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Hybrid Vehicle Technologies

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1. Introduction

Until recently a vehicle drive train had a single power train consisting of a conventional internal combustion engine power source and a single energy source such as gasoline or diesel. However, this single configuration drive train landscape is rapidly changing. Vehicles with two or more power sources and two or more energy sources are called hybrid vehicles. A vehicle that has electricity as one of the energy sources for one of its power sources is called a hybrid electric vehicle (HEV). Most hybrid vehicles are limited to two power trains because of the system design complexity. The primary design objective of hybrid drive trains is saving energy. The addition of an electric motor to the conventional gasoline or diesel engine drive train can save energy in several ways:

- **"Regenerative braking**. The motor is used in generator mode to brake the vehicle, generating electricity to be stored in the battery and thus recapturing some of the energy normally lost as heat in conventional brakes.
- **Engine downsizing**. The power added by the electric drive may allow the engine to be downsized, maintaining most engine operation at a higher percentage of rated torque, which is generally more efficient.
- **Idle-off**. Use of the motor as a starting motor, with the battery available to run the accessories, allows the engine to be turned off during stops, braking and coasting, saving energy that would otherwise be lost during these events.
- **Electric launch.** In some configurations, the motor alone can be used to accelerate from a stop, avoiding a driving mode where the engine in a conventional drive train would be particularly inefficient". [1]
- **Electrically powered alternatives.** Components such as hydraulic steering can be replaced with more efficient electrically powered steering, using the electric motor.

In addition to these energy savings, there is also the added advantage of lower level of emissions since one of the power sources is an emission free electric motor. It should also be noted that another advantage of the hybrid model is that it opens the possibility of other engine technologies such as turbines, etc. which would not be appropriate in a single power train but with proper control systems could be accommodated within an HEV system.

These energy savings are attractive when one considers the following facts relating to conventional vehicles [1]:

- "At best, only one-fifth of the fuel energy reaches the wheels and is available to overcome the tractive forces, and this is on the highway when idling losses are at a minimum, braking loss is infrequent, and shifting is far less frequent.
- Braking and idling losses are extremely high in urban driving and even higher in more congested driving, e.g. within urban centers during rush hour. Braking loss, that is, the shedding of the kinetic energy of motion through heat generated by the brakes, represents 46% of all tractive losses in urban driving. Idling losses represent about one sixth of the fuel energy.
- Losses to aerodynamic drag, a fifth or less of tractive losses in urban driving, are more than half of the tractive losses during highway driving." [1]

A major downside of hybrids is the complexity of their design and the accompanying costs in competition with the lower cost high volume conventional vehicle design and production. It is also possible that a hybrid of comparable performance to a conventional vehicle will be of greater weight, even though the engine is downsized, because of the weight of the motor, storage device and other components.

We have already mentioned the two key reasons why hybrid concepts are generating so much interest: energy savings and lower emissions. So we can summarize the larger issues that are driving the development of hybrid technologies as follows:

- Hybrids are the logical first step in the transition out of the internal combustion engine pollution problem that is becoming a critical global issue.
- Hybrids are also the first logical step towards becoming less dependent on foreign oil imports from politically unstable regions of the world, not to mention that the world oil supply may actually be peaking as well.

From an engineering perspective it is indeed an exciting time to observe the landscape of so many possibilities for hybrid designs and alternative energy sources emerging and competing for the best "clean car" design.

It is also interesting to note that this is not the first such competition among power sources for automotive use. In many respects it is déjà vu. Exactly one hundred years ago there was another race that, of course, the gasoline combustion engine won, but it was not at all obvious which power source among the field of candidates would win at the outset. We outline some of the details of that race in the next section.

2. The Old Idea of Hybrids

The emergence of the automobile on the scene in the late 1800's and early 1900's brought with it a wildly competitive scene in many ways. Visionary business people saw the vast future market and no fewer than fifty-seven companies, in Detroit alone, were at work to capture this market [4]. There was also diversity among these companies in the choice of vehicle energy source. By 1900 the race can be characterized in terms of the number of vehicles manufactured in the U.S. [4]:

- Steam 1,684
- Electric 1,575
- Gasoline 963

The steam car had problems of frequent water requirements and could require a start-up time of 45 minutes on a cold day, but steam power was the established power source in factories and on railroads. So it is actually not surprising that steam was initially popular using the tried and true power source of the day. Although certainly not the only steam car of the time, the Stanley Steamer car became an icon of the era. The twin Stanley brothers who built it liked to point out that the engine had only 13 moving parts.

The range of the electric car was limited by battery charging and was relatively costly technology. Did I mention déjà vu? The gasoline car had great range, but the hand cranking, gear shifting and noisy engine were worrisome and unattractive features. One of the major deciding events in favor of the gasoline car was the invention of the electric starter.

The Woods Gasoline-Electric car introduced in 1916 in the U.S. is most interesting. This car had a four cylinder gasoline engine that was coupled to an electric motor-generator. The motor-generator was coupled to the rear axle. The car could operate in a gasoline-only mode, electric only mode, or combined gasoline-electric mode with the electric motor serving as supplementary power or recharging the battery. Sound familiar? Unfortunately the price for this early hybrid was much higher than the pure electric and far higher than the increasingly popular gas car and only a few were sold. Several other hybrid designs were introduced in Europe as early as 1899.

Dr. Jim Gover of Kettering University (previously General Motors Institute) has said, "there is an infinite space for the design of hybrid vehicles that can range from mild hybrids to full hybrids. If cost was not a factor, one could design a hybrid vehicle that's optimized for the driving style, driving conditions and cost needs of each driver."

Hopefully the sections that follow will give the reader some perspective on this large landscape of potential designs, power sources and energy sources. There is much talk about fuel cells, but major advancements in battery technology could push fuel cells deep into the future and open the time window needed to more fully develop the engineering opportunities in this "infinite space" of hybrids.

3. Hybrid Electric Design Concepts

The drive train of a vehicle must meet the following requirements:

- Provide the level of power needed for vehicle performance.
- Pollute the environment as little as possible.
- Operate at high efficiency.
- Carry enough energy for the targeted driving range.

A hybrid vehicle drive train has more than one power train, each with a different power source and energy source. Most hybrids are limited to two power trains.

