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An Investigation into the Sustainability of Advanced Materials and Systems as Energy Sources in Commuter Transportation

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StairCase II

Modern society depends on cheap and plentiful sources of energy. For most of the 20th century, fossil fuel in the form of coal, natural gas, and petroleum have been this energy source. The majority of petroleum in the U.S. goes in to fueling the light duty transportation fleet. However, we know that coal, natural gas, and crude oil have an expiration date, and we have recently learned that their use has caused and is still causing severe damage to the earth's atmosphere. With these reasons in mind, new sources of inexpensive and abundant energy must be found, which are renewable and environmentally sound. Alternative such as hydrogen fuel and battery technology may play a key role in this search for new energy sources. This paper gives a sustainability overview of the major alternatives to petroleum for fueling the light duty transportation sector.

INTRODUCTION:

Modern society depends on cheap and plentiful sources of energy. For more than a century, that source of energy has come in the form of fossil fuels.[1] However, we know that coal, natural gas, and crude oil are being rapidly depleted. In addition, we have also learned that their use has caused--and is still causing--severe damage to the earth's atmosphere.[2,3] With these reasons in mind, new sources of inexpensive and abundant energy are in high demand. These energy sources must be renewable and environmentally sound and must be substitutable for fossil fuels to enable the development of a sustainable and environmentally sound economy.

In ancient times, energy storage was quite natural and simple. Originally, mankind made fire using charcoal and wood; biomass energy storage carriers for solar energy. In time, fire would bring bronze ware and iron ware, and thus charcoal energy acted as one of the most important driving powers for ancient civilization.[4]

Roughly 1000 years ago, mankind discovered rocks that would hold a flame and began using them as an energy source. These rocks, coal, evolved from buried plants grown billions of years ago and store solar energy in a much higher density than charcoal and wood. In the 18th century, coal was used for the steam engine power and then later to produce power. Then in the early 20th century, petroleum, a derivative of biodegradable organic material was used and still is as another high density energy storage medium for solar energy. It is mined and used massively

THE TRANSPORTATION SECTOR

Currently, the majority of petroleum in the U.S. goes in to fueling the light duty transportation fleet. In 1993, this sector accounted for over 27 percent of the U.S. energy consumption, using 22.8 quads out of a total 83.9 quads of energy consuming approximately 64 billion mega joules per day. This is equivalent to 10.5 million barrels of petroleum per day and amounts to 65 percent of the total U.S. petroleum supply. Highway transportation accounts for 75 percent of the petroleum demand, 80 percent of this is light duty transportation.[5] The demand for transportation has continued to grow, both in the U.S. and around the world since 1993. Thus, the need for petroleum in the U.S. has continued to grow as well.

As a result, the transportation sector is responsible for a significant fraction of emissions of greenhouse gases and urban air pollutants. It has been estimated that Americans spend $53 billion annually to counter these negative externalities even with extensive emission control systems.[6] In addition, 3.9 billion gallons of fuel are wasted in traffic congestion.[7]

With these reasons in mind, new sources of inexpensive and abundant energy must be found, which are renewable and environmentally sound. These sources and systems are the target in the large effort to introduce renewable technologies and energy efficiency improvements to mitigate greenhouse gas emissions and wean society off of fossil fuels.

LIMITS TO STUDY

The alternatives to petroleum for use in light duty transportation are numerous. Most of these alternatives are only in their infancy and will not be commercially available in the next five years. Other alternatives lack the characteristics necessary for wide acceptance in society. One of these characteristics is the ability to travel relatively long distances on a single charge or fueling. Finally, to ensure survival of modern society, these alternatives must be more environmentally friendly than fossil fuels. With these reasons in mind, this paper seeks to give an overview of the alternatives that will be commercially available in the next five years and are able to travel 250 mile on a single charge or fueling. In addition, these alternatives must be carbon free to significantly decrease the production of greenhouse gas emissions (GHG). Although batteries are environmentally friendly during use, the generation of power stored within the battery can produce large quantity of GHG depending on the source of power. To eliminate the effect of these GHG emissions, this study will assume that the nuclear power will be the source of all electricity.

