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Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040

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Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040

March 2020

A Research Report from the National Center for Sustainable Transportation

Andrew Burke, University of California, Davis

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The objective of this study is to project the introduction of battery-electric and fuel cell technologies into the medium-duty and heavy-duty vehicle markets and to identify which markets will be most suitable for each of technologies and the factors (technical, economic, operational) which will be most critical to their successful introduction. The use of renewable energy sources to generate electricity and produce hydrogen are key considerations of the analysis. The present status of the battery-electric and hydrogen/fuel cell technologies are reviewed in detail and the futures of these technologies are projected. The design and performance of various types of buses and trucks are described based on detailed simulations of the various electrified vehicles. The total cost of ownership (TCO) of each bus/truck type were calculated using EXCEL spreadsheets and their market prospects projected for 2020-2040. It was concluded that before any of the electrified vehicles can be cost competitive with the corresponding diesel powered vehicle, the unit cost of batteries must be $80-100/kWh and the unit cost of the fuel cell system must be $80-100/kW. The long term economics of battery-electric buses and trucks looks more favorable than that for the fuel cell/hydrogen option if the range requirement (miles) for the vehicle can be met using batteries. This is primarily due to the significantly lower energy operating cost ($/mi) using electricity than hydrogen.</td></tr>
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Disclaimer

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EXECUTIVE SUMMARY

The objective of this study was to project the introduction of battery-electric and fuel cell/hydrogen technologies into the medium-duty (MD) and heavy-duty (HD) vehicle markets and to identify which markets will be most suitable for each of technologies and the factors (technical, economic, operational) which will be most critical to their successful introduction. The study considered trucks and buses of various types—delivery vans, transit buses, intercity buses, long haul and short haul tractor trailer trucks, and heavy-duty pickup trucks.

The initial sections of the report contain detailed reviews of lithium battery and PEM fuel cell technologies and their application in the powertrains of trucks and buses. The fuel cell technology review includes hydrogen storage as a high-pressure gas and a cyro-compressed liquid and in liquid organic hydrogen carriers (LOHC). Efficient and cost–effective storage of the hydrogen on–board the vehicles is critical to the marketing of fuel cell/hydrogen powered trucks and buses.

In the next section of the report, the energy consumptions (Wh/mi and kgH_2/mi) for the trucks of various types are calculated using the ADVISOR vehicle simulation program. Simulation results were obtained for each truck type for several appropriate driving cycles. From the energy consumption results, the battery (kWh) and hydrogen (kg) storage required were calculated to meet specified ranges of the trucks and buses. The initial energy storage results were for vehicle operation on level roads and it was determined that to account for operation on grades and increased accessory loads, the energy storage required for a specified range should be about doubled to provide that range with confidence in real world operation.

After determining the energy storage requirements, consideration was given to providing the infrastructure needed to charge the batteries onboard the trucks and refueling the trucks with hydrogen. The infrastructure at both truck/bus terminals and along highways were analyzed. In the case of battery-electric buses, both fast charging the batteries along the city routes and overnight charging at the bus terminal were considered. In the case of trucks powered by hydrogen fuel cells, refueling along an interstate highway was analyzed utilizing an electrolyzer connected to the grid to produce hydrogen on-site at large hydrogen refueling stations. These stations could produce and dispense hydrogen at about $5/kg if the cost of the grid electricity was $.1/kWh or less.

Sustainability aspects of fueling trucks and buses were discussed in terms of the Low Carbon Fuel Standard (LCFS) being implemented in California. The LCFS is intended to fuel vehicles using fuels produced from renewable resources having a low carbon intensity (gm CO_2/MJ). For the battery-electric and fuel cell/hydrogen trucks, this means refueling using primarily

electricity from solar and wind resources directly to charge batteries or indirectly to produce hydrogen using an electrolyzer. Both California and the United States are producing an increasing fraction of their electricity from solar and wind and at costs approaching that of electricity produced from natural gas. Hence there is reason to believe that when trucks and buses using batteries and fuel cells are marketed, renewable (sustainable) electricity/hydrogen will be available to fuel them. The future costs of the electricity and hydrogen at the present time are uncertain.

The final sections of the report deal with the initial cost of the battery-electric and hydrogen fuel cell trucks and buses and their ownership costs and the prospects for marketing the electrified vehicles in 2020-2040. The initial purchase costs of the electrified vehicles depend primarily on the unit costs ($/kWh and $/kW) of the batteries and fuel cell systems. The operating cost ($/mi) of the vehicles depends primarily on the energy costs ($/kWh of electricity and $/kg of hydrogen) and their reduced maintenance costs. In general, the economic analyses indicate that none of the electrified trucks become cost competitive until the battery and fuel cell costs decrease to the lowest values (70-100/kWh for batteries and $80-100/kW for fuel cells) assumed in the calculations even for the relatively low electricity ($.10/kWh) and hydrogen ($5/kg) prices assumed. How soon the maturing technologies will reach those cost values is uncertain, but it seems likely to occur in the next 10-20 years.

Even at the battery cost of $80/kWh, the long haul truck (300 miles), the short haul truck (150 miles) and the pickup truck (150 miles) would not be competitive with the diesel trucks. Battery-electric vehicles of the other types would be cost competitive and their sales should be promising as their initial costs approach those of the conventional diesel vehicles and the energy costs ($/mi) of the battery-electric vehicles are less than the diesel vehicles. The maintenance costs of the battery-electric were assumed to be one-half (1/2) the cost per mile of the corresponding diesel truck.

In the case of the fuel cell-electric trucks and buses, the fuel cell costs required for the electrified vehicles to become cost competitive were $80-100/kW. This is the cost of the complete fuel cell system including all accessories to the vehicle manufacturer/assembler. It does not include the cost of the hydrogen storage which was assumed to cost $ 200/kgH_2. For the low fuel cell costs ($80-100/kW) and hydrogen at $5/k, the delivery van and buses are cost competitive with the diesel both in terms of initial cost and TCO. Under these conditions, the sales of the delivery vans and buses would be promising if the required infrastructure for hydrogen is available. The economics of the long-haul trucks using fuel cells and hydrogen are more promising than with batteries. First, the range of the fuel cell long haul truck has been increased to 600 miles from 300 miles using batteries. Second, the cost of the tractor with the low-cost fuel cell would be $156K compared to $227K with the batteries. However, the TCO of the fuel cell/hydrogen truck ($.97/mi) for hydrogen at $5/kg would be higher than of the battery-electric long-haul truck ($.71/mi). The TCO of the diesel truck is estimated to be $.78/mi. Hence the marketability of the fuel cell truck would be dependent on the price of hydrogen which would need to be less than $5/kg. The short haul truck (150 mile range) seems to be best suited to be battery-electric unless the cost of hydrogen is well below $5/kg or the price of electricity for truck companies is considerably higher than the $.10/kWh value assumed in all the battery-electric economic calculations.

In summary, the long-term economics of battery-electric buses and trucks looks more favorable than that for the fuel cell/hydrogen option if the range requirement (miles) for the truck can be met using batteries. This is primarily due to the significantly lower energy operating cost ($/mi) using electricity than hydrogen. The difference is, of course, dependent on the relative costs of the electricity and hydrogen. The differences in the initial costs of the battery-electric and fuel cell trucks depends on the range assumed for the respective vehicles. In general, the ranges of the fuel cell vehicles can be greater than the battery-electric vehicles for the same initial cost. If the energy costs are higher than assumed, the battery and fuel cell unit costs will have to be lower than those discussed in this study for the electrified vehicles to be cost-competitive with the diesel vehicles for the same diesel fuel cost.

1. Introduction

The objective of this study is to project the introduction of battery electric and fuel cell technologies into the MD/HD vehicle markets and to identify which markets will be most suitable for each of technologies and the factors (technical, economic, operational) which will be most critical to their successful introduction. The degree to which the markets will utilize sustainable energy sources will be assessed.

The study was performed in terms of the following tasks.

Task 1: Projection of the characteristics of heavy-duty battery characteristics for use in buses and trucks

Task 2: Projection of the characteristics of heavy-duty fuel cell systems for use in buses and trucks

Task 3: Projection of the characteristics of hydrogen energy storage for buses and trucks

Task 4: Projections of the cost of buses and various MD/HD trucks having specified ranges using batteries and fuel cells

Task 5: Summary of the design and operational characteristics of battery charging and hydrogen refueling infrastructure for urban terminals and intercity stations

Task 6: Sustainable energy availability and economics

Task 7: Estimation of the ownership costs of buses and various MD/HD trucks meeting user requirements

Task 8: Projection of the markets and prospects for the sale of battery powered and hydrogen fuel cell buses and trucks for 2020-2040

2. Battery characteristics for use in buses and trucks

As indicated in Table 1 below, there are a number of lithium battery chemistry that could be used in MD/HD vehicles. These are the same chemistry that can be used in light-duty vehicles. In fact, for the most part, the same cells are used to assemble batteries for all the vehicles from the smallest to the largest vehicles.

Table 1. Characteristics of lithium batteries of various chemistries [2]

Lithium battery type	Wh/kg	Wh/L	Cycle life	Cost *$/kWh	Power capability	Fast charge capability
NiCoMn (NCM)	200-250	420-525	1000-2000	200-300	moderate	Fair
$LiFePO_4$ (LFP)	100-140	220-310	2000-3000	200-300	Low	Good
LiTiOxide (LTO)	45-100	85-190	10000-20000	400-500	High	Excellent

*cost in 2016-2017, battery costs will lower in 2020 and beyond

One of the key questions to consider is whether it is appropriate to use the same lithium cells for all the vehicle types. To investigate this question, it is instructive to compare the batteries that would be used in a small vehicle like the Chevy Bolt with the battery for a HD short haul truck. Both battery packs use the same 56 Ah NCM cell used in Bolt which are supplied by LG Chem. The characteristics of the small battery pack (V, kWh, and kW) are the same as that in the 2017 Bolt. In the case of the battery pack for the short haul truck, the battery stores 500 kWh and the truck has a maximum power of 320 kW. It is somewhat counter-intuitive that the cells in the Bolt are more highly stressed (higher W/kg) than the cells in the short haul truck EV during maximum effort accelerations requiring peak power from the battery. This is the case because the battery in the HD truck is much larger and contains ten (10) times more cells. Hence each cell in the larger battery does not work as hard. This is even true when the small and large vehicles are traveling at 60 mph. Hence it appears that there should be no problem in using the cells designed for use in the passenger cars in MD/HD trucks. In fact, it might be appropriate to design special cells for use in the trucks that have lower power capability and as a consequent can have higher energy density, longer life, and lower cost if manufactured in the same quantities as the smaller cells used in cars.

One of the big differences shown in Table 2 is in the deep discharge cycles per year. The battery in the Bolt will experience only 50 deep discharge cycles/yr while the battery in the short haul truck will experience over 300 cycles/yr, because it will be deep discharged nearly every day. Hence in terms of years, the cycle life of the battery in the truck will be shorter than in the passenger car. The average power (W/kg) for the discharge of both batteries will be relatively low.

Table 2. Comparison of the physical and working characteristics of the battery in light-duty and heavy-duty vehicles

Parameter	Light-duty vehicle (Bolt)	Heavy-duty vehicle (short haul truck EV)
Energy stored (kWh)	60	500
Pack voltage (V)	355	750
NCM Battery cell Ah (1.04 kg/cell)	56	56
Pack cell configuration	96s3p (288 cells)	192s13p (2500 cells)
Total weight of cells (kg)	300	2600
Cell energy density (Wh/kg)	200	200
Maximum Power (kW)	150	320
Power density (W/kg)	**500**	**123**
Miles per year	12000	40000-85000
Battery deep discharge cycles/yr	**50 (250 Wh/mi)**	**360 (2.1 kWh/mi)**
Average power (kW; W/kg)		
60 mph	15; 50	96; 37
City driving	5; 17	21; 8

The battery packs in the trucks will be much larger, have many more cells, and generate more heat to remove. For that reason, the thermal management and battery management (BMS) systems for the truck batteries will be more complex and expensive. The packaging of the large batteries will also have to more robust as the physical environment (vibration, exposure to the weather and road conditions) will be more extreme. Hence it appears that the same cells can be used in the batteries for cars and trucks, but the surrounding packaging and monitoring will be more demanding.

The work on this task has involved both testing of lithium-ion cells of various chemistries in the UCD-ITS Battery Lab and detailed reviews of the literature concerned with present and projected characteristics of lithium batteries. Testing has been completed for a A123 $LiFePO_4$ cell, a LG Chem NCM cell, and a Toshiba LTO cell. One of the cell characteristics of particular interest is the cell resistance and how that influences its pulse current capability. Battery manufacturers often do not give information on the resistance of their cells. A paper was presented at EVS 32 [33] that summarizes the results of our recent battery testing. It is concerned with comparing the power capability of lithium batteries and supercapacitors.

Contact was made with Microvast [1], a battery manufacturer headquartered in Texas, but with its engineering and manufacturing in China. Microvast has announced it will be building a large facility in Texas to assemble large battery packs for trucks and busses. Microvast is the only battery manufacturer in the world that specializes in batteries for trucks and buses. They design and manufacture the cells and then assembly them into battery packs. Until the last few years, Microvast has specialized in LTO batteries and emphasized fast charging applications. In more recent years, Microvast has developed batteries with other chemistries than LTO. As indicated in Figure 1, Microvast now has developed products with cell voltages and energy densities similar to NCM like LG Chem. As indicated in Figure 2, their cells have a maximum voltage of 4.25V and an energy density of 225 Wh/kg, 650 Wh/L. This performance is as good as any other manufacturer in the world and their battery modules and packs are designed for heavy-duty applications. The cells are designed for pulse discharges up to 6C and charging up to 3C (20 minutes charge). The R&D road map from Microvast (Figure 1) shows a target of an energy density of 350 Wh/kg, 800-1000 Wh/L and 3C fast charging by 2022. Hence Microvast intends to have batteries available for trucks and buses with the same high energy density that the auto industry hopes to have available for passenger cars.