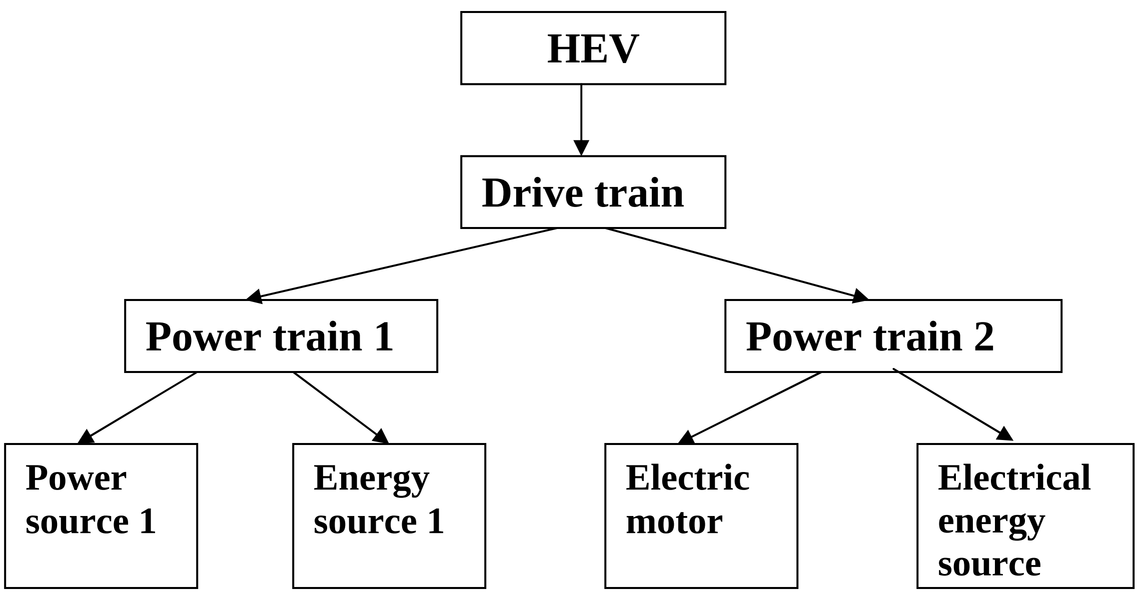

Figure 2
Major Components of the HEV Drive Train

As illustrated in the diagram of Figure 2, one of the power trains in a HEV is an electric motor and an electrical energy source, usually a battery. Power source 1 in a HEV in today's consumer market is most commonly a conventional gasoline internal combustion (ICE) engine. However, Power source 1 could also be one of a large number of potential sources, some of which are more experimental than others. Candidates will be discussed in later sections.

In general, there is also a variety of candidates for Energy source 1. For example, for the conventional gasoline engine, there is E10, E85 and pure ethanol. For diesel there is a similar diversity of energy sources. For the electrical energy source there are many types of batteries, ultracapacitors, ultra-high-speed flywheels, and of course the power grid (for plug-in hybrids). So the race for the clean car of the future has a very large field indeed when one considers all possible combinations of values in the bottom row of Figure 2. We should also mention that there are many variations of electric motor types as well.

"We see the world fragmenting into many technologies..." Eric Ridenour, DaimlerChrysler

"There is no silver bullet. We have to work on every one of these fronts, fuel cell vehicles, hybrids, alternative fuel vehicles, clean diesel, gasoline ..." Tom Stephens, Group Vice-President, General Motors Powertrain.

The design of a drive train with two power train components allows the vehicle performance requirements to be viewed in terms of steady state and dynamic components. One power train can be designed to satisfy the steady state and the other the dynamic component. The conventional gasoline engine power train is frequently used for the steady state and the electrical power train for the dynamic component. In this way, an integrated control system can be designed to restrict the gasoline engine operation to its optimal operating region, thus producing less pollution. The electric motor can then be used to provide supplementary power surges for the dynamic requirements at startup, rapid acceleration needs, etc. This description is an oversimplification of actual systems but it is a good first order conceptual model. For a given vehicle performance requirement, this design strategy also means a smaller size gasoline engine requirement.

Again, in terms of first order models, hybrid drive trains are commonly classified into two configurations, parallel and series.

Parallel HEV Drive Train

In the parallel HEV drive train, the engine and the electric motor are mechanically coupled to the transmission which in turn is coupled to the differential of the axle. Within this overall configuration there are opportunities for many design variations.

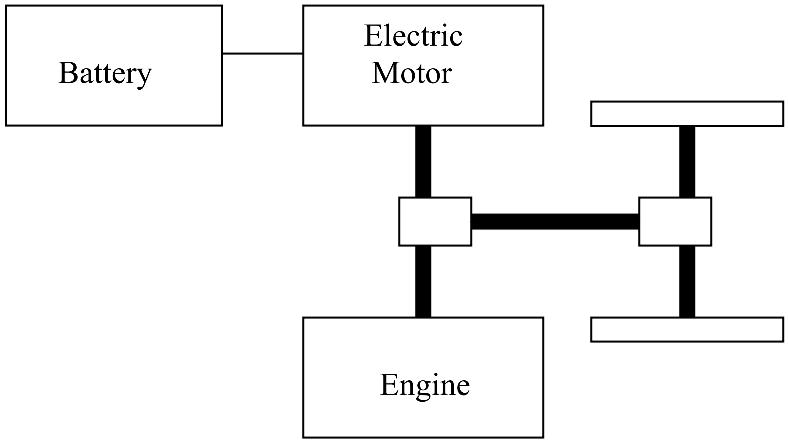

Figure 3
Parallel Configuration

Advantages of parallel configuration:

- The engine and electric motor are directly connected to the drive wheels with no energy conversion required hence energy loss is less.
- The smaller engine provides better fuel economy and when the electric motor and engine operate together more power is available.
- In most parallel vehicles a separate generator is not needed since the motor recharges the batteries.

Disadvantages:

- Mechanical couplings between the engine and wheels preclude the engine operating in the most efficient narrow range.
- Complex design and control.