ELECTRICITY PRODUCTION VIA NUCLEAR POWER

Nuclear energy offers an abundant source of energy that will be available well into the future. Nuclear fuel supply is estimated to be readily available even on a once-through fuel cycle for fifty to one hundred years. Using breeder reactors and a closed fuel cycle, it is virtually inexhaustible. Because of its relative abundance, nuclear fuel is relatively cheap compared to fossil-based fuels.[8] Nuclear power is an environmentally green and an extremely clean energy source. There are practically no greenhouse gas emissions from its use and a relatively small amount of waste results. In the Unites States 104 nuclear reactors produce approximately twenty percent of the total electric energy generated annually. These properties lead to an average cost of 0.07 US dollars per kWh of nuclear power.[9]

HYDROGEN PRODUCTION VIA NUCLEAR POWER

Currently 95 percent of hydrogen is produced by steam reforming of methane. Although effective, steam reformation still uses a limited supply of fossil fuel for its reactant and produces the greenhouse gas carbon dioxide. This leads to the belief that steam reformation may be a step towards a sustainable economy, but not the final answer. It is possible to produce a carbon-free energy system using water to produce hydrogen when using solar or nuclear energy as the primary energy source. Electrolysis from renewable sources of electricity may produce sustainable hydrogen. However, electrolysis at low temperatures and pressures is quite inefficient, but can be made considerably more efficient at higher temperatures ("hot" electrolysis). An additional method for producing sustainable hydrogen is by thermochemical water splitting.

Thermochemical water splitting is a process by where hydrogen is produced via a series of chemical reactions at a lower temperature than direct thermal water splitting.[8,10] The sulfur-iodine thermochemical (SI) process has the most potential set of reactions for hydrogen production. It has been proven that SI reactions can achieve continuous operation on a bench scale.[11,12] When the SI process is done by heat from a very high temperature reactor, the theoretical efficiency of the SI process has been estimated to be approximately 50%.[12] With the development of the SI process, intense research focused on a commercial scale of feasibility is happening in advanced countries.[13,14] Three chemical reactions makeup the SI process: the Bunsen reaction, the decomposition of sulfuric acid, and the decomposition of hydriodic acid.

$$SO_2 + I_2 + 2H_2O \rightarrow H_2SO_4 + 2HI \tag{1}$$
$$H_2SO_4 \rightarrow H_2O + SO_2 + 0.5\ O_2 \tag{2}$$
$$2HI \rightarrow H_2 + I_2 \tag{3}$$

Equation one is known as the Bunsen reaction. In this reaction, sulfuric acid and hydriodic acid are produced from the reaction of sulfur dioxide, iodine and water. When this reaction takes place in the presence of a large excess of I2, the Bunsen reaction then causes a spontaneous separation into two immiscible liquid phases (one H2SO4 – rich and the other HI- rich). As the reaction proceeds, the sulfuric acid phase decomposes into water, sulfur dioxide, and oxygen, as described in equation two. Finally, in equation three, the hydriodic acid decomposes into hydrogen and iodide. Overall in the SI process, water is decomposed into hydrogen and oxygen, with all other chemicals being recycled in the closed catalytic process. If heated with a nuclear source, the SI process could prove to be an ideal environmental solution to hydrogen production, since the SI process produces virtually no harmful byproducts or emissions. This leads to a cost effective method for producing hydrogen using only nuclear heat and water. It has been estimated that hydrogen can be produced from nuclear power at approximately 1.5 U.S. dollars per kilogram.[15]

FUEL CELL

Fuel cells (FC) are vital to the uses of hydrogen as an energy source for light duty transportation. A FC converts the chemical energy from hydrogen into electricity through a chemical reaction with oxygen.[16] FCs use three adjacent segments to work: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that hydrogen is consumed, water is generated, and an electric current is created, which can be used to power the vehicle. FCs differ from batteries in that they require a constant source of hydrogen and oxygen to run. As a result, FCs will produce electricity continually as long as these inputs are supplied. The most advanced fuel cell technology uses a proton exchange membrane (PEM) as the electrolyte. Within this electrolyte layer, platinum is embedded to act as a catalyst to increase the kinetics of the electron transfer process. Current technology produces 1.34 horsepower and uses approximately 0.2 grams of platinum for every kilowatt.[17] A 100 kilowatt FC will produce roughly 134 horsepower and use approximately 20 grams of platinum. To put this into perspective, the average catalytic converter on a light duty vehicle has between three and seven grams of platinum and the average platinum wedding band weighs 13 grams. This leads to a commercial price between $31 and $50 U.S. dollars per kilowatt. To make fuel cells more economical, research is focused on removing platinum and replacing it with ruthenium, palladium, rhenium, molybdenum, tungsten, iron and carbon.[18-23] We will assume the use of a 100-kilowatt fuel cell producing 134 horsepower at a cost of $4,000 US dollars for the remainder of the study.