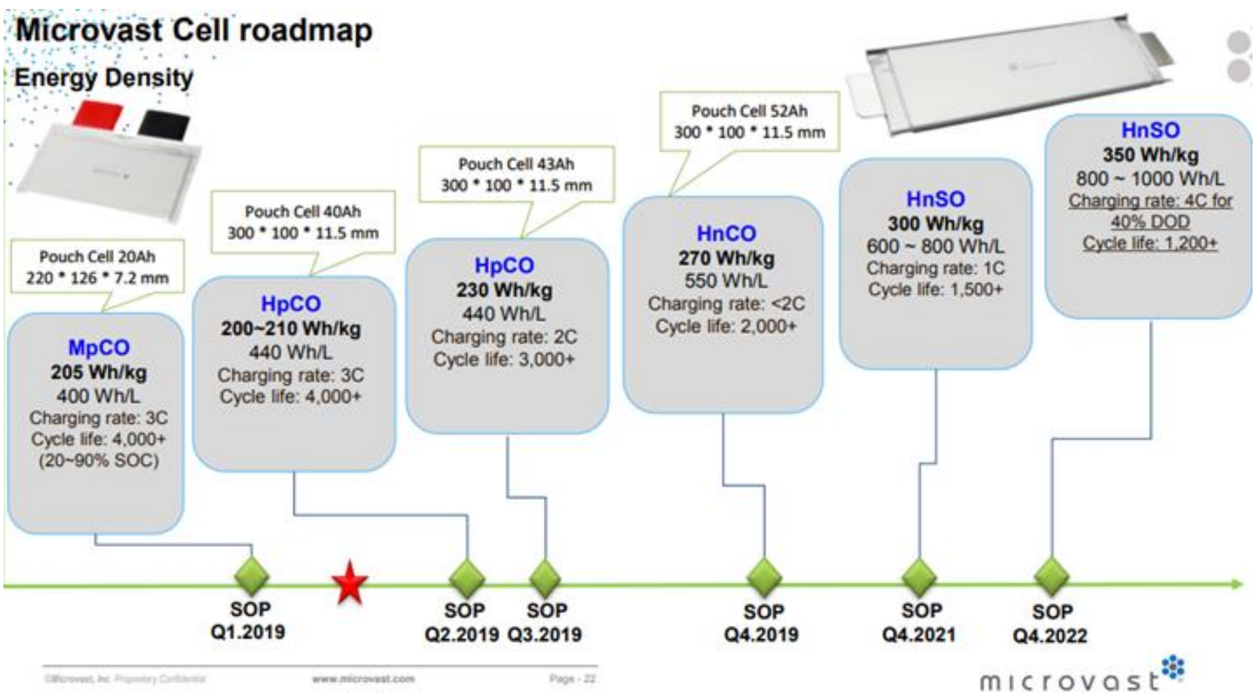
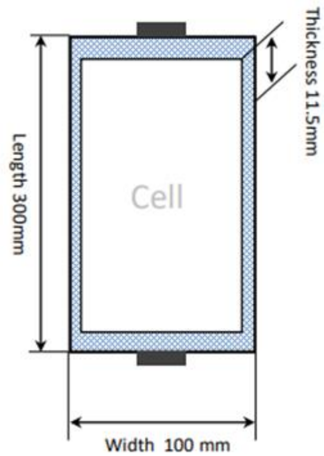


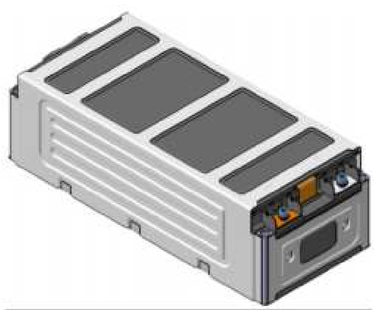
Figure 1. Microvast roadmap for battery development to 2022

New solution oriented for automotive application



NO.	Item	Parameter	Remark
1	Nominal capacity	43 Ah	HpCO 1C @25℃
2	Nominal voltage	3.7V	
3	Nominal energy	159 Wh	
4	Dimensions	300*100*11.5 mm^3	L x W x T
5	Weight	690g	
6	Voltage Range	2.7～4.25V	
7	Gravimetric Specific Energy	225Wh/kg	230 Wh/kg (C-sample)
8	Continuous Discharge Rate	2C	25℃
9	Pulse Discharge Rate	6C	10s,50%SOC,25℃
10	Continuous Charging Rate	3C	25℃
11	Pulse charge Rate	6C	10s,50%SOC,25℃
12	Cycle Life	≥3000	2CC/1CD,25℃, EOL 80%
13	Safety level	<L4	EUCAR Hazard Level

VDA Module Spec 12s1p



No.	Item	Parameter	remark
1	Nominal capacity	43 Ah	1C
2	Nominal voltage	44.4 V	
3	Voltage range	32.4 V ~ 51 V	
4	Configuration	12s1p	
5	Nominal Energy	1909 Wh	
6	Continuous charge power	3.8 kW	2C @25℃ (A-sample until C-sample)
7	Peak charge power	11.4 kW	6C, 10s@ 50% SOC, 25℃
7	Continuous discharge power	5.7 kW	3C @25℃
8	Peak discharge power	11.4 kW	6C, 10s@ 50% SOC, 25℃
9	Dimension	355*151.5*108 mm^3	L x W x H
10	Weight	10.4 kg	
11	Energy density	184 Wh/kg	

Figure 2. Microvast cell and module products for trucks

3. The characteristics of heavy-duty fuel cell systems for use in buses and trucks

This section is concerned with the determining the characteristics of PEM (Proton Exchange Membrane) fuel cells for MD/HD trucks and buses. The company that has been developing fuel cell systems for those applications for several decades is Ballard in British Columbia, Canada. The physical characteristics of the Ballard fuel cell systems—dimensions, weight, and power, but not the operating characteristics like the V vs. I curve and system efficiency, are given in their publications [3-6]. Information/data on the 100 kW Ballard fuel cell are given in Figure 3 and Table 3.

Figure 3. The Ballard 100 kW heavy-duty fuel cell system [4]

Table 3. Characteristics of the Ballard 100 kW heavy-duty fuel cell system

Component	Weight kg	Volume L	kW/kg	kW/L
Fuel cell module	285	528		
Coolant system	44	148		
Air subsystem	61	99		
Total	390	775	.256	.129

Ballard is testing their fuel cells in buses around the world [5] and those tests show that the Ballard fuel cells have excellent durability [6] of 25,000-30,000 hours in HD applications.

It is thought that the Ballard fuel cells have a maximum efficiency of 55-60%. Information on the efficiency of the present generation of fuel cells is shown in the Figure 4.

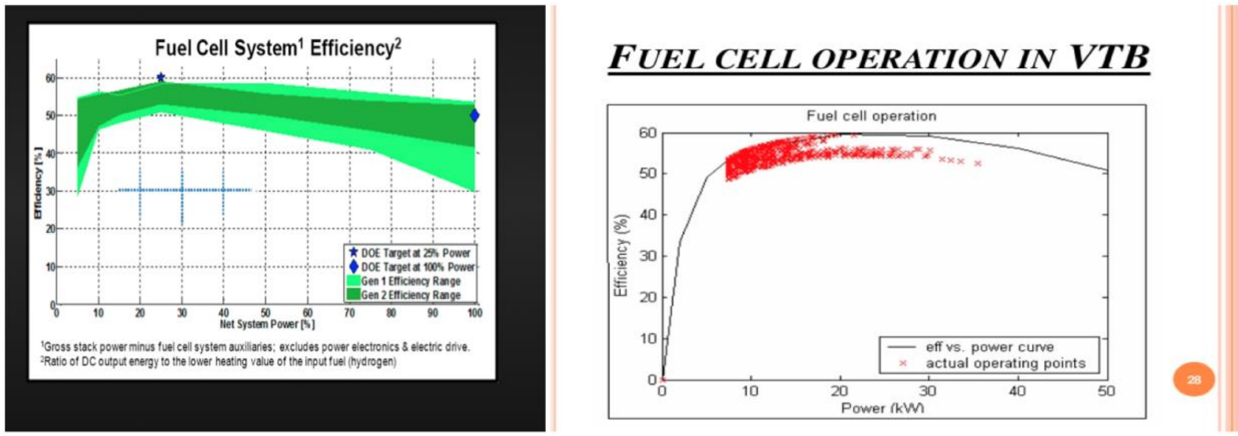


Figure 4. Fuel cell efficiency curves

Note that the peak efficiency of the fuel cell is reached at a relatively low fraction of the maximum power of the fuel cell, but the efficiency curve is relatively flat. The power shown of a fuel cell is the net power after subtracting the power needed to operate the air system that provides air (oxygen) to the cathode (positive electrode) of the fuel cells.

The basic operation of the fuel cell is given in terms of the V (voltage) vs. I (current density A/cm^2) curve shown in Figure 5. The curve on the left is a generaic V vs. I curve and the one on the right is a V vs. I curve for an actual fuel cell. Note the large drop in the voltage for low currents due to polarization effects primarily at the air cathode. The ideal voltage of the fuel cell is about 1.2V and the initial voltage for present generation fuel cells is close to .9V. This means that the maximum efficiency would be 75% if there were no other loses or auxiliary loads. That is the reason the maximum efficiency occurs at a low power fraction. Progress in reducing the polarization voltage drop has been very slow. Most of the progress has been in reducing the Ohmic loses at the high currents by improving the solid/gel electrolyte between the anode and cathode and the diffusion of the gases in those electrodes. In vehicles, the fuel cell operates at power levels close to and higher than that for the maximum efficiency.

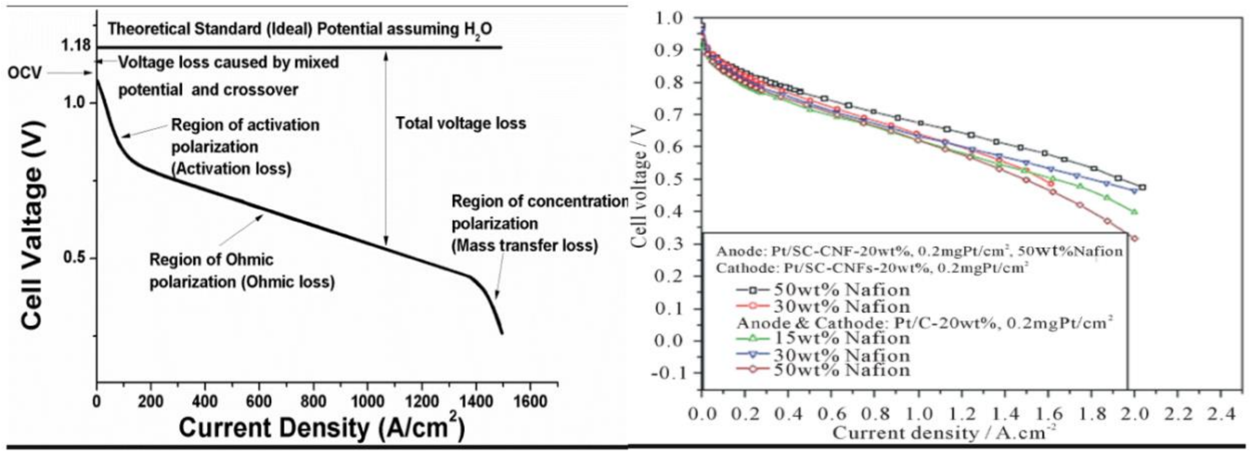


Figure 5. Fuel cell V vs. I curves

Much of the research on fuel cells in recent years has been to reduce their cost ($/kw). The DOE has had an extensive study [7] of the projected cost of fuel cells for MD/HD vehicles that indicates the cost of fuel cells will be reduced in future years by a large factor reaching about $100/kW at production rates of 100,000 units/yr. (See Figure 6). Ballard has indicated that the cost of $100/kW was a reasonable expectation in the long-term future.

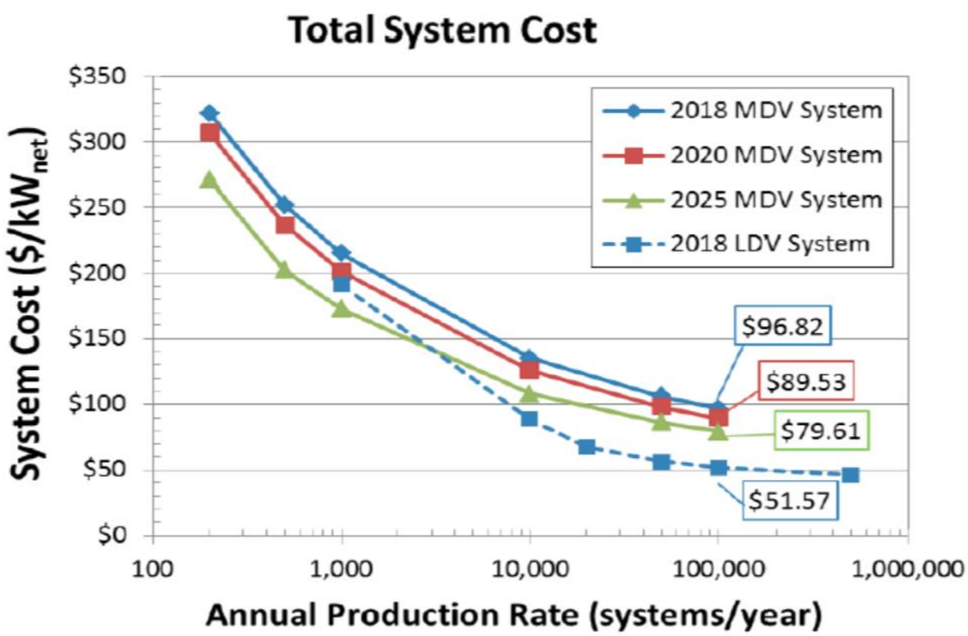


Figure 6. Fuel cell cost projections [7]

4. The characteristics of hydrogen energy storage for buses and trucks

4.1. Characteristics of presently available hydrogen storage technologies

Sufficient hydrogen must be stored onboard the vehicle to meet the range requirement of the vehicle. At the present time, nearly all fuel cell vehicles store the hydrogen as a compressed gas at either 350 atm. (5000 psi) or 700 atm. (10000 psi). There has been consideration of storing the hydrogen as a liquid at near 20 deg K at low pressure (<10 atm.) or as a liquid at about 50 deg K at high pressure (350 atm.). This later system is referred to as cryo-compressed hydrogen storage (see Figure 7) and has been studied/developed by BMW and DOE/ANL [8,9]. The present status of these various approaches to storing hydrogen are summarized in Figure 7 and Table 4. Note in Table 4 that the Toyota hydrogen storage [10] system (see Figure 8) meets the DOE targets for hydrogen storage in 2020. The cryo-compressed gas system seems to have a significant advantage in weight compared to hydrogen storage at 700 atm., but not in volume.