A variation of the above parallel model which will allow the engine to operate in the desirable efficient narrow range is the decoupling of the engine speed and wheel speed by use of a planetary gear system. This design is sometimes called a series-parallel hybrid drive train. In this configuration the engine power is split into two parts, one to the power train, the other to a second motor/generator forming the series power flow in parallel with the larger traction motor. The Prius III uses this type of design. For more details, see this website. http://www.cleangreencar.co.nz/info_toyota-priusIII-technical.asp . There are other promising technologies that are emerging for this type of continuously variable planetary application. For one example, see the following website. http://www.fallbrooktech.com.

Another variation which is functionally similar to the Prius design is the "two-mode full hybrid" recently developed by the collaborative efforts of General Motors, BMW and DaimlerChrysler. This architecture is designed to be scaled to fit multiple vehicles and can be used with both gasoline and diesel engines. The GM Chevrolet Tahoe and GMC Yukon will soon be equipped with this technology. More details at the following website: http://www.greencarcongress.com/2004/12/gm_daimlerchrys.html

Series HEV Drive Train

In the series HEV drive train, an electric motor powers the vehicle. The electrical energy source for this traction motor is primarily a generator mechanically coupled to the engine, and secondarily supplied from batteries. A rectifier is needed with the generator. The series configuration can also accommodate a design of a traction motor for each wheel rather than the single motor with differential gears to either the front or rear axle.

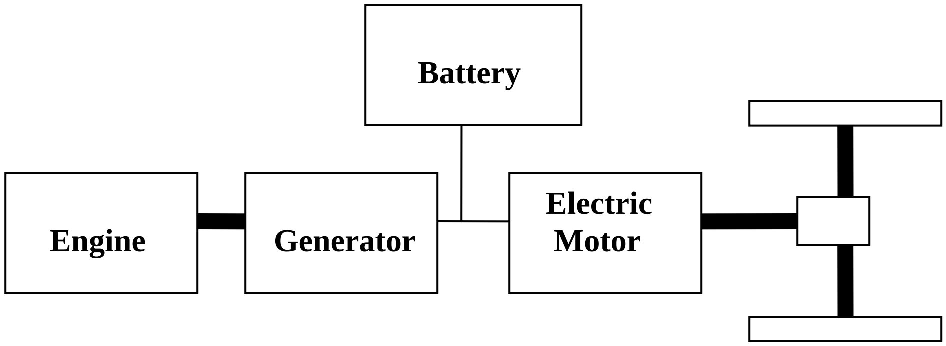

Figure 3
Series Configuration

Advantages of series design:

- A series design provides for a variety of configurations for arrangement of the engine and vehicle components.
- Do not need a multigear transmission.
- Simple control strategies may be used
- Instead of using one motor and a differential gear, two motors or even an all wheel drive of four motors could be used without the complexity and expense of differentials and drive shafts through the frame.

Disadvantages of series design:

- Additional cost and weight of the generator.
- The inefficiencies of conversion from mechanical energy of the engine to electrical in the generator and electrical to mechanical in the traction motor.
- The traction motor must be sized to meet maximum requirements since it is the only power source connected to the wheels

Mild Hybrids

Full hybrid designs with parallel or series configurations have structures that are very different from conventional vehicles and require large investments of time and money. Also the high electric power demand requires a large heavy energy storage unit. An alternative that provides some of the efficiencies of hybrid technology is called the mild or soft hybrid. The idea is to make few changes in the conventional design. One approach is to place a small electric motor behind the engine and allow it to function as the engine starter and as a generator. In this way it can add power to the drive train in high demand situations as a motor and provide regenerative braking capability as well.

Regenerative Braking

An important capability of HEVs is the regenerating braking feature. The electric motor is used in a second mode as generator to recover much of the braking energy normally lost in a conventional vehicle. This kinetic and potential energy of the vehicle is captured and stored for later use.

The breaking system design must satisfy two requirements. First, in emergency situations, it must stop the vehicle in the shortest possible timeframe. Second, it must be capable of providing braking torque equally to all wheels so that the direction of the vehicle is maintained. In general, the breaking torque required for braking exceeds the capabilities that an electric motor can produce, so mechanically frictional braking systems must be included along with electrically regenerative braking. Regenerative braking is normally designed only for the driven axle.

4. Alternative Power Sources

Power Sources

Spark-ignited gasoline internal combustion engine

This conventional dominant power source promises to be a component of the most popular HEVs, at least in the short term. It is the lowest cost engine primarily because of the huge production volume. Unfortunately polluting emissions continue to be an increasing problem. Ideally, the combustion of hydrocarbon fuel produces only carbon dioxide and water which are not environmentally harmful. However, the reality is this process in an internal combustion engine is never ideal and harmful products such as carbon monoxide, nitrogen oxides and unburned hydrocarbons are also produced. The spark-ignited engine is also very complex with a large number of moving parts and typically losing 80% of the combustion energy to heat.

Compression-ignited internal combustion engine

The conventional diesel engine has been in commercial use since the early days of the automobile. It has the following characteristics: direct cylinder fuel injection that is not premixed with air prior to combustion, compression ignition, little or no intake air throttling, high air-to-fuel ratios and high compression ratios. In the United States, there are few personal vehicles available with the diesel engine option, but new models are appearing. The European market is quite different with diesel engines accounting for about 50 percent of all new car sales. Diesel engines of comparable size to gasoline engines are typically more costly, more durable and more efficient. However, in the past diesel combustion has resulted in higher levels of NOx and particulate matter emissions partly because emissions after treatment solutions have been much more difficult for diesel engines than for gasoline.

Diesel-hybrid-electric personal vehicles are currently only at the concept vehicle stage with automakers. Higher costs of diesel engines seem to be the primary obstacle. Even so, a number of automakers have laboratory development projects focused in this direction, including GM, Ford, Mercedes-Benz and Volkswagen. A plus for the diesel-hybrid is the multitude of potential alternate energy sources for diesel fuel production. See this website for more information. http://www.ehow.com/facts_4798740_alternative-diesel-fuels.html

Sterling engine

The Sterling engine is a reciprocating external combustion engine that has piston and cylinder designs that are similar to conventional internal combustion engines. However, the hydrogen or helium working fluid is sealed inside the system. Heating and cooling the working fluid produces a pressure change that acts on the piston to produce power. An attractive feature for possible HEV application is the relatively small increase in fuel consumption at partial load compared to conventional internal combustion engines. Combustion is a continuous process and this produces a quiet operating engine. Its multifuel and self-starting characteristics are also attractive for potential vehicle application. Some disadvantages are high manufacturing cost, heavy and bulky system, difficulties in controlling power output and hydrogen or helium leakage rate problems. The engine also takes some time to warm up before producing a useful level of output power. For additional information see website http://www.stirlingengine.com/