ENERGY NEEDED TO MOVE A CAR

To analyze the alternative to petroleum we must calculate the energy needed to move a car 250 miles, so that we can then determine the necessary amount of alternative energy needed. This calculation can be broken up into two motions: acceleration and maintaining momentum. Both are easily calculated with classical mechanics. Some assumptions need to be made before we can determine the necessary energy: the car weighs 1360.7 kilograms (3000 pounds) and is traveling at 22.3 meters per second (50 miles per hour). To calculate the acceleration we determine its kinetic energy:

$$KE = 1{,}360.7\ kg\ \times \frac{(22.3\ m/s)^2}{2}$$

$$KE = 338{,}137\ J$$

Maintaining a momentum of 22.3 meters per second takes approximately 25 horsepower:

$$25\ hp\ \left(\frac{2{,}546\ btu/h}{1\ hp}\right)\left(\frac{1\ kWh}{3{,}414\ btu}\right)\left(\frac{3{,}601{,}770\ J}{1\ kWh}\right) = 6.715 \cdot 10^7\ J/h$$

It takes 5 hours to travel 250 miles at 50 miles per hour:

$$6.715 \cdot 10^7\ J/h \times 5\ h = 3.358 \cdot 10^8\ J$$

Total energy:

$$338{,}137\ J + 3.358 \cdot 10^8\ J\ = 3.361 \cdot 10^8\ J$$

FUEL COSTS

The efficiencies of the powertrain unit must be accounted for, so that calculations can account for lost energy through the powertrain unit. Assuming we use the car previously discussed, a fuel cell powertrain is approximately 50 percent efficient:

$$3.361 \cdot 10^8\ J\ \div 50\% = 6.722 \cdot 10^8 J \left(\frac{1\ mol}{4.36 \cdot 10^5\ J}\right) = 1{,}541.71\ mol\ H_2$$

$$1{,}541.71\ mol\ H_2 \left(\frac{2.016\ g}{1\ mol}\right)\left(\frac{1\ kg}{1000 g}\right) = 3.108\ kg$$

Assuming the hydrogen is produced from the SI process heated via a nuclear source:

$$3.108\ kg \left(\frac{1.5\ US\ dollars}{1\ kg}\right) = 4.66\ US\ dollars$$

The electric powertrain is approximately 70 percent efficient:

$$3.361 \cdot 10^{8}\,J\ \div 70\% = 4.801 \cdot 10^{8} J \left(\frac{1\,kWh}{3601770\,J}\right) = 133.304\,kWh$$

Assuming the electricity is produced from nuclear power with a cost of seven cents per kilowatt hour:

$$133.304\,kWh \left(\frac{0.07\,US\ dollars}{1\,kWh}\right) = 9.33\,US\ dollars$$

To verify that our fuel estimations are in the ballpark, we can calculate the fuel cost for an internal combustion engine (ICE) running on gasoline. The ICE powertrain unit is approximately 28 percent efficient:

$$3.361 \cdot 10^{8}\,J\ \div 28\% = 1.201 \cdot 10^{9} J \left(\frac{1\,btu}{1{,}055\,J}\right)\left(\frac{1\,gal\ of\ Gasoline}{124{,}000\,btu}\right)$$
$$= 9.175\,gal\ of\ Gasoline$$

Using the current price of gasoline, we can calculate the cost to fuel the previously discussed vehicle with gasoline:

$$9.175\,gal\ of\ Gasoline \left(\frac{3.73\,US\ dollars}{1\,gal\ of\ Gasoline}\right) = 34.22\ \ US\ dollars$$

In addition, we can calculate the fuel economy from our estimation. This verifies that our calculations are accurate and applicable to the real world:

$$\left(\frac{250\,Miles}{9.175\,gal\,of\,Gasoline}\right) = 27.25\quad miles/gal$$

CHEMICAL HYDRIDES

Efficient hydrogen storage is regarded as the key challenge for the use of hydrogen in large scale light duty transportation. Currently, there are three methods for storing hydrogen that meet the criteria of this study: chemical hydrides, liquid storage, and pressurized storage. We will discuss chemical hydrides first.