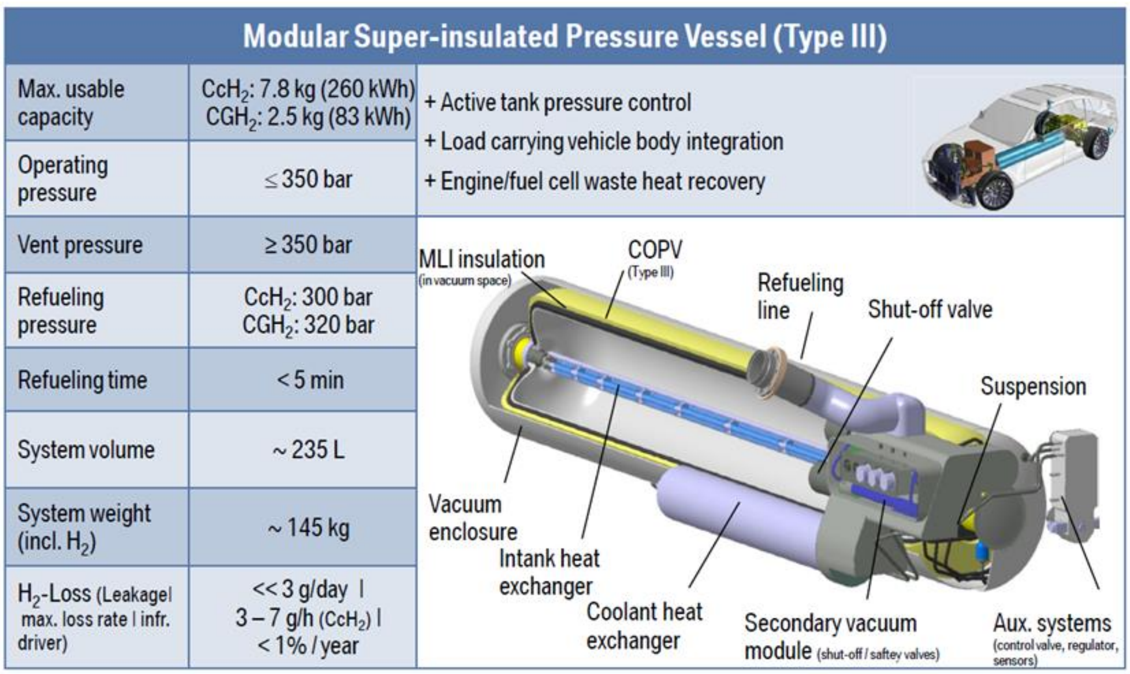


Figure 7. The cryo-compressed gas storage unit being developed by BMW [8]

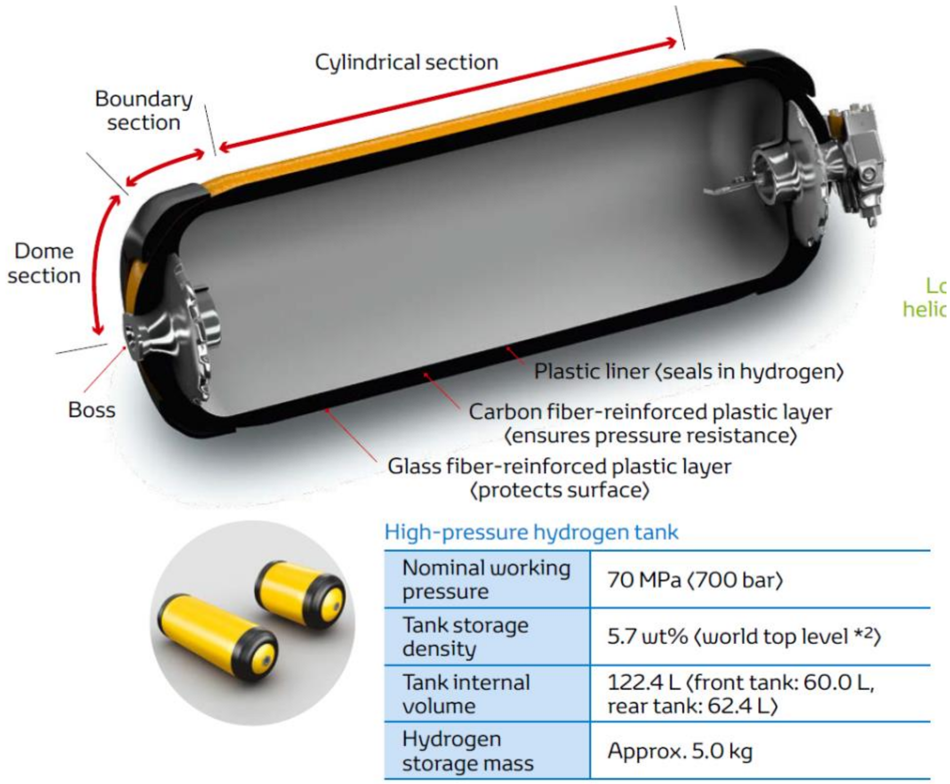


Figure 8. The Toyota/Mirai hydrogen storage unit [10]

Table 4. Hydrogen storage characteristics using several available technologies

Storage of 25kgH2 useable	**Compressed gas (350 atm.) BMW**	**Toyota (700 atm.)**	**Cryo-compressed (350 atm) BMW**	**DOE Goals**	
Weight (kg)	430	439	250		
Volume (L)	1420	678	607		
				2020	**ultimate**
kgH2/kg syst.	.058	.057	.100	.055	.075
KgH2/L syst.	.018	.037	.041	.04	.07

4.2. Liquid Organic Hydrogen Carriers for hydrogen storage

As shown in Table 4, only the cryo-compressed approach to hydrogen storage shows promise of reaching the DOE volume goal for 2020 and none of the presently available technologies shows promise of meeting the ultimate volume goal of .07 kg H_2/L_{sys} . The only hydrogen storage approach being developed which shows promise of significantly better performance than gaseous storage at 700 atm (10000 psi) is storing hydrogen in a liquid organic hydrogen carrier (LOHC) [11-15]. A wide range of lean hydrogen organic liquids [14,15] are being studied that can reversibly store and release up to 7 wt. % of hydrogen. The hydrogenated liquid would be stored in a tank like gasoline and be transported to the refueling stations like gasoline. Hence the infrastructure for the LOHC fuel would be nearly the same as for gasoline. From the literature, the goals shown in Table 5 are reasonable for the development of the LOHC hydrogen storage system for vehicles.

Table 5. Hydrogen storage system goals using LOHC

H_2 storage Technology	**DOE ultimate**	**LOHC**	**700 atm. gas**
kgH2/kg syst.	.075	.07-.10	.057
KgH2/L syst.	.07	.06- .09	.037

At the present time, the R&D on LOHC systems are focused on identification and characterization of the best organic carrier material and the catalyst needed for the dehydrogenation (release of hydrogen) in the vehicle. Current research data [12] indicates hydrogen wt.% of up to 10% may be possible in the relatively near-term. The dehydrogenation process requires a temperature of 120-150 deg C and pressure less than atmospheric. R&D on a dehydrogenation reactor for use in a vehicle has been started, but a reactor does not seem to have been demonstrated in a vehicle [12,13] to date.

LOHC is a promising approach for hydrogen storage for both vehicle and grid applications, but it is still relatively early in its development.

5. The characteristics of buses and various MD/HD trucks having specified ranges using batteries and fuel cells.

This section involves the start of the development of detailed EXCEL spreadsheets to calculate the characteristics and economics of the various types of electrified trucks and buses using batteries and fuel cells, the capacity and cost of the infrastructure needed to refuel the electrified vehicles both at a home base and on the road, projected markets for the ZEV vehicles, and potential for the use of renewable fuels in the vehicles.

This task was concerned primarily with the determination of the design characteristics of the vehicles and the powertrains for the trucks and buses of various types. The initial step in the development of the spreadsheet is the determination of the vehicle characteristics and the calculation of the vehicle energy consumption for various types of driving. The energy consumption of the vehicles was calculated using a vehicle simulation program ADVISOR [16-19] using the road load inputs given in Table 6. The energy consumption results are summarized in Table 7. These energy consumption values will be used to calculate the kWh of electricity and kg of hydrogen needed to meet the range requirements of the various vehicles. The ADVISOR simulation results are consistent with the limited test data available for the various types of MD/HD electric vehicles.

Table 6. Road load characteristics of MD/HD buses and trucks

Vehicle type	Electric motor kW	C_D/ A m^2	f_r	W_V Kg	Accessories kW
City Delivery					
2030	125	.6 / 7.8	.007	6900	1.5
2050	125	.55 / 7.2	.006	6750	1.5
City transit bus					
2030	250	.65 / 7.1	.0075	15000	6
2050	250	.55 / 7.1	.005	14000	6
Inter-city bus					
2030	250	.6 / 7.7	.0075	15000	6
2050	250	.55 /7.2	.005	14000	6
Heavy-duty truck (long- and short-haul)					
2030	300	.55 /9.5	.0055	29500	1.5
2050	300	.45/ 9.5	.005	29000	1.5
HD pick- up truck					
2030	250	.41 / 3.1	.0075	3950	.8
2050	250	.40 / 3.1	.006	3875	.8

Table 7. Energy use of battery-electric and fuel cell vehicles of various types on level ground

Vehicle type	*2030	2050
MD delivery truck (city)		
Battery- powered (kWh/100 mi)	85	72
Fuel cell (kgH_2 /100 mi)	5.6	5.2
Diesel mpg	10.5	12.5
Transit bus (city)		
Battery- powered (kWh/100 mi)	230	215
Fuel cell (kgH2 /100 mi)	9.6	9
Diesel mpg	6.5	7.3
Inter-city bus (highway)		
Battery- powered (kWh/100 mi)	123	95
Fuel cell (kgH2 /100 mi)	166	130
Diesel mpg	10.1	11.9
HD long-haul truck (highway)		
Battery- powered (kWh/100 mi)	240	200
Fuel cell (kgH2 /100 mi)	.15	
Diesel mpg	8.7	10.1
HD short-haul truck (city)		
Battery- powered (kWh/100 mi)	233	210
Fuel cell (kgH2 /100 mi)	12.9	11.6
Diesel mpg	8.2	9
HD pick-up truck (city)		
Battery- powered (kWh/100 mi)	53	58

*80% of battery capacity is used initially, 150 Wh/kg 2030, 225 Wh/kg 2050

The roads on which the vehicles will be traveling are not all level (flat). To investigate the effect of grade on energy consumption, ADVISOR simulations have been made for the various types of battery-electric trucks and for city and highway driving on roads with grades of .5 and 1%. The results of the simulations are shown in Table 8. To include the effect of most small to modest grades, a factor of 1.3 will be included in later calculations of energy requirements for specified vehicle ranges to account for use on non-level roads. ADVISOR simulation results for the diesel long haul truck indicated that their fuel economy decreased by about 45% on a 1% grade.

Table 8. The increase in energy consumption (Wh/mi) for city and highway driving on grades for electric trucks of various types

Type of driving and grade	Truck type City delivery	Transit bus	Long haul truck	HD pick up
City driving				
0	1.0	1.0	1.0	1.0
.5%	1.13*	1.2	1.24	1.19
1%	1.26	1.37	1.5	1.37
Highway driving				
0	1.0	1.0	1.0	1.0
.5%	1.23	1.15	1.39	1.25
1%	1.36	1.36	1.8	1.5

*Ratio = $(Wh/mi)_{grade}$ / $(Wh/mi)_0$

It also is of interest to consider the effect of improved cell energy density on the weight and volume of the battery pack especially compared to the weight of the tractor (3535 kg). The effect of the cell energy density on the battery pack characteristics are shown Table 9. Even for a cell energy density of 350Wh/kg, the weight of the battery pack (1200 kWh) for 500 miles on level roads will be greater than that of the diesel-powered tractor. Lithium batteries with a cell energy density of 350 Wh/kg will likely not be available for use in vehicles for at least 5 years.

Table 9. Battery pack characteristics for different cell energy densities

kWh stored in battery	Cell energy density (Wh/kg/Wh/l)	Cell weight kg	Cell volume L	Pack weight* kg	Pack volume** L
100 kWh					
	148/320	676	313	811	422
	225/495	444	202	533	273
	350/770	286	130	343	176
400 kWh					
	148/320	2703	1250	3244	1688
	225/495	1778	808	2134	1091
	350/770	1143	519		
800 kWh					
	148/320	5405	2500	6486	3375
	225/495	3556	1616	4268	2182
	350/770	2285	1039	2742	1403
1200 kWh					
	148/320	8108	3750	9730	5063
	225/495	5333	2424	6400	3272
	350/770	3423	1558	4108	2103

*Weight packaging factor 1.2
*Volume packaging factor 1.35

The vehicle spreadsheets developed can be used to quickly determine the effect of input parameters such as vehicle range and battery energy density (Wh/kg) on the energy storage requirements (electricity kWh and hydrogen kg) and the weight and volume of the battery and the fuel cell for the various types of trucks. The output tables for the city delivery truck, transit bus, and long-haul truck are shown in Tables 9–11.

Year	Vehicle Parameters Input				Battery capacity needed for specific ranges (kWh) (80% useable cap)				Battery Pack Weight (kg)				Battery Pack Volume (L)			
	Vehicle Weight (kg)	Energy Consumption (kWh/mile)	Battery Weight Energy Density	Battery Volume Energy Density (Wh/L)	75 miles	100 miles	150 miles	200 miles	75 miles	100 miles	150 miles	200 miles	75 miles	100 miles	150 miles	200 miles
2015																
2020																
2030	6900	0.83	200	400	116	155	233	310	582	776	1164	1552	291	388	582	776
2040					0	0	0	0								
2050	6750	0.72	275	600	101	135	202	269	367	490	734	979	168	224	337	449

Fuel Cell											
	Input Parameters					Results					
Year	Vehicle Parameters Input					Fuel Cell Pack Weight and Volume		H2 capacity needed for specific ranges (kgH2) (90% useable cap)			
	Vehicle Weight (kg)	Energy Consumption (kgH2/mile)	Fuel Cell Power (kW)	Fuel Cell Weight Power Density (W/kg)	Fuel Cell Volume Power Density (W/L)	Weight (kg)	Volume (L)	75 miles	100 miles	150 miles	200 miles
2015											
2020											
2030	6900	0.056	125	300	150	417	833	7	9	13	18
2040											
2050	6750	0.052	125	500	250	250	500	6	8	12	17

Figure 9. Battery and fuel cell weights and volumes for the city delivery truck

Year	Vehicle Parameters Input				Battery capacity needed for specific ranges (kWh) (80% useable cap)				Battery Pack Weight (kg)				Battery Pack Volume (L)			
	Vehicle Weight (kg)	Energy Consumption (kWh/mile)	Battery Weight Energy Density (Wh/kg)	Battery Volume Energy Density (Wh/L)	75 miles	100 miles	150 miles	200 miles	75 miles	100 miles	150 miles	200 miles	75 miles	100 miles	150 miles	200 miles
2015																
2020																
2030	15000	2.2	200	400	309	411	617	823	1543	2057	3086	4114	771	1029	1543	2057
2040					0	0	0	0								
2050	14000	1.83	275	600	257	342	513	684	933	1244	1867	2489	428	570	856	1141

Fuel Cell

	Input Parameters					Results					
Year	Vehicle Parameters Input					Fuel Cell Pack Weight and Volume		H2 capacity needed for specific ranges (kgH2) (90% useable cap)			
	Vehicle Weight (kg)	Energy Consumption (kgH2/mile)	Fuel Cell Power (kW)	Fuel Cell Weight Power Density (W/kg)	Fuel Cell Volume Power Density (W/L)	Weight (kg)	Volume (L)	75 miles	100 miles	150 miles	300 miles
2015											
2020											
2030	15000	0.096	200	300	150	667	1333	12	15	23	46
2040											
2050	14000	0.09	200	500	250	400	800	11	14	22	43

Figure 10. Battery and fuel cell weights and volumes for the transit bus

Battery Electric																
	Input Parameters				Results											
Year	Vehicle Parameters Input				Battery capacity needed for specific ranges (kWh) (80% useable cap)				Battery Pack Weight (kg)				Battery Pack Volume (L)			
	Vehicle Weight (kg)	Energy Consumption (kWh/mile)	Battery Weight Energy Density (Wh/kg)	Battery Volume Energy Density (Wh/L)	75 miles	100 miles	150 miles	300 miles	75 miles	100 miles	150 miles	300 miles	75 miles	100 miles	150 miles	300 miles
2015																
2020																
2030	29500	2.4	200	400	337	449	673	1346	1683	2244	3366	6732	842	1122	1683	3366
2040					0	0	0	0								
2050	29000	2	275	600	281	374	561	1122	1020	1360	2040	4080	468	623	935	1870

Fuel Cell											
	Input Parameters					Results					
Year	Vehicle Parameters Input					Fuel Cell Pack Weight and Volume		H2 capacity needed for specific ranges (kgH2) (90% useable cap)			
	Vehicle Weight (kg)	Energy Consumption (kgH2/mile)	Fuel Cell Power (kW)	Fuel Cell Weight Power Density (W/kg)	Fuel Cell Volume Power Density (W/L)	Weight (kg)	Volume (L)	75 miles	100 miles	150 miles	600 miles
2015											
2020											
2030	29500	0.15	250	300	150	833	1667	18	24	36	144
2040											
2050	29000	0.11	250	500	250	500	1000	13	18	26	106

Figure 11. Battery and fuel cell weights and volumes for the long haul truck.