Rotary engines

In rotary engines all the moving parts have a continuous rotary motion as contrasted with the reciprocating action. A Wankel rotary engine is about half the size and weight of a conventional gasoline engine for equivalent power output. It also has fewer moving parts. On the downside it requires expensive materials, high-precision manufacturing techniques and produces high levels of unburned hydrocarbons. See this website for more

information on rotary engine hybrid research:
http://www.greencarcongress.com/2005/10/mazda_to_displa.html

Compressed-air engine

Some envision the electric power train of an HEV being replaced with a compressed-air engine. One design provides for compressed-air from tanks at a pressure of 4,351 psi to be moved through an air injector into the cylinders of a two-cylinder engine. The expanding air provides the power to push the pistons down. At speeds less than 60 mph the engine is air powered. At higher speeds it is powered by gasoline, diesel or natural gas. The driving range on air power is 124 miles at the top speed of 60 mph. An air fill up takes four hours on a home outlet system. See the following website for more details.
http://auto.howstuffworks.com/air-car1.htm

Critics note that these cars do require electricity for powering the air compressor and may move the pollution to the electrical power plant. However, if local electrical generation like solar, wind, etc. is encouraged (as mentioned with the plug-in hybrid), this problem can be eliminated.

Solar

Solar power is generated by photovoltaic cells composed of layers of semiconductor material that release electrons when exposed to sunlight and produce a voltage across PN junctions. The single crystal (hexagonal) and polycrystalline (square) cells currently dominate the market. New and promising approaches include use of other materials than silicon (e.g. gallium arsenide) which have higher efficiencies and sensitivity to different parts of the light spectrum. This capability is significant since the spectrum of the sun changes every five minutes.

Electric Drive

An electric propulsion system consists of an electric motor and the accompanying power control electronics. DC motor drives have the appropriate characteristics for HEV applications and are simple to control. However, they are also large and have high maintenance requirements because of the mechanical commutator. With the advent of solid state power control electronics and advances in other motor drive technologies, the following types of motors seem to have the greatest potential for vehicle applications in the future.

- **Induction motor (IM).** IMs enjoy broad acceptance as a motor type for HEV applications because of their low cost, low maintenance requirements and high reliability. However, the required performance cannot be obtained with the conventional variable voltage variable frequency control and field orientation control (FOC) is more appropriate. The objective of FOC is to maintain maximum torque by keeping the rotor and stator field perpendicular. IMs are usually three phase using a pulse-width-modulated inverter.

- **Permanent magnet brushless DC motor (PM).** The PM machine is more efficient than induction motors since there is no rotor winding and rotor copper losses and has lower weight for a given torque requirement. However, the PM has a short constant power range because of the restricted field weakening capability inherent in the permanent magnet. This limitation has been addressed by the addition of field windings, producing a relatively complex structure. Because the resulting machine has both permanent magnets and field magnets, it is sometimes called a PM hybrid motor.

- **Switched reluctance (SR) motor.** SR motors are directly related to the variable-reluctance stepping motors and have the advantages of outstanding torque-speed characteristics for HEV applications. In addition, they are relatively inexpensive to produce. However, the reliability of SR motors can be affected by the sensitivity of sensors located on the shaft that locate the relative position of the rotor to the stator. Improved sensorless technologies are being developed.

For an introduction to electric motor types and operation, see the following website: http://www.freescale.com/webapp/sps/site/overview.jsp?code=DRMTROVRVU10&fsrch=1&sr=3.

Steam engines

A steam engine is an external combustion engine (ECE) that is capable of efficiencies approaching 90% as contrasted with the gasoline ICE efficiency of around 25% and is not fuel specific. A wide variety of fuels can be used. The combustion takes place at atmospheric pressure and thus does not produce carbon monoxide and nitrogen oxide pollutants. Historically startup time required to generate the steam has been a disadvantage. However, there has been a resurgence of interest in this technology as a possible auxiliary power drive that uses the waste heat present in the exhaust gases and cooling system from a gasoline ICE as its source of power. BMW is seriously exploring this concept and laboratory tests indicate that fuel consumption of a four-cylinder engine could be reduced by up to 15% while generating an additional 14 horsepower. This auxiliary power train is called the Turbosteamer. Others are speculating on the inclusion of the Turbosteamer concept in the HEV model. Three power sources? The complexity factor would be higher, but this is an exciting time of exploring new ideas. For more details on the Turbosteamer see this website: http://www.autoblog.com/2005/12/09/bmw-turbosteamer-gets-hot-and-goes/

Gas turbine

A gas turbine is a continuous internal combustion engine in which the turbine is turned by the expansion of hot combustion gases, the products of fuel supplied to a burner. It can be very compact, vibration free and operate on many potential fuels. Because of its continuous combustion, it also produces reduced emissions. Unfortunately it also carries the baggage of several disadvantages. Among them are high noise level, high temperature operation, high cost, requirement of high rotation speed and no torque at low speed.

Fuel cells

The action of a fuel cell can be viewed as the reverse of the process of electrolysis of water. In electrolysis electricity is used to separate water into its chemical components of hydrogen and oxygen. The fuel cell brings hydrogen and oxygen together for chemical combination in a controlled manner to generate electricity. Although the chemical reaction in a fuel cell is similar to that in a chemical battery, fuel cells stand in contrast to batteries that store energy rather than generate it.

An electrolyte provides the medium for the transfer of ions from one electrode to the other. The fuel cell must be continuously supplied with hydrogen and oxygen or an oxidizing agent. Of the six major types of fuel cells the Proton Exchange Membrane (PEM) type is the most investigated and the Direct Methanol (DM) cell also has potential. In the PEM the electrolyte is an acidic polymer membrane and the ions transferred are hydrogen (protons). The DM cell is attractive since its input fuel can be produced from agricultural products but is a less mature technology. The very high operating temperatures of the electrolytes of the remaining four fuel cell technologies present safety problems for vehicle applications.