In recent years, group I and II salts of alanates, amides, and borohydrides have received considerable attention as potential hydrogen storage materials. These materials are often referred to as complex hydrides. Complex hydrides tend to have high hydrogen gravimetric densities and most are commercially available. Thus, complex metal hydrides are viable candidates for hydrogen storage in light duty transportation. Hydrogen is released via cascade decomposition from the complex hydride, and the step reactions require different conditions. A general mechanism for hydrogen release from chemical hydrides can be seen below. As a result of these cascading reactions, there is a large difference between the theoretical and the practically attainable hydrogen using complex hydrides.

$$M(BH_4) \rightarrow MH + B + {}^{3}/_{2}\, H_2$$
$$A(BH_4) \rightarrow AB + 2\, H_2$$

Aluminum borohydride minimizes the difference between the theoretical and the practically attainable hydrogen. Aluminum borohydride has a hydrogen percent weight of 16.78 and can reversibly bind 80 percent of its molecular hydrogen. Using the previous assumptions, we can calculate the amount of Aluminum borohydride to fuel our vehicle:

$$71.5048\, g/mol\ \times 16.78\, H\% = 11.998\ \ g/mol$$

$$3.108\, kg\ H_2 \left(\frac{1\, mol}{0.011988\, kg\ H_2}\right)\left(\frac{0.071505\, kg}{1\, mol}\right) = 19.522\, kg\ of\ Al(BH_4)_3$$

$$19.522\, kg\ of\ Al(BH_4)_3\ \div 80\% = 23.153\, kg\ of\ Al(BH_4)_3 = 51.04\, lbs\ of\ Al(BH_4)_3$$

Currently, there are no commercial vendors that make aluminum borohydride on such a large scale, as there is only a small laboratory use for the compound. Aluminum borohydride is synthesized in the lab from sodium borohydride and aluminum trichloride. If we assume that the aluminum borohydride for our powertrain is made using a similar method we can determine the cost:

$NaBH_4$ →	$92,000
$AlCl_3$ →	$3,000
+ Overhead →	$23,750
Total	$118,750

In addition to the cost of the chemical hydride and fuel cell, the powertrain for a chemical hydride fuel cell needs the fuel lines, wiring and electric motor: The sum for a chemical hydride hydrogen fuel cell fueled with aluminum borohydride can be seen below.

Fuel lines →	$500
Fuel Cell →	$4,000
Al(BH4)3 →	$118,750
+ Wiring and Motor →	$4,000
Total	$128,250

LIQUID HYDROGEN

Another method for storing hydrogen is through gas liquefaction. Liquid hydrogen offers a higher gravimetric density than most chemical hydrides possess. Liquefaction is achieved via the Linde process, where hydrogen gas is alternately compressed, cooled, and expanded. Each time, the expansion causes a reduction in temperature for the hydrogen. As the temperature lowers, the hydrogen changes phases. The gas becomes liquid as the molecules move slower. The Linde process utilizes approximately 13-kilowatt hours of electricity per kilogram of hydrogen liquefied. Once liquid hydrogen is synthesized, it is stored in cryogenic cylinders. These cylinders are specially engineered to regulate and minimize the pressure created from the continuous boil-off of hydrogen, resulting in an average cost of 45 US dollars per liter of gas stored.

Using the assumption from the model vehicle previously discussed, we can calculate the amount of liquid hydrogen necessary for a journey of 250 miles:

$$3.108\ kg\ H_2\ \left(\frac{1\ L}{0.07099\ kg\ \ H_2}\right) = 43.78\ L\ \ of\ H_2$$

Cryogenic cylinders are only filled up to 80 percent due to safety precaution. Accounting for this precaution we can estimate the cost of the cryogenics tank:

$$43.78\ L\ \ of\ H_2\ \div 80\% = 54.725\ L\ \ of\ H_2 = 14.457\ gal\ L\ \ of\ H_2$$

$$54.725\ L\ \ of\ H_2 \left(\frac{45.0\ US\ Dollars}{1\ L}\right) = \sim 2450.\ US\ Dollars$$

The cost of liquefying hydrogen using nuclear power can be accounted for:

$$3.108\ \ kg\ H_2 \left(\frac{13kWh}{1\ kg\ H_2}\right)\left(\frac{0.07\ US\ Dollars}{1\ kWh}\right) = \sim 3.00\ US\ Dollars$$

Similar to the chemical hydride powertrain, the liquid hydrogen powertrain needs the additional fuel cell, fuel lines, wiring, and electric motor. The sum for a liquid hydrogen fuel cell can be seen below.