6. The design and operational characteristics of battery charging and hydrogen refueling infrastructure for urban terminals and intercity stations

6.1. Battery charging for Electric Transit Buses

Most electric transit buses being sold in the United States have ranges of 100-200 miles and battery packs that store 200-300 kWh of electrical energy. The batteries in these buses would in most cases be recharged overnight in a bus depot. Another class of electric transit buses being sold are intended to have the batteries recharged at selected locations along the route of the bus in 5-10 minutes. The battery pack in these buses store only 50-110 kWh of energy and have a range between battery recharges of 20-40 miles. The use of the smaller battery greatly reduces the cost of the battery and the fast recharge of the battery at selected known locations reduces any range anxiety of the bus company. The short-range buses use Lithium Titanate Oxide (LTO) batteries and the long-range buses use Lithium Nickel Cobalt Manganese (NCM) batteries. The LTO batteries have a relatively low energy density of about 100 Wh/kg, but very long cycle life of over 10,000 cycles and the ability to accept very fast charge (several minutes) without damage. The NCM batteries have a high energy density of 200-250 Wh/kg and a cycle life of 1000-2000 cycles. The optimum charge time of the NCM battery is of one hour or longer. Recent sales data for electric buses indicate that in the United States the transit agencies strongly prefer the long-range buses and charge the batteries overnight at their terminal.

We have performed fast charge testing on both NCM and LTO cells. The results are shown Table 10 and Table 11. The LTO cell can clearly be recharge in 10 minutes or less. Note that for the LTO batteries, the charge Ah to the maximum voltage (2.8V) changes only a small amount with charge rate even for a 6C charge. This not the case for the NCM cell.

Table 10. Fast charge tests of a LTO cell

Charge Current		Charge Time minutes	Ah to 2.8V	Total Ah to charge time
1C	20A	60	18.8	19.47
2C	40A	30	17.71	18.8
3C	60A	20	17.32	18.7
4C	80A	15	16.92	18.5
5C	100A (3V)	12	17.05	18.8
6C	120A (3V)	10	18.1	19.4

Table 11. Fast charge tests of a NCM cell

Charge Current		Charge Time minutes	Ah to 4.2V	Total Ah to charge time
1C	3A	60	2.4	2.97
2C	6A	30	2.0	2.87
3C	9A	20	1.86	2.78
4C	12A	15	1.6	2.65

The on-route charging of a Proterra [20] is shown in Figure 12. The connection with the bus is through an overhead pantograph that provides very high power (500 kW) to charge the battery in 7 minutes.

Figure 12. Charging station for the Proterra Bus [20]

EXCEL spreadsheet models for the analysis of the economics of MD/HD trucks and buses including the calculation of the cost of providing depot charging of the batteries have been developed. The input parameters for the models include the following: number of vehicles in the fleet, the average kWh needed to be charged, the average charging time, the period in which the vehicles are charged, the cost of the chargers for different charging power (kW), and the cost of the electricity including demand charges. The charging facility is assumed to consist of low power chargers (50 kW) or a combination of both low and high-power chargers (50 kW and 350 kW). The model calculates the capital cost of the charging facility, the charging power and energy per day for charging, and the cost of the electricity for charging the vehicle fleet. The model [21] can be run for one vehicle class (ex. Buses) or for the complete set of MD/HD vehicles. Examples of the output sheets for the charger model for a city transit bus and a delivery truck are shown in the Figure 13 and 14. The green shaded zones of the tables are the charger power (kW) that are the best economic choices for the particular case being analyzed. Also the input values in the green zone can be changed by the user and the table will recalculate.

Infrastructure Capital Expenses													
Battery Size (kWh)	Max Charging Power (kW)	No of vehicles in the fleet	Charger Power (kW)	Time to charge (hrs)	No of ports	Number of free hours to charge vehicles (hrs)	Number of vehicles that can be charged on one charger	Cost of one charger ($)	No of chargers required	Cost of charging infrastructure	Charging Power/Day (kW)	Charging Energy/Day (kWh)
413	200	50	**50**	2.07	0.25	10	1	40000	41	**1652000**	2065	20650
	200	50	**100**	2.07	0.50	10	2	50000	21	**1032500**	2065	20650
	200	50	**150**	2.07	0.75	10	4	65000	14	**894833**	2065	20650
	200	50	**250**	2.07	1.25	10	6	80000	8	**660800**	2065	20650
	200	50	**350**	2.07	1.75	10	8	100000	6	**590000**	2065	20650
	200	50	**500**	2.07	2.50	10	12	150000	4	**619500**	2065	20650
	200	50	**1000**	2.07	5.00	10	24	300000	2	**619500**	2065	20650
Operating Expenses												
No. of days	Charging Power/day (kW)	Charging Energy/day (kWh)	Energy Charges ($/kWh)	Fixed Charges ($/month)	Demand Charges ($/kW)	Monthly Energy Charges ($)	Monthly Demand Charges ($)	Total Monthly Charges ($)	Energy Consumption (kWh/mi)	Range (mi)	Monthly Fleet Range (mi)	Operating Cost ($/mi)
30	2065	20650	0.15	100	15	92925	30975	124000	2.2	150	225273	**0.55**

Figure 13. Charging model results for a city transit bus

Infrastructure Capital Expenses													
Battery Size (kWh)	Max Charging Power (kW)	No of vehicles in the fleet	Charger Power (kW)	Time to charge (hrs)	No of ports	Number of free hours to charge vehicles (hrs)	Number of vehicles that can be charged on one charger	Cost of one charger ($)	No of chargers required	Cost of charging infrastructure	Charging Power/Day (kW)	Charging Energy/Day (kWh)
156	100	50	**50**	1.56	0.50	10	3	40000	16	**624000**	780	7800
	100	50	**100**	1.56	1.00	10	6	50000	8	**390000**	780	7800
	100	50	**150**	1.56	1.50	10	10	65000	5	**338000**	780	7800
	100	50	**250**	1.56	2.50	10	16	80000	3	**249600**	780	7800
	100	50	**350**	1.56	3.50	10	22	100000	2	**222857**	780	7800
	100	50	**500**	1.56	5.00	10	32	150000	2	**234000**	780	7800
	100	50	**1000**	1.56	10.00	10	64	300000	1	**234000**	780	7800
Operating Expenses												
No. of days	Charging Power/day (kW)	Charging Energy/day (kWh)	Energy Charges ($/kWh)	Fixed Charges ($/month)	Demand Charges ($/kW)	Monthly Energy Charges ($)	Monthly Demand Charges ($)	Total Monthly Charges ($)	Energy Consumption (kWh/mi)	Range (mi)	Monthly Fleet Range (mi)	Operating Cost ($/mi)
30	780	7800	0.15	100	15	35100	11700	46900	0.83	150	225542	**0.21**

Figure 14. Charging model results for a MD delivery truck

Infrastructure Capital Expenses

Battery Size (kWh)	Max Charging Power (kW)	No of vehicles in the fleet	Charger Power (kW)	Time to charge (hrs)	No of ports	Number of free hours to charge vehicles (hrs)	Number of vehicles that can be charged on one charger	Cost of one charger ($)	No of chargers required	Cost of charging infrastructure	Charging Power/Day (kW)	Charging Energy/Day (kWh)
437	200	50	**50**	2.19	0.25	10	1	40000	44	**1748000**	2185	21850
	200	50	**100**	2.19	0.50	10	2	50000	22	**1092500**	2185	21850
	200	50	**150**	2.19	0.75	10	3	65000	15	**946833**	2185	21850
	200	50	**250**	2.19	1.25	10	6	80000	9	**699200**	2185	21850
	200	50	**350**	2.19	1.75	10	8	100000	6	**624286**	2185	21850
	200	50	**500**	2.19	2.50	10	11	150000	4	**655500**	2185	21850
	200	50	**1000**	2.19	5.00	10	23	300000	2	**655500**	2185	21850

Operating Expenses

No. of days	Charging Power/day (kW)	Charging Energy/day (kWh)	Energy Charges ($/kWh)	Fixed Charges ($/month)	Demand Charges ($/kW)	Monthly Energy Charges ($)	Monthly Demand Charges ($)	Total Monthly Charges ($)	Energy Consumption (kWh/mi)	Range (mi)	Monthly Fleet Range (mi)	Operating Cost ($/mi)
30	2185	21850	0.15	100	15	98325	32775	131200	2.33	150	225064	**0.58**

Figure 15. Production, storage, and dispensing hydrogen at an on-road station

6.2. Production, storage, and dispensing hydrogen at an on-road station

The long distance, long-haul trucks will store on-board hydrogen (70 kg) for a maximum range of about 500 miles and will require refueling to complete their daily trip of up to 800 miles. The refueling time for hydrogen will not be a problem—10-15 minutes at a rate of 5 kgH_2/minute. It is assumed that each of the stations along the 500 mile section of the highway will service on average 1/10 of the 5000 trucks traveling along the highway. These calculations are for a busy interstate highway, like Route I-5 between the Bay Area and Los Angeles, after the fuel cell truck technologies are mature. They will indicate the volume of hydrogen needed and the capital cost of providing it.

Each station will need to dispense 35000 kg (500 x 70) of hydrogen per day. It is further assumed that the hydrogen will be produced onsite with an electrolyzer. If the electrolyzer has an efficiency of 65%, the electricity from the grid required by the electrolyzer will be 1.166 $x10^6$ kWh (1166 MWh). If the electrolyzer operates 24 hr/day, the continuous power would be about 50 MW for each of the 10 stations along the 500 mile section of highway. Continuous operation of the electrolyzer will require storage of about half of the hydrogen produced or about 17500 kg. This storage will be at a relatively low pressure (about 500-1000 psi). This is a very large station. For the large amount of hydrogen required by this station, production of hydrogen on-site is the most economical approach. Large stations using electrolyzers have been analyzed by NREL in [22-24]. The components needed to control the flow of the hydrogen from production to dispensing have been analyzed in NREL reports [23,24]. However, the magnitude of the daily hydrogen dispensed in the stations being evaluated is more than an order of magnitude greater than treated in the NREL studies. Hence estimates of the costs resulting from extrapolating from the NREL results will be uncertain, but they should be enlightening for comparison with economic estimates for fast charging stations for battery-electric heavy-duty trucks.

A schematic of the station is shown in Figure 16. The electrolyzer produces 1458 kgH_2 /hr. For purposes of the analysis, it is assumed that the hydrogen is dispensed to trucks during a 12 hour period. During the remainder of the day, the hydrogen is put into low pressure storage. It is further assumed that the hydrogen needed to refuel the average number of trucks per hour (50 trucks- 3500 kgH_2) will be maintained in high pressure storage at 800 atm in order to fuel trucks at 700 atm. As shown in Figure 16, the station will have both low- and high-pressure compressor systems. To service, on average 50 trucks per hour, the station will need at least 15 dispensing hoses—20 hoses would be better to handle periods of high demand. The hose systems would be designed to provide fueling at 5kgH_2/minute and have pre-cooling of -40C [27]. The components to construct the hydrogen station outlined above are not currently (2018) commercially available in the sizes needed. The cost data given in [23,24] have been extrapolated to estimate the cost of the components needed in this station. For most of the components, the costs used from [24] were those labeled “future” for 2025.

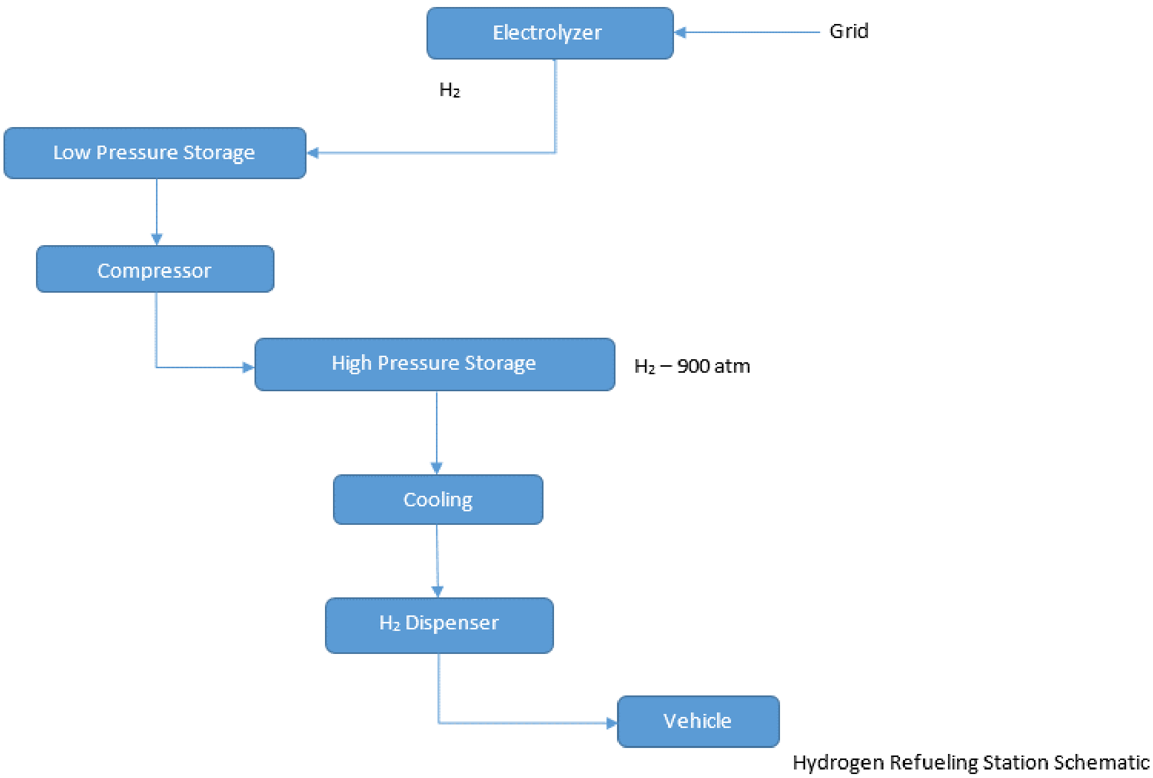


Figure 16. Schematic of the hydrogen refueling station

The costs of the components in the station are summarized in Table 12. The station is sized to refuel trucks requiring 35,000 kgH_2 per day at a pressure of 700 atm. It has been assumed that every truck is fueled once each day (500 trucks per station) and that the fueling time is done in 10-15 minutes and there are 20 hoses per station. The total cost of the station is estimated to be $75 million, which corresponds to $2127/ kg$H_2$. As shown in Figure 17, this unit cost is consistent with the results shown in [24]. The cost of electricity (assumed to be $.1/kWh) for the refueling is $360 corresponding to $5.14/ kg$H_2$. As indicated in Figure 17, the effect of the fixed operating costs on the cost of the hydrogen will be small compared to the electricity costs.