One of the greatest challenges to future fuel cell vehicles is how to store enough onboard hydrogen for the typical 300 mile range requirement. Some strategies for storing hydrogen onboard are:

- **Liquified hydrogen.** Hydrogen liquefies at -253° C at atmospheric pressure and has about 30 percent of the energy density of gasoline. Issues that must be confronted are: need for special safety precautions for handling and special container insulation. The BMW Hydrogen 7 vehicle recently introduced uses liquid hydrogen.

- **Complex hydrides.** When hydrogen is chemically bound to certain complex hydrides such as sodium aluminum hydride, the hydrogen atoms are more densely packed than in liquid hydrogen. The hydrogen can be released when needed by applying heat. Currently the 200° C operating temperature required is too high and the hydrogen release rate is too slow for vehicle applications. However, research in this direction is said to be promising.

- **Chemical hydrides.** Chemical compounds, such as decalin, release hydrogen when heated and convert to another compound called naphthalene. The naphthalene byproduct must be reclaimed at a service station and sent to a facility which can reverse the process back to decalin by exposing the naphthalene to pressurized hydrogen.

- **Hydrogen adsorbents.** Nanoscale research is producing special carbon structures and metal-organic materials that have very high surface areas to which hydrogen atoms can bond. However, these bonds are very weak and the bonding system is viable only if the temperature is maintained around that of liquid nitrogen, -196° C. The challenge is to produce a system that will work at room temperature.

5. Candidate Alternative Energy Sources

Over the past two decades there have been significant advances in energy storage technologies. We briefly review the current and potential contenders for HEV application.

Alternative Energy Storage Systems

Hydraulic Storage

The EPA is exploring the use of a hydraulic system that operates a pump that compresses nitrogen gas to store braking energy as a potential replacement of the commonly used heavy batteries in current HEVs. Nitrogen is inexpensive and inert. Braking drives the hydraulic pump and compression of the nitrogen. When accelerating, the energy in the pressurized nitrogen drives the pump in reverse and powers the rear wheels. Testing indicates the system will capture 70 percent of the braking energy, which translates into a 60 percent increase in fuel economy and a 40 percent reduction in emissions. Interestingly, the engine type in the project is the diesel. For more detailed information about hydraulic hybrid technology, see this website http://www.epa.gov/otaq/technology/index.htm#hydraulic .

Ultrahigh-Speed Flywheels

The concept of flywheels for storing mechanical energy has been around for a very long time. The type of advanced energy storage device called an ultrahigh-speed flywheel is typically a light weight composite rotor weighing perhaps 30 kilograms and spinning at 10,000 rpm with research systems working toward 30,000 to 100,000 rpm. The power capacity of a flywheel system is a function of the power of the electric machine that is used the charge the flywheel. The ultrahigh-speed flywheel technology is in the early stages of development. A typical flywheel system can achieve a specific energy (energy per unit mass) of 10 watt hours to 150 watt hours and a specific power (power delivered per unit mass) of 2 to 10 kilowatts. Gyroscopic effects can be reduced by using multiple small systems in pairs spinning in opposite directions. There are serious safety concerns. There have been at least two fatal accidents in research laboratories working with this technology, one at Chrysler on the Patriot LeMans race car project and another in a BMW laboratory in Germany.

Electrical Storage

The holy grail of electrical storage is an energy storage system that charges rapidly, provides power on demand and is scalable. Because of the importance of low weight, it is also important that the system have high specific energy and high specific power.

Ultracapacitors

Ultracapacitors are devices that store an electrostatic charge between two closely spaced conductors. Storage capacity is proportional to the surface area of the interface. HEV applications for ultracapacitors are power assist during acceleration as well as recovery of braking energy thus complementing batteries or fuel cells. Ultracaps can completely charge and discharge at high rates and with little degradation. This could be the technology that drives major advances in the HEV and electric vehicle field. Recent research and development directions by a company in Texas named EEStor indicate that it may be possible to produce ultracaps with exceptionally high specific energy, about 280 watt hours per kilogram. To understand just how exceptional, consider that lithium-ion batteries have a specific energy of 120 - 150 watt hours per kilogram and lead-acid gel batteries 32-40 watt hours per kilogram. For additional information, see the following website. http://www.technologyreview.com/Biztech/18086/page2/

Batteries

Lead-acid battery

The lead-acid battery has been used very successfully for over a century in automotive applications. Electrodes are porous lead (anode) and porous lead oxide (cathode). It is a low cost mature technology. However, the sulfuric acid electrolyte is a potential safety problem and its performance degrades at low temperatures. It also has a low specific energy of 32 – 40 watt hours per kilogram.

Nickel-iron battery

Nickel-iron batteries are a mature technology that has been used commercially for many decades. Applications have included fork-lift trucks and railway locomotives. The electrodes are nickel hydroxyl-oxide (NiOOH) (anode) and iron (cathode) in a solution of potassium hydroxide and lithium hydroxide. Advantages include high power density and high number of deep discharge cycles. Its problems are cost of nickel, gassing and corrosion safety.

Nickel-cadmium battery

Nickel-cadmium batteries have a positive electrode of nickel hydroxyl-oxide and a negative of metallic cadmium. Their performance is similar to the nickel-iron battery. Advantages include high specific power and long cycle life. However, the cadmium may present health hazards and it has a high initial cost.

Nickel-metal hydride battery

This technology was introduced in the early 1990s. Its characteristics are similar to the nickel-cadmium battery, but because of the attractive features of higher specific energy and no toxicity, it is replacing them in the market place. The negative electrode uses hydrogen which is absorbed in a metal hydride. The chemical reaction is shown below.

$$MH + NiOOH \leftrightarrow M + Ni(OH)_2$$

During discharge the metal hydride is oxidized producing metal alloy and the nickel oxyhydroxide is reduced to nickel hydroxide. The reverse reaction takes place during charging. Rare-earth alloys, with one of the more common ones being based in lanthanum nickel are used for the hydrogen storage. Cost is a significant problem with this technology.

Lithium-based batteries

Some very promising advancements in battery technology have been based on lithium, the lightest of all metals, producing batteries of very high specific energy and specific power. Two types of technologies have emerged from these developments, lithium-polymer and lithium-ion batteries.

