83*	2	*-89*	9	*-91*	14	*-97*
OC: Total	1	*31*	2	*29*	6	*28*	10	*26*

Route	**SBTC to Redlands to SBTC**				**SBTC to LAUS to SBTC**			
Configuration - Hybrid RDEMU	**2-Car**		**4-Car**		**2-Car**		**4-Car**	
ENERGY COMPARISON, WELL-TO-WHEEL								
Energy Requirements (in kWh)	905		1474		5775		9007	
Energy Reduction	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***	**In kWh**	***In %***
	106	*11*	113	*7*	404	*7*	299	*3*
WELL-TO-WHEEL EMISSIONS								
	Total Emissions		**Total Emissions**		**Total Emissions**		**Total Emissions**	
	In grams	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***	**In grams**	***Reduc. In %***
GHGs	52023	*81*	84786	*80*	332067	*80*	517929	*80*
NOx: Total	2189	*25*	3568	*23*	13975	*22*	21797	*19*
PM2.5: Total	28	*68*	45	*66*	177	*66*	277	*65*
PM10: Total	66	*25*	108	*23*	424	*22*	661	*19*
CO: Total	163	*63*	266	*61*	1040	*61*	1622	*60*
VOC: Total	130	*8*	212	*4*	832	*4*	1298	*0*
SOx: Total	52	*-45*	85	*-50*	332	*-51*	517	*-57*
CH4	91	*73*	149	*72*	583	*72*	909	*71*
N2O	51	*-651*	83	*-680*	327	*-685*	509	*-713*
CO2 (w/ C in VOC & CO)	34992	*87*	57030	*86*	223360	*86*	348377	*86*
BC: Total	6	*14*	11	*11*	41	*11*	65	*8*
OC: Total	54	*26*	88	*23*	346	*23*	540	*20*

14.3 Data Tables for Calculations

14.3.1 Estimate Powertrain Component Efficiency Values

Powertrain Efficiency Values		
Note: Estimated, average component efficiencies over duty cycle		
TRACTION PACKAGE EFFICIENCY	**Value**	**Source / Notes**
Power Electronics	98.0%	MSU estimate from previous work
Traction Motor	90.0%	MSU estimate from previous work
Mechanical Gears	97.0%	MSU estimate from previous work
TOTAL	**86%**	
DIESEL / BIODIESEL GENSET EFFICIENCY	**Value**	**Source / Notes**
Diesel Engine	33.0%	MSU estimate from previous work and literature
Diesel Engine Hybrid	36.0%	MSU estimate from previous work and literature
Generator / alternator	94.0%	MSU estimate from previous work
DC:DC converter	98.0%	MSU estimate from previous work
TOTAL	**30%**	
HYBRID TOTAL	**33%**	
ALTERNATOR & DC:DC CONVERTER ONLY	**Value**	**Source / Notes**
Generator / alternator	94.0%	MSU
Converter	98.0%	MSU
TOTAL	**92%**	
TRACTION BATTERY	**Value**	**Source / Notes**
Battery Charge & Discharge	86.0%	ABB LTO article for EOL
TOTAL	**86%**	
REGEN BRAKING EFFICIENCY (wheel to wheel)	**Value**	**Source / Notes**
Wheel to DC bus	85.6%	Combination of traction package
Battery efficiency	86.0%	ABB LTO article for EOL
DC bus to wheel	85.6%	Combination of traction package
TOTAL	**63%**	
FUEL CELL GENSET	**Value**	**Source / Notes**
Fuel Cell System (FCS)	52.5%	Literature review and supplier engagement
Hybrid Fuel Cell System (HFCS)	50.0%	Literature review and supplier engagement
DC:DC converter	98.0%	MSU estimate from previous
TOTAL	**51%**	
HYBRID TOTAL	**49%**	
NATURAL GAS GENSET	**Value**	**Source / Notes**
Natural Gas Engine	33.0%	Based on diesel engine
Generator / alternator	94.0%	MSU estimate from previous work
Converter	98.0%	MSU estimate from previous work
TOTAL	**30%**	