Table 12. Estimated cost of a highway hydrogen refueling station for long-haul trucks

Component	Unit cost	Size parameter	Cost $million
Electrolyzer	$800/kW	50 MW	**40**
Low pressure Storage	$725/kgH$_2$	17500 kgH$_2$	**12.7**
Low pressure compressor	$700/ kgH$_2$/hr	1500 kgH$_2$/hr	**1**
High pressure Storage	$1000/ kgH$_2$	3500 kgH$_2$	**3.5**
High pressure compressor	$2000/kgH$_2$/hr	3500 kgH$_2$/hr, 900 atm.	**7**
Dispenser hoses and pre-cooling	$430,000 for 3 hose unit	5 kgH$_2$/min., -40C 20 hoses	**3**
Total w/o installation	**$1900/kgH$_2$**		**67**
Total with installation	**$2127/ kgH$_2$**		**75**
Present value (10%, 10 yr)			**177**
Electricity for hydrogen compression (4kWh/ kgH$_2$)	70 kgH$_2$	280 kWh	**.4/ kgH$_2$ ($.10/kWh)**
Electricity for producing hydrogen by electrolyzer	70 kgH$_2$	3597 kWh	**$5.1/ kgH$_2$ ($.10/kWh)**

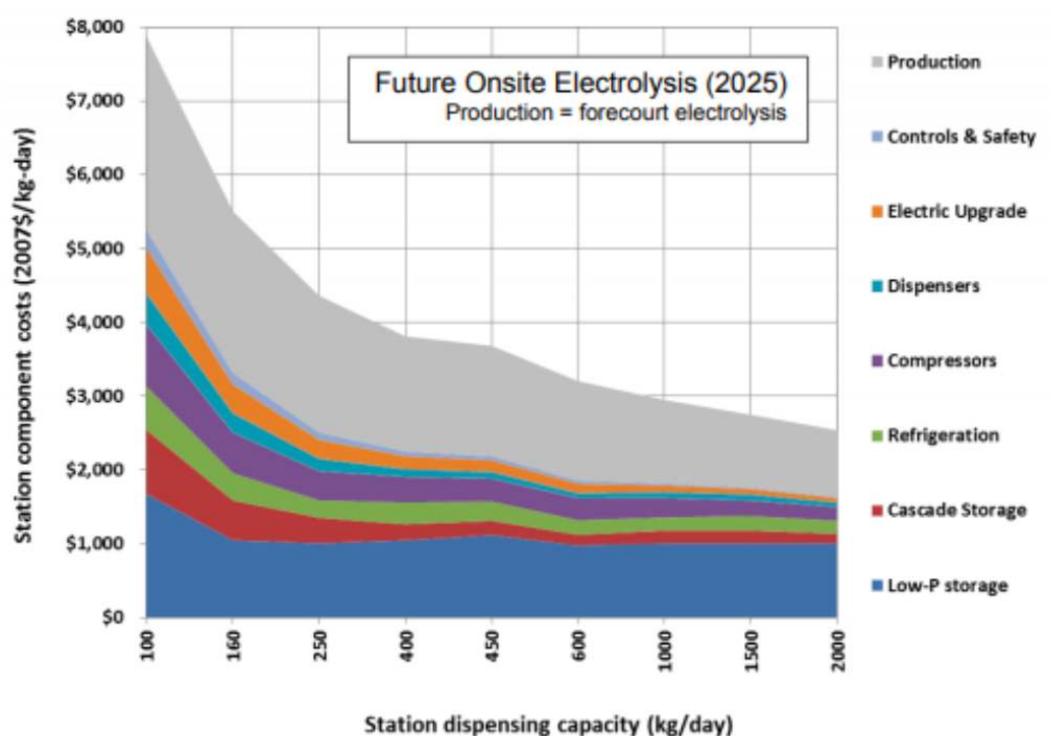


Figure 17. Capital costs for the hydrogen refueling station [24]

6.3. Comparison of the costs of the hydrogen station and fast charger infrastructure

The range of the fuel cell powered trucks are about 500 miles and that of the battery-electric trucks are about 300 miles. These ranges for the fuel cell and battery-electric trucks were selected as later economic analyses in the report indicate they can become cost competitive with diesel trucks for mature fuel cell and battery technologies. The refueling stations are spaced so that either type of truck can be refueled conveniently. Both stations are sized to handle 500 trucks per day accounting for the difference in refueling time—45 minutes for the battery powered trucks and 10-15 minutes for the hydrogen fuel cell trucks. The capital cost per station for refueling the hydrogen fuel cell trucks is estimated to be $75 million and that of the battery-electric trucks to be $24 million [2, 25]. The size (MW) of the substation needed for the hydrogen refueling would be 50 MW and for the fast charger station would be 60 MW. The substation for the hydrogen refueling would operate continuously and that for the battery trucks would be drawing power from the grid only during fast charging events. The fast charger would use 555 kWh for each battery charge and the hydrogen station would use about 3900 kWh per hydrogen refueling. Hence the hydrogen stations are more costly and energy intensive than the battery fast charging stations. The high capital cost of the hydrogen refueling stations has a relatively small effect on the cost of the hydrogen ($/kg). Over ten years of dispensing hydrogen at the station, the contribution of the capital cost would be only $.60/kg.

7. Sustainable energy availability, greenhouse gas emissions, and economics

This section involves consideration of the availability of fuels and electricity from sustainable sources, such as solar and wind for electricity and bio-mass for diesel fuel, and the greenhouse gas (GHG) emissions from the various fuel/energy sources. The GHG emissions will be discussed in terms of the Low Carbon Fuel Standards (LCFS) [26]. The availability of sustainable energy sources for battery-electric and hydrogen fuel cell vehicles is an important reason for converting vehicles to operate on those powertrains.

7.1. LCFS considerations

The LCFS are expressed in terms of the carbon intensity ($gmCO_2$/ MJ) of the various fuels/energy attained using the different pathways available for producing them. A summary of the carbon intensities is shown in Table 13. Note that the carbon intensities vary over a wide range. The GHG/CO_2 emission reduction for a specific vehicle/fuel combination is given by the following:

$$\text{Delta } (gmCO_2/\ mi) = (gmCO_2/\ kWh)_D\ (kWh/mi)_{Dveh} - (gmCO_2/\ kWh)_{altfuelveh}\ (kWh/mi)_{altfuel}$$

Substituting EER= $(kWh/mi)_D/(kWh/mi)_{altfuel}$, 1 kWh =3.6 MJ, and introducing \$/tonne CO_2,

$$(\$/kWh)_{altfuel} = ((EER \times (gmCO_2/MJ)_D - (gmCO_2/MJ)_{altfuel}) \times 3.6 \times 10^{-6} \times (\$/tonne\ CO_2)$$

ERR is the energy efficiency ratio relating the energy use per mile of the vehicle using the reference fuel/energy to the same vehicle using the alternative fuel/energy. Note from Table 14 that all cases using an electric driveline are significantly more efficient than using an engine/transmission driveline [26]. The ERR value shown in the Table 14 for trucks and buses is 5.0.

Table 15 indicates that the value of 5.0 for ERR for delivery trucks and transit buses using diesel engines is consistent with the UCD simulation results for battery-electric vehicles given in [30]. However, the EER value for electric long-haul trucks is much lower. The results for the calculation of the ERR values for hydrogen fuel cell vehicles are also shown in Table 15. The values for ERR for the fuel cell vehicles are 2.2-2.6 much less than for the battery-electric vehicles. This is the case because the maximum efficiency of the fuel cell is only marginally higher than that of the diesel engine (50% compared to 42% for the diesel engine). Note from Table 13 that the carbon intensity of hydrogen produced from natural gas or non-renewable electricity is greater than diesel fuel (120-150 gCO_2 /MJ for hydrogen and 90 gCO_2 /MJ for diesel). The effective carbon intensity of the hydrogen is not markedly less than diesel fuel for an ERR value of 2.5 (135/2.5 = 54). Hence from the GHG point-of-view for trucks and buses, battery-electric powertrains produce much less carbon than fuel cell vehicles unless the hydrogen is produced from solar or wind electricity.

Table 13. Carbon intensity values for various fuels, electricity, and hydrogen from different pathways of production 2017 [26]

Fuel	Fuel Pathway Code	Fuel Pathway Description	Carbon Intensity Values (gCO_2e/MJ)
CARBOB	CBOB	CARBOB - based on the average crude oil supplied to California refineries and average California refinery efficiencies	100.82
Diesel	ULSD	ULSD - based on the average crude oil supplied to California refineries and average California refinery efficiencies	100.45
Compressed Natural Gas	CNGF	Compressed Natural Gas from Pipeline Average North American Fossil Natural Gas	79.21
Propane	PRPF	Fossil LPG from crude oil refining and natural gas processing used as a transport fuel	83.19
Electricity	ELCG	California average grid electricity used as a transportation fuel in California	93.75 (and subject to annual updates)
	ELCR	Electricity that is generated from 100 percent zero-CI sources used as a transportation fuel in California	0.00
	ELCT	Electricity supplied under the smart charging or smart electrolysis provision	(See Table 7-2)
Hydrogen	HYF	Compressed H2 produced in California from central SMR of North American fossil-based NG	117.67
	HYFL	Liquefied H2 produced in California from central SMR of North American fossil-based NG	150.94
	HYB	Compressed H2 produced in California from central SMR of biomethane (renewable feedstock) from North American landfills	99.48
	HYBL	Liquefied H2 produced in California from central SMR of biomethane (renewable feedstock) from North American landfills	129.09
	HYEG	Compressed H2 produced in California from electrolysis using California average grid electricity	164.46
	HYER	Compressed H2 produced in California from electrolysis using zero-CI electricity	10.51

[2] For comparison on an equivalent basis (gCO_2e per MJ of conventional fuel displaced), the CIs listed in Tables 7-1 and 7-2 must be divided by the EER in Table 5 for the appropriate fuel-vehicle combination. The EER-adjustment is made when fuel quantities are reported in the LRT-CBTS to calculate the correct number of credits or deficits, using the equations in 95486.1(a).

Table 14. EER values for different vehicle types and alternative fuel/energy combinations [26]

Light/Medium-Duty Applications (Fuels used as gasoline replacement)		***Heavy-Duty/Off-Road Applications (Fuels used as diesel replacement)***		***Aviation Applications (Fuels used as jet fuel replacement)***	
Fuel/Vehicle Combination	***EER Values Relative to Gasoline***	***Fuel/Vehicle Combination***	***EER Values Relative to Diesel***	***Fuel/Vehicle Combination***	***EER Values Relative to Conven-tional Jet***
Gasoline (incl. E6 and E10) Or E85 (and other ethanol blends)	1	Diesel fuel Or Biomass-based diesel blends	1	Alternative Jet Fuel	1
CNG/ICEV	1	CNG or LNG (Spark-Ignition Engines)	0.9		
		CNG or LNG (Compression-Ignition Engines)	1		
Electricity/BEV, or PHEV	3.4	Electricity/BEV or PHEV* Truck or Bus	5.0		
		Electricity/Fixed Guideway, Heavy Rail	4.6		
		Electricity/Fixed Guideway, Light Rail	3.3		

Table 15. ERR values for trucks and transit buses based on UCD vehicle simulation results

Vehicle	Delivery truck	Transit bus	Long haul truck
Diesel engine			
Mpg 2017 2030	9.6-11	3.7-4.6	8.7-10.1
MJ/mi 2017 2030	14.0-12.2	36.4-29.2	15.4 -13.3
Battery-electric			
kWh/mi 2017 2030	.83-.7	2.2-1.8	2.4 – 2.2
MJ/mi 2017 2030	2.99-2.52	7.92-6.48	8.6 – 7.9
ERR 2017 2030	4.68-4.76	4.6-4.51	1.79 – 1.68
Hydrogen fuel cell			
kWh/mi 2030-2050	19.9-21.4	8.4-9.5	5.25
MJ/mi 2030-2050	6 - 5.6	14.2 – 12.6	7.14
ERR 2030	2.3	2.56	2.15

7.2. Availability of renewable fuels and electricity

The goal of the LCFS (**Low Carbon Fuel Standard**) program [26] is to replace fuels and electricity produced from fossil energy sources with fuels and electricity from renewable sources with much lower carbon intensity. The renewable energy sources are bio-mass and solar and wind-based electricity. At the present time, bio-mass is utilized to produce bio-diesel fuel and the renewable electricity can be used to charge the batteries in battery-electric vehicles and to produce hydrogen using an electrolyzer.

The carbon intensity of bio-diesel (renewable diesel) is usually given in terms of direct CO_2 emissions from the collection and processing of the bio-mass and the indirect CO_2 emissions from changes in the land use of the ground where the bio-mass is grown. The direct and indirect carbon intensities from renewable diesel from various bio-mass are shown in Table 16. If the indirect GHG emissions from renewable diesel are included, the carbon intensity of renewable diesel can be higher than regular diesel fuel. Even with this uncertainty in the carbon intensity of renewable diesel (bio-mass based), the production of bio-diesel in the United States has increased to nearly 2.6 billion gallons (3.5 x 10^5 MJ) in 2018. In 2016, California used 250 million gallons of renewable diesel fuel (7% of the total diesel).