The lithium-polymer battery has a thin solid polymer electrolyte which improves safety and provides flexibility in the physical form of battery produced. One configuration consists of a negative electrode of lithium foil and a positive electrode of vanadium oxide. The variety of shapes and sizes together with the added safety aspects of a solid state battery make it very attractive.

The lithium-ion battery is often cited as the most promising technology for HEV applications. This battery uses a lithiated carbon material for the negative electrode and a lithiated transition metal oxide for the positive electrode. The electrolyte can be a liquid organic solution or a solid polymer. The lithium ions are said to "swing" through the electrolyte. Candidates for the transition metal oxide are nickel-based, cobolt-based or manganese-based. Because of its lower cost, it is expected that future lithium batteries will be manganese-based. The general reaction equation is:

$$Li_xC + Li_{1-x}M_yO_z \Longleftrightarrow C + LiM_yO_z$$

In addition, there is promising work in the application of nanotechnology to battery development. For additional information, see the following website.
http://web.mit.edu/newsoffice/2006/batteries-0208.html

Hybridization of Energy Storage Systems

The disadvantage of an energy storage system can sometimes be overcome by combining (hybridizing) it with another energy storage system that can compensate for this weakness. For example a chemical battery can be hybridized with an ultracapacitor to compensate for low specific power of the battery and low specific energy of ultracapacitors, thus achieving a combined system with the desirable properties of high specific energy and high specific power.

Alternative Energy Sources

In addition to the development of hybrid vehicle technologies, another strategy for reducing emissions and dependence on foreign oil is the development of alternative fuels to fossil fuels as an energy source.

Alternative fuels

Ethanol. Ethyl alcohol is used as an additive in gasoline. Ethanol is produced almost exclusively from corn in the United States, although other sources such as wheat, barley and other plants could be used. The ten percent blend of ethanol with gasoline is called E10 and can be used in conventional gasoline engines without any changes. E10 delivers about the same miles per gallon as gasoline itself and also produces a more complete and hence cleaner fuel burn.

Another common blend is E85 which is 85 percent ethanol. Vehicles must have special modifications to the gas lines, pumps and fuel injectors to use E85 since ethanol is more corrosive than gasoline. These modifications also include the addition of a sensor to detect the level of ethanol in the fuel. General Motors has been a strong advocate of these so called flex-fuel vehicles.

A promising direction that is being explored is the production of ethanol from cellulose, the most common organic compound on the planet. Cellulose is the primary component of plant cell walls and is found in large quantities in grass, straw, wood chips, switchgrass and even municipal waste. If an economical method could be developed for producing cellulosic ethanol the U.S. Department of Agriculture and Department of Energy are hopeful that ethanol could replace up to 30 percent of the oil use in this country.

The advantages of ethanol are as follows:

- Burns cleaner than gasoline
- Completely renewable
- Potential for reducing foreign imports
- Creates an expanded market for corn
- Potential for reducing farm subsidies

Disadvantages of ethanol are the following:

- Current availability limited primarily to corn producing states in the Midwest
- E85 often costs more than gasoline and contains less energy so produces fewer miles per gallon than straight gasoline.
- Ethanol cannot be distributed through the conventional pipelines because it is drawn into the water that often exists in pipelines and tanks. Distribution must be made in trucks.
- Some claim that it takes more conventional energy to produce the ethanol than it yields. Others claim studies show the opposite.

Biodiesel. Biodiesel is a cleaner burning diesel replacement fuel made from natural renewable sources such as new and used vegetable oils and animal fats. Just like petroleum diesel, biodiesel operates in compression-ignition engines. Blends of up to 20 percent (B20) can be used in nearly all diesel equipment, are compatible with most storage and distribution systems and do not generally require any engine modifications. The use of biodiesel in a conventional diesel engine substantially reduces emissions of unburned hydrocarbons, carbon monoxide, sulfates and particulate matter. This reduction increases with the amount of biodiesel added to diesel fuel.

Advantages of biodiesel are as follows:

- It is completely renewable
- Less emissions than petroleum
- Has the potential to reduce dependence on foreign oil
- A better lubricant than regular diesel fuel
- Contributes to longer engine life
- Absence of sulphur contributes to longer life of catalytic converters
- Yields three times the energy needed to produce it
- Provides fuel mileage comparable to straight diesel fuel

Disadvantages of biodiesel are the following:

- Can damage rubber hoses in older vehicles
- Can gel at temperatures near freezing
- Not currently available across the U.S.

Natural Gas. Dedicated natural gas vehicles (NGVs) are designed to operate using only natural gas. Vehicles can store compressed natural gas (CNG) at 3,000 or 3,600 psi or as liquified natural gas (LNG) at pressures ranging over 20 to 150 psi. There are also bi-fuel NGVs that have two separate fueling systems that enable the vehicle to use either natural gas or a more conventional fuel such as gasoline or diesel. In general, dedicated NGVs demonstrate better performance and have lower emissions than bi-fuel vehicles since the vehicle is optimized to run on natural gas and also does not have the additional weight requirement of carrying two types of fuel. CNG fueling stations are located in most major cities and in many rural areas. LNG is available through suppliers of cryogenic liquids. Honda produces the Civic, GX and NGV, but most other passenger car manufacturers have moved away from NGVs citing low consumer demand.

Advantages of natural gas are:

- NGVs can produce significantly lower amounts of harmful emissions.
- The cost of CNG can be comparable to gasoline, but varies depending on the market prices.

- Natural gas is primarily produced in the U.S. with almost all imports coming from Canada.
- There are reports that NGVs have service lives 2 to 3 years longer than conventional gasoline or diesel vehicles.

Disadvantages of natural gas are:

- Vehicle range for CNG and LNG vehicles is somewhat less than for gasoline or diesel counterparts since the energy content of natural gas is lower.
- Home refilling stations, such as Phill available from Honda, are relatively expensive.

For additional information on NGVs, see the following website: http://www.afdc.energy.gov/afdc/fuels/natural_gas.html

Natural Gas and Hydrogen Blend. Fuels that are a blend of natural gas and hydrogen (HCNG) are seen as a first step in the transition toward building an early demand for the infrastructure required for hydrogen-based fuel cell vehicles of the future. Experimental work is being done by DOE to test various blends from pure hydrogen to pure CNG for light and heavy-duty vehicles. For additional information, see the following website http://avt.inel.gov/hydrogen.html.