14.3.2 Energy Value of Fuels

Energy Contained in Different Fuels										
Conversion factor for BTU to kWh	0.000293071									
Conversion US gallon to litre	3.78541									
Fuel	**Heating Value***				**Density***			**C ratio***	**S ratio***	**S ratio***
	LHV							**(% by wt)**	**(ppm by wt)**	**Actual ratio by wt**
Fuels:	**Btu/gal**	**kWh/gal**	**kWh/litre**	**MJ/kg**	**grams/gal**	**kg/gal**	**kg/litre**			
Diesel for non-road engines	128,450	37.64	9.94	42.61	3167.00	3.17	0.84	86.5%	11.00	0.000011
Renewable Diesel I (SuperCetane)	117,059	34.31	9.06		2835.00	2.84	0.75	87.1%	-	0.000000
Natural gas	983	0.29	0.076		22.00	0.022	0.0058	72.4%	6.00	0.000006
Gaseous hydrogen	290	0.08	0.022	120.210	2.55	0.0026	0.00067	0.0%	-	0.000000
* Values from GREET model										

14.3.3 Hydrogen Tank Data

Hydrogen Cylinder Calculations based on Hexagon Composites Data Sheet

Model	Pressure	Cylinder Ext Dia	Cylinder Ext Radius	Cylinder Length	Cylinder Volume	Storage Volume	Cylinder Mass	Stored H2 Mass	Volume / Stored Mass
					(Pi x R x R x L)	(D x D x L)			
	bar	m	m	m	m3	m3	kg	kg	m3 / kg
E	**350**	**0.420**	**0.210**	**3.190**	**0.44**	**0.56**	**101**	**7.5**	**0.075**
F	350	0.509	0.255	2.342	0.48	0.61	112	8.4	0.072

14.3.4 Battery Pack Data

Battery Calcultions

ABB LTO "LARGE ENERGY" BATTERY PACK	BOL*	EOL*		Notes / Source
Capacity	69	**55**	kWh	ABB article
Max C Rating (continuous) - discharge	6.0	**6.0**		ABB atricle
Max discharge power according to C rating	414	**330**	kW	
Max C Rating (continuous) - charge	6	**6**		ABB atricle
Max charge power according to C rating	414	**330**	kW	
Battery mass including cooling	2000	**2000**	kg	

PROPOSED FLIRT BATTERY PACK - Hybrid DEMU / Hybrid FCEMU	BOL*	EOL*		Notes / Source
Number of ABB battery packs	2	**2**		In series
Capacity	138	**110**	kWh	
Max rated discharge power according to C rating	828	**660**	kW	
Max rated charge power according to C rating	828	**660**	kW	
Battery mass	4000	**4000**	kg	

PROPOSED FLIRT BATTERY PACK - 2/4-car BEMU running SBTC to Redlands	BOL*	EOL*		Notes / Source
Number of ABB battery packs	4	**4**		In series
Capacity	276	**220**	kWh	
Max rated discharge power according to C rating	1656	**1320**	kW	
Max rated charge power according to C rating	1656	**1320**	kW	
Battery mass	8000	**8000**	kg	

PROPOSED FLIRT BATTERY PACK for 2-car BEMU running SBTC to LAUS	BOL*	EOL*		Notes / Source
Number of ABB battery packs	20	**20**		In series
Capacity	1380	**1100**	kWh	
Max rated discharge power according to C rating	8280	**6600**	kW	
Max rated charge power according to C rating	8280	**6600**	kW	
Battery mass	40000	**40000**	kg	

PROPOSED FLIRT BATTERY PACK for 4-car BEMU running SBTC to LAUS	BOL*	EOL*		Notes / Source
Number of ABB battery packs	25	**25**		In series
Capacity	1725	**1375**	kWh	
Max rated discharge power according to C rating	10350	**8250**	kW	
Max rated charge power according to C rating	10350	**8250**	kW	
Battery mass	50000	**50000**	kg	

* Beginnng Of Life / End Of Life