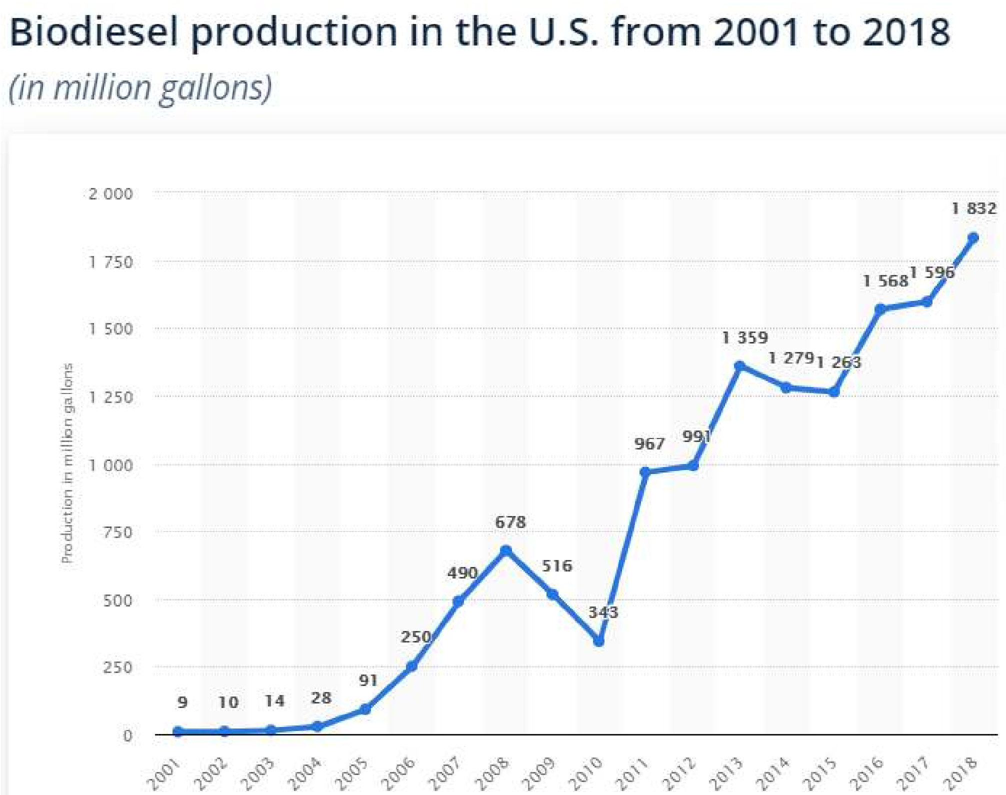


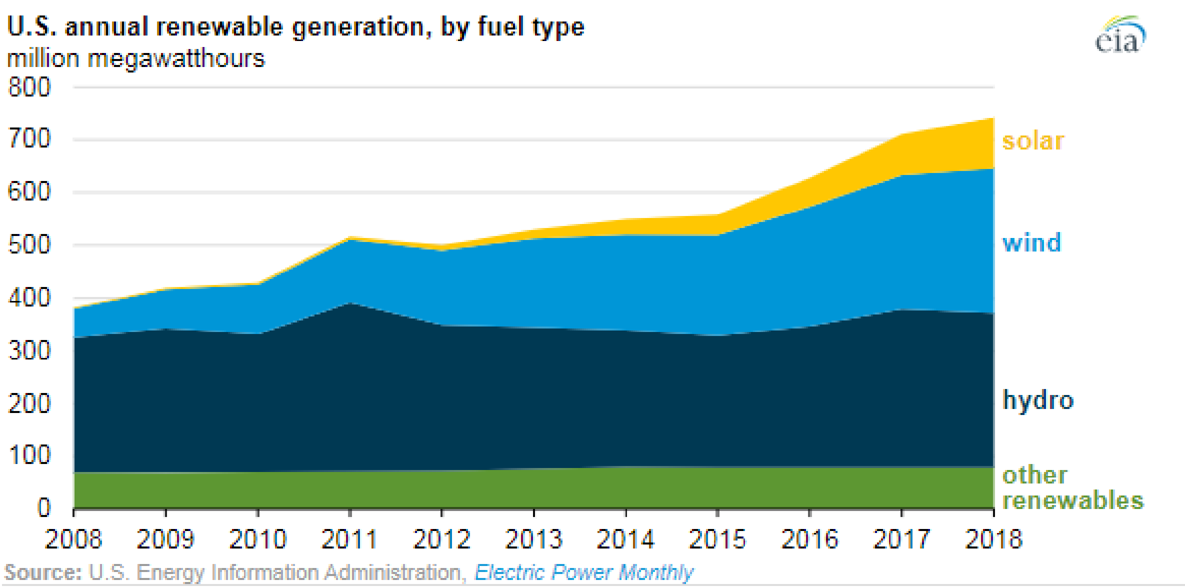
Figure 18. Bio-diesel production in the United States

Table 16. Carbon intensities of renewable diesel from various bio-mass

Bio-mass	Carbon intensity-Direct	Carbon intensity-indirect
Waste oils	10-20	0
Soy beans	50	29
Palm oil	55	71
canola	50	15
jatropha	32	NA
Rape seed	45	NA

The largest source of renewable energy is electricity from solar and wind. This is true for both the United States and California. The rapid growth of the generation of renewable electricity in the United States is shown in Figure 19. The renewable electricity generation in the United States and California for 2018 are summarized in Table 17. Using 10% of the renewable electricity in California in 2018, we could recharge about 55000 battery-electric trucks and refuel 14000 fuel cell trucks assuming 50000 miles/yr and 1.5 kWh/mi for the battery-electric truck and 12 mi/kgH_2 for the fuel cell truck.

U.S. renewable electricity generation has doubled since 2008



Renewable generation provided a new record of 742 million megawatthours (MWh) of electricity in 2018, nearly double the 382 million MWh produced in 2008. Renewables provided 17.6% of electricity generation in the United States in 2018.

Figure 19. U.S. annual renewable electricity generation 2008-2018

Table 17. Electricity generated from solar and wind in 2018 in the United States and California

	United States	California
Total (GWh)	386 $\times10^3$	41 $\times10^3$
Solar (GWh)	100 $\times10^3$	27 $\times10^3$
Wind (GWh)	286 $\times10^3$	14 $\times10^3$
Total generated GWh	4100 $\times10^3$	195 $\times10^3$

7.3. The economics (costs) of renewable fuels and electricity

For ZEV and near-ZEV trucks at the present time, the renewable fuels include bio-diesel from non-food crops having a low carbon intensity and hydrogen from renewable electricity. Ethanol is a renewable fuel that is mixed (up to 15%) with gasoline on a commercial basis, but it is not used primary to reduce GHG emissions of cars or trucks. The results of a recent study of the costs of the renewable bio-fuels with low carbon intensity is given in [27]. It was found that the cost of commercial bio- diesel was about $3.70/gge (gal. gasoline equivalent). The cost of advanced bio-fuels processed from cellulosic bio-mass are not yet commercial and their cost is much higher, being in the range of $4–8/gge depending on the bio-mass being used (see Figure 20).

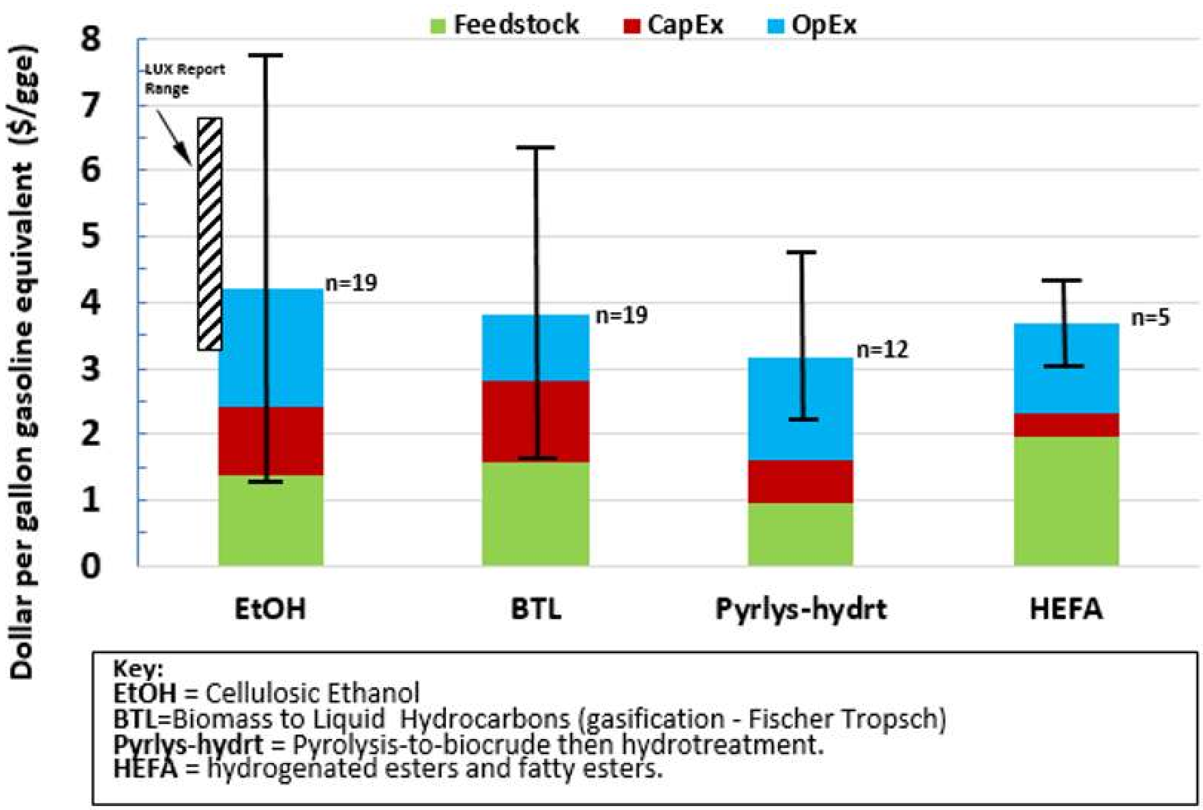
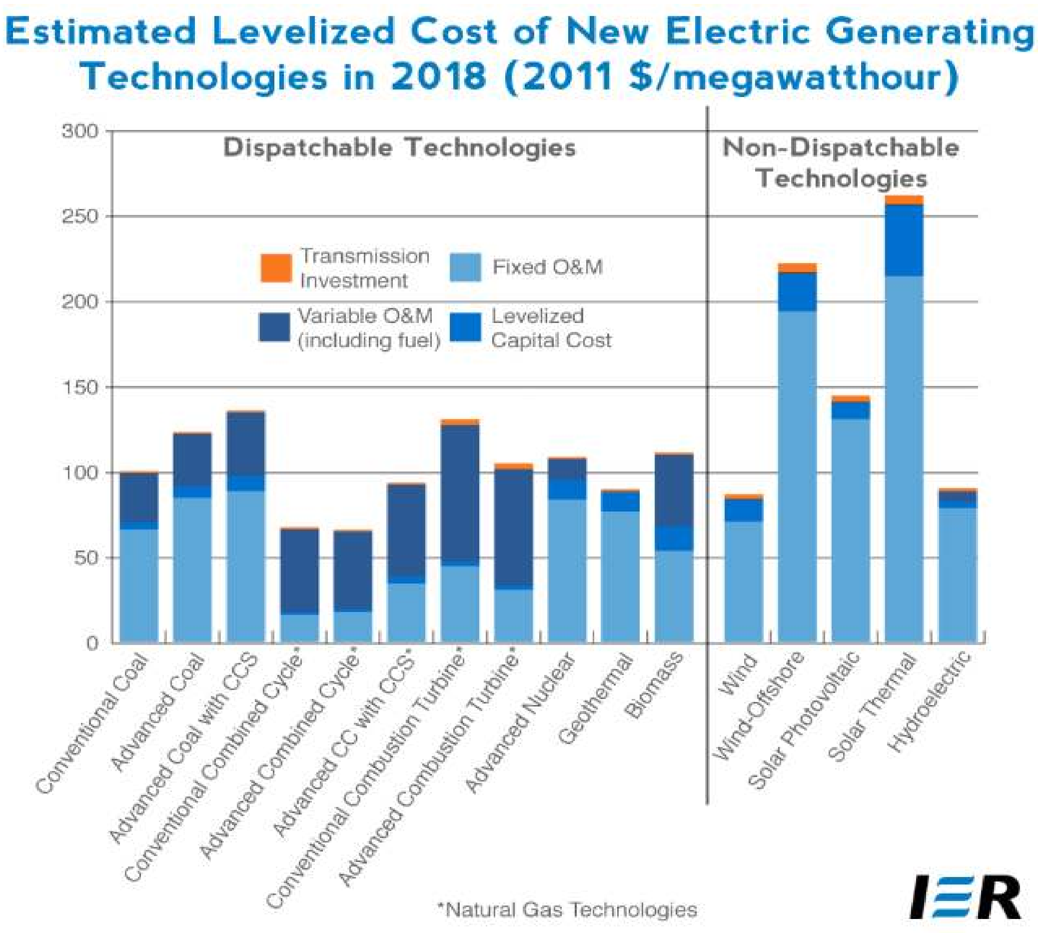


Figure 20. Recent production costs of bio-fuels from bio-mass [27]

The Levelized Cost of Energy (LCOE) is a method of comparing the cost of different complex energy technologies over their lifetime. It is the total life cycle cost of electricity for a given technology divided by the total life cycle electricity produced, expressed as dollars per million watt hours ($ per MWh). On a utility scale, the levelized cost of producing electricity from powerplants of different technologies and energy sources are shown in Figure 21 and Table 18. Figure 21 indicates that the levelized cost of electricity from conventional technologies/sources (6-8 cents/kWh) is less than renewable sources except for land-based wind sources (8 cents/kWh). However, Table 18 indicates that the levelized cost of electricity produced from both PV solar and land-based wind are about 6 cents/kWh, which is close to the cost of electricity from combined cycle natural gas (5 cents/kWh). The latter costs of renewable electricity are those most often quoted in the literature for the future. During periods in which the generation of renewable electricity greatly exceeds that needed to meet total demand, the price of electricity from solar or wind can be very low—1 to 2 cents/kWh or even lower. Hence at any given time or place, the price of renewable electricity is uncertain.