Fuel lines →	$500
Fuel Cell →	$4,000
Cryogenics Tank →	$2,450
+ Wiring and Motor →	$4,000
Total	$10,950

COMPRESSED HYDROGEN

The final method for storing hydrogen is through compression. Compression hydrogen is the most technologically advanced form of storing hydrogen and has been demonstrated with prototypes from multiple manufacturers.[24] Compressing hydrogen is more energy efficient than liquefaction, taking only 62 percent of the energy (8 kilowatts per kilogram). Additionally, compressed hydrogen offers indefinite storage times and relatively high gravimetric densities. Onboard storage of high pressure hydrogen is achieved by the use of composite tanks. These composite tanks are generally composed of a fiberglass or carbon fiber woven outer layer with a polymer liner and are capable of holding pressures greater than 700 bar (690.85 atmospheres).[25] The utilization of exotic materials and precision engineering causes composite tanks to have high capital cost of $1,210 US dollars per kilogram of gas.

Using the assumption from the model vehicle previously discussed, we can calculate the cost of composite tank for a light duty vehicle:

$$3.108\ kg\ H_2\ \left(\frac{1210\ US\ Dollars}{1\ kg\ \ H_2}\right) = \sim 3760.\ US\ Dollars$$

The cost of compressing hydrogen using nuclear power can be accounted for:

$$3.108\ kg\ H_2 \left(\frac{8\ kWh}{1\ kg\ \ H_2}\right) \left(\frac{0.07\ US\ Dollars}{1\ kWh}\right) = \sim 1.75\ \ US\ Dollars$$

Similar to the chemical hydride and liquid hydrogen powertrain, the compressed powertrain needs the additional fuel cell, fuel lines, wiring, and electric motor. The sum for a compressed hydrogen fuel cell can be seen below.

Fuel lines →	$500
Fuel Cell →	$4,000
Compressed gas tank →	$3,760
+ Wiring and Motor →	$4,000
Total	$12,260

LITHIUM ION BATTERIES

In addition to hydrogen, electrochemical storage in the form of lithium-ion batteries is a feasible alternative to fossil fuels. The makeup of a lithium battery consists of a mesoporous graphite anode, a lithium metal oxide cathode, and lithium salt in a mixed organic solvent for an electrolyte implanted in a felt design to isolate the anode and cathode. High specific energy, high efficiency and long lifetimes have made lithium-ion batteries the power source of choice for most consumer electronics. These same characteristics make them ideal for sustainable light duty transportation. The progressive diffusion is essentially assured with the use of the lithium-ion batteries in hybrid (HEV), Plug-in hybrid (PHEV) and battery (BEV) electric vehicles.[26] The combination of an internal combustion engine and lithium-ion battery has proven benefits not only for fuel economy, but for emission control. Therefore, this produces similar driving performances but strictly for petroleum light duty vehicles. Currently there are a handful of light duty vehicles on the market that employ lithium-ion batteries as a source of energy. The plug-in hybrid Chevy Volt is one of these vehicles and it will be the basis for the capital cost estimation of a lithium ion battery light duty vehicle. The Chevy Volt, introduced 2011, has a 16 kilowatt hour lithium-ion battery and is capable of traveling 45 miles on only the battery. The Volt's powertrain consists of the lithium-ion battery, battery pack structure, the cooling, the high-voltage wiring, and the motor. Chevy estimates the battery pack structure, the cooling, the high-voltage wiring, and the motor cost approximately \$4,000 US dollars.[27] For our calculation, we assume a small increase (\$5,000) to this value due to the larger battery, the battery pack structure, and the cooling system. The battery costs roughly \$6,000 US dollars (\$375 per kilowatt hour).[27] Assuming the model vehicle previously discussed and 80 percent discharge on the battery for maximum battery life, we can calculate the cost of lithium-ion battery for a light duty vehicle:

$$133.304\,kWh \div 80\% = 166.63\,kWh\left(\frac{375\ US\ Dollars}{1\ kWh}\right) = \sim\ 62{,}490.\,US\ Dollars$$