Hydrogen. A liquefied form of hydrogen can be used as a fuel for an internal combustion engine in the same way that gasoline or diesel fuel is currently used. This approach is being seriously explored by BMW. The infrastructure envisioned involves the production of hydrogen using solar power. The hydrogen produced is then liquefied and stored at very low temperature. In collaboration with Shell Oil Company, BMW has developed robotic technology for automatically dispensing hydrogen at filling stations, the first of which opened at the Munich Airport in 1999.

The Hydrogen 7 executive car, available in the Fall of 2006, is designed to operate with either hydrogen or standard gasoline (has both onboard) and has a range of 125 miles on hydrogen and 300 miles on gasoline for a total vehicle range of 425 miles.

For additional information, see the following website: http://www.bmw.com/com/en/insights/technology/efficient_dynamics/phase_2/clean_energy/overview.html.

6. Plug-In Hybrid Strategies

Plug-in hybrids are hybrids that are designed to accept external charging of its batteries from a home wall socket in addition to the internal vehicle recharging systems. The idea is to charge the batteries at home each night, and on the resulting full charge be able to commute round trip to work using batteries only.

The available energy capacity of the battery pack in today's hybrid is not sufficient for this requirement. So why not just add more batteries? Increasing the number of battery cells not only increases vehicle weight, but the additional volume produces design challenges as well. One might also be tempted to extend the battery-only range of vehicles by deep charge and discharge cycling, but unfortunately this will often reduce the useful life of the battery. Designers must take care not to push the batteries too hard or the goal of making batteries last as long as the car may not be attained. By the way, in EPA research studies, the useful life of a car is assumed to be 14 years.

The 2006 Prius that I own has a warranty on the Nickel Metal Hydride batteries of 100,000 miles or 8 years. EPA believes that by 2010 battery technology will be greatly improved and will indeed endure for the 14 year useful life of cars. GM is betting on it too with their new Volt plug-in hybrid concept car that can travel for an EPA-estimated 35 miles on batteries alone and can be recharged on a standard 110-volt household outlet. The market target is the 78 per cent of commuters in the U.S. whose daily round trip is 40 miles or less, according to the Department of Transportation. GMs ambitions are to develop a family of similar plug-in hybrid systems called E-Flex.

Some are promoting the plug-in hybrid concept as the ultimate short-term strategy on the way to the emission-free vehicle of the future. The goal of 100 miles per gallon has been mentioned as a magic number in the automotive community by using lithium ion battery technology. Lithium is an abundant metal but some are concerned about the early demand level outstripping capacity, especially given the increasing demand in the portable electronics sector.

One might ask about the capacity of the grid to handle massive new demand envisioned by the future plug-in community. A recent study in 2006 by the North American Electric Reliability Corporation projects that grid demand will increase by about 19% over the next decade with an increase of only 6% in capacity for the same period. Plug-in advocates' answer is that most people are going to do their charging at night and that is the time that the grid is under utilized.

A very futuristic solution to the recharging problem is to take a lesson from electric commuter trains that take their power from the road bed. Recharge lanes could be added to streets and highways to implement this vision. [5]

One could also claim that the shiny picture of plug-ins is tarnished by the fact that the overnight on-grid power used to charge the batteries is often generated by polluting power generating plants. This has led to interest in and promotion of off-grid generating strategies to replace this overnight charging energy. Of course these strategies can scale up to much more than replacing the overnight charging requirements and can potentially reduce one's monthly electric bill as discussed below. Candidates most often mentioned are solar, wind and micro-hydro.

Off-Grid Home Power Alternatives for Plug-In Battery Charging

A good reference for practical information and details involved in home installations of these three technologies is The Homeowner's Guide to Renewable Energy [10]. Another resource that may be helpful is http://www.homepower.com .

Solar Energy Generation

In a word, solar energy today is expensive relative to other electrical generating technologies. Having said that, one should also hasten to say that it also depends on what part of the U.S. one lives in. There are circumstances where solar could actually be less expensive than conventional electricity in rural areas where one has to pay for power line extensions.

Off-grid solar electric systems can be grid-connected or grid-connected with battery backup. The grid-connected system is the simplest of the two consisting of solar module (multiple units increase capacity), an inverter (solar units produce DC) and a service panel for connecting to the grid. Excess electricity can be automatically diverted to the electrical grid and produce reductions in the monthly electric bill. Grid-connected with battery backup includes a bank of batteries for backup power and when the batteries are fully charged excess electricity flows into the grid. A web resource that has useful content on solar installation as well as tax incentive information is http://www.findsolar.com.

Wind Energy Generation

A residential wind turbine can be a relatively large device and is not appropriate if the location is in an urban area. Local zoning regulations and covenants should be consulted as part of any planning for this type equipment. Most small turbines are relative maintenance free, operate automatically and have very few moving parts. As in solar, excess generating capacity can be diverted to the grid. For more detailed information on home wind energy systems see the following website. http://www.energysavers.gov/your_home/electricity/index.cfm/mytopic=10880.

Microhydro Energy Generation

If your residence is near a stream you might want to consider microhydro. In general, for a water turbine you need at least 3 feet of fall and at least 20 gallons per minute of flow. Water turbines are sometimes used as a complement to solar installations since they produce power 24/7. For more details on home installation of microhydro, see website http://www.microhydropower.com.

Smart Power Grids

The increase in the number of plug-in hybrids and the future emergence of electric vehicles will place demands on the power grid that will require a re-invention of the electrical power grid as we know it. The key word for this new vision is “smart grid” and it will define a new model which incorporates the above small local producers of electrical power as well as the traditional large ones, creating a new community some are calling “prosumers” meaning those who both produce and consume power. “Unlike existing grids where electricity generally flows one-way from generators to consumers, the smart grid will result in flows of electricity that vary in magnitude and direction continuously” [13]. An overview of the smart grid vision is given at the following website:
http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf.

7. Software Tools for Hybrid Vehicle Design, Evaluation and Impact

Software is available in both the public and commercial domains for the simulation of design and evaluation processes of hybrid vehicle development and the impact of the implementation of these new technologies. Some examples of this software are provided in the sections that follow.