Source: Energy Information Administration, *Annual Energy Outlook 2013*,

Figure 21. Estimated levelized cost of electricity from powerplants using various technologies and energy sources in 2018

Table 18. Levelized cost of energy from various sources and technologies

Energy Plant Type	**Lifetime Cost $ per MWh**
Offshore Wind	138.0
Coal with 30% CCS	130.1
Coal with 90% CCS	119.1
Biomass	95.3
Advanced Nuclear	92.6
Nat Gas Combined Cycle with CCS	74.9
PV SOLAR	**63.2**
Hydro-electric	61.7
Land Based Wind	59.1
Natural Gas Combined Cycle	50.1
Geothermal	44.6

In California, there is a LCFS credit for low carbon fuels and electricity based on their carbon intensity and the market price of carbon on the LCFS trading market. The LCFS credit can be calculated from the following relationship:

$$\text{LCFS credit (\$/kWh)} = ((CI)_{diesel} \times EER - (CI)_{elec.}) \times 3.6 \times 10^{-6} \times (\$/\text{tonne } CO_2) \quad (1)$$

For $(CI)_{diesel}$ = 90, $(CI)_{elec}$ = 10, ERR=5, \$/tonne CO_2 = 100, the LCFS credit = \$.16/ kWh. LCFS credit values calculated from Eq (1) agree closely with those given by the CARB LCFS Calculator available on the internet. Note that the LCFS credit is quite sensitive to the EER value that can value significantly with vehicle type (see Table 15). Since the LCFS credit can be quite large, it should be considered in calculating the operating energy cost of the electrified vehicles.

8. The ownership costs of buses and various MD/HD trucks meeting user requirements

This section is concerned with the determination of the ownership costs of the battery-electric and hydrogen fuel cell trucks. The ownership costs depend on the initial purchase price of the vehicles and their operating costs (energy and maintenance costs) and the depreciation of the vehicle and the batteries in a specific time period (5 years in the present analysis). The method used in the ownership analyzes are presented in detail in the following pages. This approach has been used in previous cost studies [2,28-30].

The initial cost of the battery-electric trucks can be estimated as shown below.

$(\text{Vehcost})_{\text{batelec.}}$ = glider + Electric drive component cost + battery cost

Glider = Price Diesel Vehicle – cost of engine and transmission of the diesel vehicle

Electric drive cost = $/kW x kW of EM x system integration factor

Battery cost = $/kWh x battery kWh x system integration factor

Battery kWh = $(\text{kWh/mi})_{\text{on level}}$ x bat. oversize factor x minimum range requirement (miles)

The system integration factor is intended to account for the cost of integrating the component into the vehicle and the overhead and profit associated with that component.

For the battery-electric vehicle, the estimation of the size of the battery (its kWh) for a specified vehicle range is key to calculating the initial cost of the vehicles. The vehicle range is the minimum dependable range of the vehicle for expected vehicle operating conditions—speed, driving cycle, ambient temperature, and terrain—over the lifetime of the battery. Hence the energy use of the vehicle (kWh/mi) used to calculate the energy storage requirement of battery should not be the kWh/mi for a level road and near minimum accessory loads. In addition, the battery sizing should include the effect of battery deterioration over its lifetime and some margin to assure the battery has some remaining charge at the end of the day's driving. These considerations will result in oversizing the battery.

As discussed in Section 5, the average energy use should be increased by a factor of at least 1.3 to account for variations in road grade, traffic, and accessory loads. A second reason to oversize the battery is due to battery degradation and the need to maximize the cycle life of battery. The standard criteria for end-of-life of the battery is a loss of 20% in capacity (kWh). Hence to maintain a constant range over the lifetime of the battery it will need to be oversized by 1/.8 or by a factor of 1.25. Otherwise, it will be necessary to reduce the expected range of the electric vehicle gradually as the battery ages. In addition, it is advisable not to discharge the oversized battery to zero state-of charge (minimum cell voltage) at any time to maximize the range as the battery degrades. This means limiting the maximum energy discharged from the battery to less than 80% of that initially stored in the battery, which would result in an oversize factor of about 1.33. Otherwise, the battery cycle life will be less than projected by the manufacturer. The two factors would result in a total oversize factor as high as 1.3 x1.33 =1.76.

For the hydrogen fuel cell vehicles, the initial vehicle cost is given by

$(\text{Vehcost})_{\text{H2 FC.}}$ = glider + Electric drive cost + Power battery cost + fuel cell system cost

fuel cell cost = ($/kW x kW of fuel cell x integration factor

hydrogen storage cost = $/kg$H_2$stored x kg stored H_2 x integration factor

kg stored H_2 = $(\text{kg/mi})_{\text{on level}}$ x H_2 oversize factor

fuel cell system cost = fuel cell cost + hydrogen storage cost

power battery cost =$(\$/\text{kWh})_{\text{powerbat}}$ x $(\text{kwh})_{\text{powerbat}}$ x integration factor

The ownership cost of the electric vehicles can be calculated for short periods like 5-7 years which is typical for buyers of long haul trucks or for the lifetime of the vehicle (12-15 years) which is more typical for fleet owned vehicles. In this study, the 5 year period was selected to calculate the lifetime cost for two reasons. First, it is typical for first owners of long haul trucks and second, it should not require a battery replacement, which adds an uncertainty to the truck economics. In calculating the depreciated value of the battery-electric buses and trucks, it has been assumed that the diesel and battery electric trucks are depreciated by 50% in the 5-year time period being considered. In the case of the battery electric truck, the cost of the battery is subtracted from the depreciated value of the truck and the battery is assumed to have depreciated to 15% of its initial cost. Hence

$\text{Vehicle Deprecation}_{5\text{ years}}$ = .5 (Vehcost - battery cost) + .85 battery cost

In calculating the depreciated value of the fuel cell buses and trucks, it is assumed that the diesel and fuel cell trucks are depreciated by 50% in the 5-year time period being considered. The fuel cell system cost is subtracted from the fuel cell truck cost and the fuel cell cost is depreciated by 50%.

$\text{Vehicle Deprecation}_{5\text{ years}}$ = .5 (Vehcost – fuel cell system cost) + .5 fuel cell cost

The costs of electricity and hydrogen per mile to operate the battery-electric and fuel cell vehicles are

$(\$/\text{mi})_{\text{elec}} = (\$/\text{kWh})_{\text{elec}}$ x $(\text{kWh/mi})_{\text{veh on level}}$ x (bat over energy use factor)

$(\$/\text{mi})_{\text{H2FC}} = (\$/\text{kgH}_2)$ x $(\text{kgH}_2/\text{mi})_{\text{veh on level}}$ x (H_2 over use factor)

It is expected that the maintenance cost of the electrified vehicles will be lower than that of the baseline diesel vehicles they replace by a factor of MFR. The maintenance cost of the electrified vehicles will be

$(\$/\text{mi})_{\text{maint elec}} = (\$/\text{mi})_{\text{maint diesel}}$ x (1- MFR)

In the 5-year period being considered, it is assumed the vehicles will operate a fixed miles per year.

$(\text{miles traveled})_{5\text{ years}}$ = 5yr. x (miles of operation/yr)

The total operating cost of the electric vehicles is

($/mi) = Vehicle Deprecation /(miles traveled) + ($/mi)elec + ($/mi)maint. elec

The corresponding relationship for the diesel truck is

($/mi)diesel = .5 Vehcost)diesel + ($/gal)diesel / (mpg)diesel + ($/mi)maint diesel

The payback miles for the electrified vehicles can be calculated from the following:

(payback miles) =(Vehcost) elec - Vehcost)diesel)/(($/mi)diesel fuel - ($/mi)elec) + ($/mi)maint diesel x MFRelec)

The factors used in the battery-electric and hydrogen fuel cell truck design and economic analysis equations are given in Table 19. The payback miles calculation results in a positive number only when the cost of the electrified vehicle is greater than that of the baseline diesel powered vehicle.

Table 19. Factors used in the vehicle design and economic spreadsheet models

Parameter	Battery-electric trucks	Hydrogen fuel cell trucks
Integration factor	1.5-1.15	1.5-1.15
Bat/H_2 storage over size factor	1.8	1.6
Energy over use factor	1.3	1.3
Vehicle depreciation factor	.5	.5
Energy storage depreciation factor	.85	.5
Maintenance reduction factor	.5	.5
Time period for economic analysis	5 years (battery cycle life 1500 cycles)	7 years (fuel cell stack life 25000 hours)

It is of interest to calculate the number of deep discharge cycles the battery pack in the battery-electric trucks would experience in the 5 year period of the economic analysis. The total throughput for the battery in the electric truck in 5 years will be

$(\text{battery throughput})_{5\ years}$ = $(\text{miles traveled})_{5\ years}$ x $(\text{kWh/mi})_{lev}$ x (bat over use factor)

The corresponding number of deep discharge cycles of the battery is

Battery deep discharge cycles = (battery throughput)5 years / (battery kWh)

The fuel cell stack life (hours) required for a long haul truck service life of 7 years is

(Fuel cell stack service life) 7 years = 7 yrs x 12 hr/day x 300 day/yr = 25200 hrs.

EXCEL spreadsheet models for the truck designs and related economic analyzes have been written for various types of trucks and buses. The model treats the design and economics of each type of truck separately and then summaries the economic results for all the truck types on a separate spreadsheet for specific economic inputs for the design and components. The vehicle design and economic spreadsheets showing inputs and outputs for the delivery truck, transit bus, and the Pickup truck are shown in Figure 22-24 and the summary economic output for all the truck types is shown Figure 25.

	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Battery Energy Density (Wh/kg)	Glider Cost ($)	Electric Drive ($/kW)	Power Battery ($/kWh)	Energy Battery ($/kWh)	Electricity Cost ($/kWh)	Integration markup	75 miles	100 miles	150 miles	200 miles	Total Vehicle Cost ($)	Cost per mile ($/mi)
2015					36000	52	600	300	0.1	1.5						
2020					36000	45	350	150	0.1	1.4						
2030	6900	150	0.83	150	36000	30	350	200	0.1	1.3	116	155	233	310	102382	0.08
2040					36000	25	175	80	0.1	1.2	0	0	0	0	36000	
2050	6750	150	0.72	225	36000	20	150	70	0.1	1.15	101	135	202	269	55708	0.07

Fuel Cell																
	Input Parameters										Results					
Year	Vehicle Parameters Input				Cost Parameters Input						H2 capacity needed for specific ranges (kgH2) (90% useable cap)				For 150 miles	
	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Fuel Cell Power (kW)	Glider Cost ($)	Electric Drive ($/kW)	Fuel Cell ($/kW)	H2 Storage ($/kgH2)	H2 Cost ($/kgH2)	Integration markup	75 miles	100 miles	150 miles	200 miles	Total Vehicle Cost ($)	Cost per mile ($/mi)
2015					36000	52	200	900	5	1.5						
2020					36000	45	150	500	5	1.4						
2030	6900	150	0.056	125	36000	30	175	250	5	1.3	6.72	8.96	13.44	17.92	77386	0.28
2040					36000	25	80	200	5	1.2	0.00	0.00	0.00	0.00	37260	
2050	6750	150	0.052	125	36000	20	80	200	5	1.15	6.24	8.32	12.48	16.64	54855	0.26

Figure 22. Spreadsheet model output for the city delivery truck

Year	Vehicle Parameters Input				Cost Parameters Input						Battery capacity needed for specific ranges (kWh) (80% useable cap)				For 150 miles	
	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Battery Energy Density (Wh/kg)	Glider Cost ($)	Electric Drive ($/kW)	Power Battery ($/kWh)	Energy Battery ($/kWh)	Electricity Cost ($/kWh)	Integration markup	75 miles	100 miles	150 miles	200 miles	Total Vehicle Cost ($)	Cost per mile ($/mi)
2015					360000	52	600	300	0.1	1.5						
2020					360000	45	350	150	0.1	1.4						
2030	15000	250	2.2	150	360000	30	350	275	0.1	1.3	309	411	617	823	539453	0.22
2040					360000	25	175	80	0.1	1.2	0	0	0	0		
2050	14000	250	1.83	225	360000	20	125	100	0.1	1.15	257	342	513	684	417082	0.18

Fuel Cell

	Input Parameters										Results					
Year	Vehicle Parameters Input				Cost Parameters Input						H2 capacity needed for specific ranges (kgH2) (90% useable cap)				For 300 miles	
	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Fuel Cell Power (kW)	Glider Cost ($)	Electric Drive ($/kW)	Fuel Cell ($/kW)	H2 Storage ($/kgH2)	H2 Cost ($/kgH2)	Integration markup	75 miles	100 miles	150 miles	300 miles	Total Vehicle Cost ($)	Cost per mile ($/mi)
2015					360000	52	200	900	5	1.5						
2020					360000	45	150	500	5	1.4						
2030	15000	250	0.096	200	360000	30	250	250	5	1.3	12	15	23	46	456551	0.48
2040					360000	25	80	200	5	1.2	0	0	0	0	363150	
2050	14000	250	0.09	200	360000	20	125	200	5	1.15	11	14	22	43	406592	0.45

Figure 23. Spreadsheet model output for the transit bus

Year	Input Parameters										Results					
Year	Vehicle Parameters Input				Cost Parameters Input						Battery capacity needed for specific ranges (kWh) (80% useable cap)				For 150 miles	
	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Battery Energy Density (Wh/kg)	Glider Cost ($)	Electric Drive ($/kW)	Power Battery ($/kWh)	Energy Battery ($/kWh)	Electricity Cost ($/kWh)	Integration markup	75 miles	100 miles	150 miles	300 miles	Total Vehicle Cost ($)	Cost per mile ($/mi)
2015					36000	52	600	300	0.1	1.5						
2020					36000	45	350	150	0.1	1.4						
2030	3950	250	0.53	150	36000	30	350	200	0.1	1.3	74	99	149	297	84403	0.05
2040					36000	25	175	80	0.1	1.2	0	0	0	0		
2050	3950	250	0.58	225	36000	20	150	100	0.1	1.15	81	108	163	325	60459	0.06

Fuel Cell

Year	Input Parameters										Results					
Year	Vehicle Parameters Input				Cost Parameters Input						H2 capacity needed for specific ranges (kgH2) (90% useable cap)				For 150 miles	
	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Fuel Cell Power (kW)	Glider Cost ($)	Electric Drive ($/kW)	Fuel Cell ($/kW)	H2 Storage ($/kgH2)	H2 Cost ($/kgH2)	Integration markup	75 miles	100 miles	150 miles	500 miles	Total Vehicle Cost ($)	Cost per mile ($/mi)
2015					36000	52	200	900	5	1.5						
2020					36000	45	150	500	5	1.4						
2030	3950	250	0.029	150	36000	30	175	250	5	1.3	3.48	4.64	6.96	23.20	84412	0.15
2040					36000	25	80	200	5	1.2	0.00	0.00	0.00	0.00	37890	
2050	3950	250	0.026	150	36000	20	80	200	5	1.15	3.12	4.16	6.24	20.80	58538	0.13