Therefore the lithium-ion battery powertrain has a capital cost:

Lithium-ion battery →	\$64,490
+ Battery extras and Motor →	\$5,000
Total	\$69,490

MULTI- ELECTRON MATERIALS

With the potential ability to create batteries with a higher energy density than a lithium-ion battery, many novel battery materials and new concepts have arisen.[28] Most of these materials have come in the form of multi-electron materials. Multi-electron materials are materials that undergo multiple oxidation states during a redox reaction that occurs in a battery. The most widely known material that possesses this property is titanium boride, which undergoes a six-electron redox reaction. Recently, vanadium boride and its seven-electron redox reaction has been spotlighted. . The vanadium boride cell can be seen below. The cell combines a conventional air cathode with a zirconia-stabilized vanadium boride anode.[29] Oxygen brought in via the cathode reacts in the Vanadium cell with the anode producing electricity. The reaction is irreversible within the cell; spent anodes need to be replaced in a "refueling" operation and chemically regenerated.

Anode:

$$VB_2 + 11\ OH^- \rightarrow {}^{1}/_{2}\ V_2O_5 + B_2O_3 + {}^{11}/_{2}\ H_2O + 11e^-$$

Cathode:

$$O_2 + 2\ H_2O + 4e_- \rightarrow 4\ OH^-$$

Overall:

$$VB_2 + {}^{11}/_{4}\ H_2O \rightarrow V_2O_5 + B_2O_3$$

Vanadium boride has a charge density of 5.3 kilowatt hours per kilo gram.[29] Assuming the vehicle previously discussed, we can calculate the amount of vanadium boride to fuel our vehicle:

$$133.304\ kWh\left(\frac{1\ kg}{5.3\ kWh}\right) = \sim\ 25.152\ kg = 55.45\ lbs$$

The current market value of vanadium boride is approximately 5,130 US dollars per kilogram. From this information we can calculate the cost for vanadium boride for the previous assumptions:

$$25.152\ kg\left(\frac{5{,}130\ US\ dollars}{1\ kg}\right) = \sim 129030.\ US\ dollars$$

In addition to the cost of the vanadium boride, the powertrain for a vanadium boride fueled electric vehicle needs a cell pack structure, wiring and an electric motor:

Lithium-ion battery →	$129,030
cell pack structure →	$2,000
+ Battery extras and Motor →	$5,000
Total	$136,030

ULTRACAPACITORS

Similar to capacitors, ultracapacitors store energy in an electric field created by two conductors separated by a non-conductive region. Ultracapacitors differ from capacitors by having the two metal plates coated with a porous carbon. The two plates are then immersed in an electrolyte solvent.[30] During charging, ions from the electrolyte accumulate on the surface of each carbon-coated plate, creating a higher charge density than capacitors. Ultracapacitors are currently available on the commercial market, but at a high price tag. Nanotune Technologies currently sells ultracapacitors at a price between $2,400 and $6,000 US dollars per kilowatt hours.[31] Assuming the model vehicle previously discussed and an average cost of $4,200 US dollars per kilowatt hours, we can calculate the cost of lithium-ion battery for a light duty vehicle:

$$133.304\ kWh\left(\frac{4{,}200\ US\ Dollars}{1\ kWh}\right) = \sim\ 559{,}880.\ US\ Dollars$$

The sum for an ultracapacitor electric vehicle can be seen below.