Figure 24. Spreadsheet model output for the HD Pickup truck

Vehicle Type	Energy Source	Year	Range (miles)	Energy Capacity Needed (kWh or kgH2)	Total Vehicle Cost ($)	Energy Consumption (kWh/mi or kgH2/mi or mpgD)	Energy Cost ($/unit energy)	Running Cost ($/mi)	Vehicle Depreciation in 5 years ($)	Maintenance Cost ($/mi)	Avg. Annual Miles (mi)	Miles travelled in 5 yrs. (mi)	TCO ($/mi)	Breakeven Miles (miles)
City Delivery Truck	Battery Electric	2030	150	233	102382	0.83	0.1	0.11	67488	0.156	20000	100000	0.94	110563
		2050	150	202	55707.78	0.72	0.1	0.09	32802	0.156		100000	0.58	1598
	Fuel Cell	2030	150	13.44	77386	0.056	5	0.36	38693	0.156		100000	0.91	129807
		2050	150	12.48	54855	0.052	5	0.34	27428	0.156		100000	0.77	-729
	Diesel				55000	10.5	4	0.38	27500	0.311		100000	0.97	
City Transit Bus	Battery Electric	2030	150	617	539453	2.2	0.1	0.29	329122	0.500	50000	250000	2.10	168140
		2050	150	513	417082	1.83	0.1	0.24	226507	0.500		250000	1.64	19466
	Fuel Cell	2030	300	46.08	456551	0.096	5	0.62	228276	0.500		250000	2.04	115085
		2050	300	43.20	400842	0.09	5	0.59	200421	0.500		250000	1.89	1588
	Diesel				400000	6.5	4	0.62	200000	1.000		250000	2.42	
Intercity Bus	Battery Electric	2030	350	805	657550	1.23	0.1	0.16	406260	0.500	60000	300000	2.01	317693
		2050	350	622	437254	0.95	0.1	0.12	240389	0.500		300000	1.42	43979
	Fuel Cell	2030	500	132.80	484735	0.166	5	1.08	242368	0.500		300000	2.39	-781603
		2050	500	104.00	415258	0.13	5	0.85	207629	0.500		300000	2.04	121488
	Diesel				400000	8.5	4	0.47	200000	1.000		300000	2.14	
Long Haul Truck	Battery Electric	2030	300	2244	584988	2.4	0.1	0.31	508479	0.095	100000	500000	1.42	1857675
		2050	300	1870	227080	2	0.1	0.26	178990	0.095		500000	0.71	315771
	Fuel Cell	2030	600	144.00	249900	0.15	5	0.98	124950	0.095		500000	1.32	-275801
		2050	600	105.60	157988	0.11	5	0.72	78994	0.095		500000	0.97	-149710
	Diesel				134000	8.7	4	0.46	67000	0.190		500000	0.78	
Short Haul Truck	Battery Electric	2030	150	654	335349	2.33	0.1	0.30	230580	0.095	65000	325000	1.11	772939
		2050	150	589	164641	2.1	0.1	0.27	102937	0.095		325000	0.68	147321
	Fuel Cell	2030	150	30.96	202112	0.129	5	0.84	101056	0.095		325000	1.24	-325043
		2050	150	27.84	135503	0.116	5	0.75	67752	0.095		325000	1.06	-96400
	Diesel				119000	8.2	4	0.49	59500	0.190		325000	0.86	
HD Pickup Truck	Battery Electric	2030	150	149	84403	0.53	0.1	0.07	52608	0.144	24000	120000	0.65	146139
		2050	150	163	56717	0.58	0.1	0.08	32914	0.144		120000	0.49	51885
	Fuel Cell	2030	150	6.96	84412	0.029	5	0.19	42206	0.144		120000	0.68	248672
		2050	150	6.24	58538	0.026	5	0.17	29269	0.144		120000	0.56	87016
	Diesel				42000	18.6	4	0.22	21000	0.288		120000	0.68	

Figure 25. Spreadsheet summary output for all the truck and bus types

9. The markets and prospects for the sale of battery-electric and hydrogen fuel cell buses and trucks for 2020-2040.

The results of the spreadsheet economic models for the various types of battery-electric and fuel cell-electric buses and trucks can be used to project the prospects for sales of the various vehicles in 2020-2040. The economic analyses of the electrified vehicles indicated that the main driving forces for the sales prospects are the battery and fuel cell costs as those technologies mature over the next 20-25 years and the energy costs for electricity ($/kWh) and hydrogen ($/kg) as they are produced from renewable sources. It will also be critical that the infrastructure needed for both battery charging and hydrogen refueling be developed so that electricity and hydrogen will be conveniently available at prices needed to make the economics of the electrified buses and trucks competitive with the diesel-powered vehicles. The economics of battery-electric and fuel cell-electric trucks of various types are summarized in Table 20 and Table 21 for the battery and fuel cell cost driving factors. From the tables, the cost factors that will make the electric trucks and buses competitive with the conventional diesel vehicles are apparent for the various types of vehicles. The energy prices assumed in the economic calculations were $.10 /kWh for electricity and $5/kg for hydrogen and $4/gal. for the diesel fuel.

Table 20. Summary of the economic model results for battery-electric trucks for different battery costs ($/kWh)*

Vehicle type	Nom. Range (mi)	Miles/yr.	Battery cost ($/kWh)	Vehicle cost($)	TCO $/mi for 5 yr.	Breakeven miles
City Delivery						
Diesel		20000		55000	.97	
Battery-electric	150	20000	200	102382	.94	110563
	150	20000	100	62675	.63	17332
	150	20000	70	55707	.58	1600
Transit Bus						
Diesel		50000		400000	2.42	
Battery-electric	150	50000	275	539453	2.10	168140
	150	50000	150	442747	1.73	48716
	150	50000	100	417082	1.64	19476
Intercity Bus						
Diesel		60000		400000	2.14	
Battery-electric	350	60000	275	657550	2.01	317693
	350	60000	150	473006	1.52	86185
	350	60000	100	437254	1.42	44000
Long Haul Tractor						
Diesel		134000		134000	.78	
Battery-electric	300	100000	275	585000	1.42	>10^6
	300	100000	150	291595	.84	534637
	300	100000	100	227081	.71	315771
Short Haul Tractor						
Diesel		65000		119000	.86	
Battery-electric	150	65000	275	335349	1.11	773000
	150	65000	150	245229	.86	333509
	150	65000	100	164641	.68	147321
HD pickup truck						
Diesel				42000	.68	
Battery-electric	150	24000	200	84403	.65	146139
	150	24000	100	60459	.52	65077
	150	24000	70	56837	.48	45290

Table 21. Summary of the economic model results for fuel cell trucks for different fuel cell costs ($/kW)*

Vehicle type	Nom. Range (mi)	Miles/yr.	Fuel cell cost ($/kWh)	Vehicle cost ($)	TCO $/mi for 5 yr.	Breakeven miles
City Delivery						
Diesel		20000		55000	.97	
Fuel cell electric	150	20000	175	77386	.91	129807
	150	20000	80	54855	.77	------
Transit Bus						
Diesel		50000		400000	2.42	
Fuel cell electric	300	50000	250	456551	2.04	115085
	300	50000	125	406592	1.90	12429
	300	50000	100	400842	1.8	1588
Intercity Bus						
Diesel		60000		400000	2.14	
Fuel cell electric	500	60000	250	484735	2.39	------
	500	60000	125	421008	2.05	167273
	500	60000	100	415258	2.04	121488
Long Haul Tractor						
Diesel		134000		134000	.78	
Fuel cell electric	600	100000	250	249900	1.32	-----
	600	100000	125	165176	.98	------
	600	100000	100	157988	.97	------
Short Haul Tractor						
Diesel		65000		119000	.86	
Fuel cell electric	150	65000	250	202112	1.24	-----
	150	65000	125	142691	1.07	-----
	150	65000	100	135503	1.06	------
HD pickup truck						
Diesel				42000	.68	
Fuel cell electric	150	24000	175	84442	.68	248672
	150	24000	80	658538	.56	87016

*hydrogen cost $5/kg

The primary measures of the competitiveness of the various electric vehicle options are the purchase price differential of the electrified vehicles and their total ownership costs ($/mi) for the first 5 years of operation compared to the conventional diesel vehicles. These cost values are given in Table 20 and Table 21 for ranges of battery and fuel cell costs. The operating costs ($/mi) would be somewhat lower for a 15 year time period than for 5 year period.

In general, the results in the tables indicate that the electrified trucks do not become cost competitive until the battery and fuel cell costs decrease to the lowest values assumed in the calculations even for the relatively low electricity and hydrogen prices assumed. How soon the maturing technologies will reach those cost values is uncertain, but it seems likely to occur in the next 10-20 years.

In the case of the battery-electric buses and trucks, the battery costs [31, 32} required were $80-100/kWh. This is the cost of the complete pack to the vehicle manufacturer/assembler. Even at that battery cost, the long haul truck (300 miles), the short haul truck (150 miles) and the pickup truck (150 miles) would not be competitive with the diesel trucks. Battery-electric vehicles of the other types—buses and delivery trucks—would be cost competitive and their sales should be promising as their initial costs approach those of the conventional diesel vehicles and the energy costs ($/mi) of the battery-electric vehicles are less than the diesel vehicles. The batteries in all the vehicles have been oversized for the specified vehicle range to account for the uncertainty in energy use in real world travel which should make the vehicle ranges more realistic. The maintenance costs of the battery-electric and fuel cell/hydrogen trucks were assumed to be one-half (1/2) the cost per mile of the corresponding diesel truck. Information on the maintenance costs of the various types of trucks is limited, but it seems to be much higher for diesel transit buses than other types of HD vehicles.

In the case of the fuel cell-electric trucks and buses, the fuel cell costs [7] required were $80-100/kW. This is the cost of the complete fuel cell system including all accessories to the vehicle manufacturer/assembler. It does not include the cost of the hydrogen storage which was assumed to cost $ 200/kgH_2. For the low fuel cell costs ($80-100/kW) and hydrogen at $5/kg, the delivery van and buses are cost competitive with the diesel both in terms of initial cost and TCO. Under these conditions, the sales of the delivery vans and buses would be promising if the required infrastructure for hydrogen is available. As in the case of batteries, the hydrogen storage on-board the vehicles was oversized by 1.6 to account for uncertainties in energy consumption.

The economics of the long haul trucks using fuel cells and hydrogen is more promising than with batteries. First, the range of the fuel cell long haul truck has been increased to 600 miles from 300 miles using batteries. Second the cost of the tractor with the low cost fuel cell would be $156K compared to $227K with the batteries. However, the TCO of the fuel cell long haul truck ($.97/mi) would be higher than that of the conventional diesel ($.78/mi) for hydrogen at $5/kg. Hence the marketability of the fuel cell truck would be dependent on the price of hydrogen which would need to be less than $5/kg. The short haul truck (150 mile range) seems to be best suited to be battery-electric unless the cost of hydrogen is well below $5/kg or the price of electricity for truck companies is considerably higher than the $.10/kWh value assumed in all the battery-electric economic calculations.

The market situation for HD pickup trucks seems similar to that of short haul trucks in that at $.1/kWh for electricity and $5/kg for hydrogen, the pickup trucks (150 mile range) seem best suited to be battery-electric rather than fuel cell/hydrogen. The key factor is that for the energy costs assumed, the operating energy cost of the battery-electric pickup truck, as is the case for all the trucks, is much less than the corresponding fuel cell/hydrogen truck.

10. Conclusions

The objective of this study was to project the introduction of battery-electric and fuel cell/hydrogen technologies into the medium-duty (MD) and heavy-duty (HD) vehicle markets and to identify which markets will be most suitable for each of technologies and the factors (technical, economic, operational) which will be most critical to their successful introduction. The study considered trucks and buses of various types—delivery vans, transit buses, intercity buses, long haul and short haul tractor trailer trucks, and heavy-duty pickup trucks.

Sustainability aspects of fueling trucks and buses were discussed in terms of the Low Carbon Fuel Standard (LCFS) being implemented in California. The LCFS is intended to encourage fueling vehicles using fuels produced from renewable resources having a low carbon intensity (gm CO_2/MJ). For the battery-electric and fuel cell/hydrogen trucks, this means refueling using primarily electricity from solar and wind resources directly to charge batteries or indirectly to produce hydrogen using an electrolyzer. There is reason to believe that when trucks and buses using batteries and fuel cells are marketed, renewable (sustainable) electricity/hydrogen will be available to fuel them.

The initial cost of the battery-electric and hydrogen fuel cell trucks and buses and their ownership costs and the prospects for marketing the electrified vehicles in 2020-2040 were evaluated using EXCEL spreadsheet models. The initial purchase costs of the electrified vehicles depend primarily on the unit costs ($/kWh and $/kW) of the batteries and fuel cell systems. The operating cost ($/mi) of the vehicles depends primarily on the energy costs ($/kWh of electricity and $/kg of hydrogen) and their reduced maintenance costs. In general, the economic analyses indicate that the electrified trucks do not become cost competitive until the battery and fuel cell costs decrease to the lowest values (70-100/kWh for batteries and $80-100/kW for fuel cells) assumed in the calculations even for the relatively low electricity ($.10/kWh) and hydrogen ($5/kg) prices assumed. How soon the maturing technologies will reach those cost values is uncertain, but it seems likely to occur in the next 10-20 years.

Even at that battery cost of $80/kWh, the long haul truck (300 miles), the short haul truck (150 miles) and the pickup truck (150 miles) would not be competitive with the diesel trucks. Battery-electric vehicles of the other types would be cost competitive and their sales should be promising as their initial costs approach those of the conventional diesel vehicles and the energy costs ($/mi) of the battery-electric vehicles are less than the diesel vehicles.

In the case of the fuel cell-electric trucks and buses, for fuel cell costs of $80-100/kW and hydrogen at $5/kg$H_2$, the delivery van and buses are cost competitive with the diesel both in terms of initial cost and TCO. Under these conditions, the sales of the delivery vans and buses would be promising if the required infrastructure for hydrogen is available. The economics of the long haul trucks using fuel cells and hydrogen is more promising than with batteries. First the range of the fuel cell long haul truck has been increased to 600 miles from 300 miles using batteries. Second the cost of the tractor with the low cost fuel cell would be $156K compared to $227K with the batteries. However, the TCO of the fuel cell/hydrogen truck ($.97/mi) for hydrogen at $5/kg would be higher than of the battery-electric long haul truck ($.71/mi). The

TCO of the diesel truck is estimated to be $.78/mi. Hence the marketability of the fuel cell truck would be dependent on the price of hydrogen which would need to be less than $5/kg. The short haul truck (150 mile range) seems to be best suited to be battery-electric unless the cost of hydrogen is well below $5/kg.

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Data Management

Products of Research

Most of the data used in this study were generated during the course of the study using either vehicle simulation programs that have been used at UC Davis over the last 10-15 years or EXCEL spreadsheet models that were developed as part of the study. The results of the vehicle simulations and the spreadsheet models are given in table form throughout the report.

Data Format and Content

The data are presented in the tables in the report in forms suitable to describe its proper interpretation and understanding in each section of the report.

Data Access and Sharing

The EXCEL spreadsheet models are provided as part of the data sharing with the report and can be used by anyone reading the report.

Reuse and Redistribution

The data used in the report are available to all readers. The same is true of the EXCEL spreadsheet models are available in the dataset provided with the report.