Ultracapacitors →	$559,880
+ Wiring and Motor →	$5,000
Total	$564,880

HYBRID SYSTEMS

In recent years, fuel cell hybrid vehicles that consist of a fuel cell and lithium-ion battery are under great interest. Hybridization of a fuel cell allows for a more efficient use of energy and increases the lifetime of the fuel cell and lithium-ion battery.[32] When power demand is high, such with higher loads or acceleration, the battery and the fuel cell work in unison to generate power more efficiently. When the power demand is low, the fuel cell provides the required power and the battery is recharged with any extra power. Additionally, the use of a battery allows for fast start-up of the fuel cell and allows the capture of regeneration energy from braking.[33] The calculations above suggest that the only alternative energy sources that are currently economically feasible are lithium-ion batteries, liquefied hydrogen, and compressed hydrogen. Although technologically feasible, lithium-ion battery/liquefied hydrogen fuel cell hybrid have the disadvantage of continuous boil-off. This continuous boil-off of hydrogen limits the possible uses of liquid hydrogen storage systems to applications where the cost of hydrogen is not an issue and the gas is consumed in a short time. As a result, the lithium-ion battery/compressed hydrogen fuel cell hybrid has the best chance to be a successful. Table 1 summarizes the calculated results for a compressed hydrogen fuel cell hybrid. The results are based on the pervious calculations for the lithium ion battery vehicle and the compressed hydrogen fuel cell vehicle. The total cost of the powertrain unit for each scenario is seen in the far right column. This value included a $5,000 US dollar addition to account for the battery pack structure, the cooling system, wiring and motor of each hybrid except for the compressed hydrogen FC vehicle which has a $4,000 US dollar addition for the wiring and motor.

ENVIRONMENTAL IMPACTS

Environmental impacts such as pollution of air, water, soil, and climate change induced by emissions of greenhouse gases (GHG) or ozone depleting substances need to be considered when looking at alternatives to current technology. In 1990s GHG emission came to the spotlight as a source to climate change. The majority of these GHG emissions are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulfur hexafluoride (SF_6), which have GHG impact weighting coefficients relative to CO_2 of 1, 21, 310 and 24,900, respectively.[34] Nearly all of these emissions come from the combustion of petroleum in the modern internal combustion engine. Research indicates that with the use of alternative energy sources in light duty transportations, the amount of GHG release into the environment can be drastically decreased.[35-37]

OVERALL ASSESSMENT

The total capital costs for the alternatives for light duty transportation (i.e. the cost of the energy source is not included) are summarized below. In addition, for the alternatives that use hydrogen, the energy needed to compress or liquefy the hydrogen is not included. Liquefied hydrogen, compressed hydrogen, and lithium-ion batteries are the only alternatives that are economical at the current moment. Liquefied hydrogen has the disadvantage of continuous boil-off, which limits its application to where cost of hydrogen is not an issue and gas is consumed in a short period.

Alternative technology	Total capital cost (US dollars)
Chemical Hydrides	$128,250
Liquefied Hydrogen	$10,950
Compressed Hydrogen	$12,260
Lithium-Ion Batteries	$69,490
Multi-Electron Materials	$136,030
Ultracapacitors	$564,880

Hybridization allows for a more efficient use of energy along with increasing the lifetime of both the fuel cell and the battery. The lithium-ion battery/compressed hydrogen fuel cell hybrid has the best chance to be successful. With higher power demands, the battery and the fuel cell work in unison to generate power more efficiently. While when power demand is low, the fuel cell provides the power and the battery is recharged with any extra energy. The total capital costs for the alternatives for light duty transportation (i.e. the cost of the energy source is not included) are summarized below. Once again, these values do not include the cost of the energy sources in order to pressurize the hydrogen.

Hybrid Model	Total capital cost (US dollars)
100 mile battery	$36,750
75 mile battery	$30,840
Chevy Volt battery	$18,580

Table 1: A summary of cost associated with a lithium-ion/hydrogen fuel cell hybrid powertrain. * denotes the additional cost of the battery pack structure, the cooling system, wiring and motor.

	Battery Energy (Joules)	**H_2 Fuel Cell Energy (Joules)**	**Cost of H_2 Fuel (US dollars)**	**Cost of Electricity (US dollars)**	**Cost of pressurization of H2 (US dollars)**	**Cost of Li-ion Battery (US dollars)**	**Cost of composite tank (US dollars)**	***Total Cost (US dollars)**
Li-ion electric vehicle	$4.80\cdot10^8$	-	-	9.33	-	64,490	-	69,490
100 mile battery hybrid	$1.92\cdot10^8$	$4.03\cdot10^8$	2.80	4.67	1.05	24,990	2,260	36,750
75 mile battery hybrid	$1.44\cdot10^8$	$4.71\cdot10^8$	3.26	3.43	1.22	18,710	2,630	30,840
Chevy Volt hybrid	$1.92\cdot10^8$	$5.50\cdot10^8$	3.82	1.12	1.42	6,000	3,080	18,580
Compressed H_2 FC vehicle	-	$6.72\cdot10^8$	4.66	-	1.75	-	3,760	12,260

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