ADVISOR

Advanced Vehicle SimulatOR (ADVISOR) is one of the most widely used tools for hybrid electric vehicle development support. It was developed by the National Renewable Energy Laboratory (NREL) and can predict vehicle performance, energy consumption, emissions output, control strategy function and average component efficiencies over urban and highway driving cycles. It is designed for performing sensitivity and parametric studies for conventional, electric and hybrid vehicles. It has been used by many organizations including engineering schools and major automotive companies such as General Motors and Chrysler. For additional information see website http://www.nrel.gov/vehiclesandfuels/vsa/related_links.html#advisor.

PSAT

Powertrain System Analysis Toolkit (PSAT) is a simulation package that can be licensed from Argonne National Laboratory. It was developed with the objective of supporting the entire automotive engineering process from design modeling to control. DOE selected PSAT as the primary simulation tool to support the FreedomCAR and Fuels Partnership activities. It is also used in engineering development in major automotive companies and in university research. It is also worth noting that the accuracy of its dynamics components models allow PSAT models to be implemented directly in a vehicle. For additional information see the following website:
http://www.transportation.anl.gov/pdfs/TA/420.pdf

MathWorks Tools

MathWorks tools such as MATLAB are familiar to many engineers. The MathWorks model-based design software tools are widely used in the automotive industry. Simulink, SimDriveline and Stateflow simulation packages can be used to model the electrical, mechanical and control systems of hybrid vehicles. Engineering schools have found these packages particularly useful in vehicle design projects. For example, insights into how planetary gear sets interact with more than one power source and the remainder of the drive train have been particularly valuable. For additional information, see website http://www.mathworks.com/products/simulink/.

GREET

Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) is a public domain fuel cycle model that provides an evaluation of engine and fuel combinations. For a given vehicle and fuel system, it calculates total energy consumption, emissions of CO_2-equivalent greenhouse gases and six criteria pollutants. The system includes all major vehicle technologies in the market and R&D area including grid-independent and grid-connected hybrid vehicles. GREET is implemented in Microsoft **Excel** and its user community includes government agencies, universities, automobile industry, energy industry and public interest groups. For additional information, see website http://greet.es.anl.gov/

Very High Speed Hardware Description Language

The IEEE standard modeling language VDHL-AMS has gained broad acceptance as a language that can be used to model complex systems that contain components that are electrical, mechanical, fluidic, thermal as well as other physical systems. In particular, SystemVision™, an implementation of VDHL-AMS by Mentor Graphics, has been used to model the power electronics control systems of HEVs.

Additional Tools

For information on a broad range of simulation tools for vehicle design and evaluation at various levels, see website http://www.nrel.gov/vehiclesandfuels/vsa/vehicle_simulation.html.

8. U.S. Government Initiatives

In 1993 the U.S. Department of Energy initiated the Hybrid Electric Vehicle (HEV) Program. It was created as a five-year cost-shared partnership with General Motors, Ford and Daimler-Chrysler to produce production-feasible HEV propulsion systems by 1998, first-generation prototypes by 2000 and market-ready HEVs by 2003. The National Renewable Energy Laboratory (NREL) was the technical manager of the program and continues to assist the automotive industry with HEV development in a variety of ways including battery thermal management and vehicle simulation and analysis.

The HEVs developed in this program were to achieve twice the fuel economy of comparable gasoline vehicles and have comparable performance, safety and costs. As the program progressed, its goals began to merge with the goals of the Partnership for a New Generation of Vehicles (PNGV). In 2003, PNGV was refocused and transformed into the FreedomCAR program which now allows DOE to focus on long-term, high-risk, pre-competitive research and development in fuel cells and hydrogen infrastructures and technologies. For more details about the programmatic goals and activities of the current FreedomCAR and Vehicle Technologies Program, see the following website: http://www1.eere.energy.gov/vehiclesandfuels/index.html.

Course Summary

This course presents an introduction to storage, power and fuel systems that have potential or are currently being used in hybrid electric vehicles. The development of this type vehicle is being driven by the need for independence from foreign oil and a reduction of polluting emissions from the current dominant gasoline internal combustion engine. Computer simulation packages for design and performance evaluation as well as government initiatives for stimulating hybrid car development are also discussed.

Selected References

NOTE: The book below by Ehsani et al is a very good engineering reference on hybrid automotive powertrain design and related topics. It is intended as an engineering textbook on the subject.

1. Plotkin, S., D. Santini, A. Vyas, J. Anderson, M. Wang, J. He, and D. Bharathan, "Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results", ANL/ESD/02-2, October 2001.

2. Ehsani, Mehrdad, Gao, Yimin, Sebastien E. Gay and Ali Emandi, "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design", CRC Press, 2005.

3. Boschert, Sherry, "Plug-In Hybrids: The Cars That Will Recharge America", New Society Publishers, 2006.

4. Westbrook, Michael H., "The Electric Car: Development and Future of Battery, Hybrid and Fuel-Cell Cars", 2005. IEE Power and Energy Series Volume 38.

5. Boberg, Evan, "Common Sense Not Required", First Books, 2004

6. Motavalli, Jim,"Forward Drive: The Race to Build "Clean" Cars for the Future", Sierra Club Books, 2000.

7. Rifkin, Jeremy,"The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth", Jeremy P. Tarcher/Putnam, 2002.

8. Anderson, Judy and Curtis D. Anderson, "Electric and Hybrid Cars: A History", McFarland and Company, Inc. Publishers, 2005.

9. Yost, Nick, "The Essential Hybrid Car Handbook: A Buyer's Guide", The Lyons Press, 2006.

10. Chiras, Dan, "The Homeowner's Guide to Renewable Energy", New Society Publishers, 2006.

11. Foster, Kit, "The Stanley Steamer: America's Legendary Steam Car", The Stanley Museum, 2004. (**NOTE:** A beautiful 548 page commemorative edition book about the amazing story of the Stanley Steamer. There are two Stanley museums, one in Kingfield, Maine and another in Estes Park, Colorado.)

12. Satyapal, Sunita, John Petrovic and George Thomas, "Gassing Up with Hydrogen", Scientific American, (April) 296, 4, 80 – 87, 2007.

13. Ramchurn, Sarvapali et al, "Putting the "Smarts" into the Smart Grid: A Grand Challenge for Artificial Intelligence", *Communications of the ACM*, (April), Volume 55, No. 4, 86-97, 2012.

Selected Web Resources

General information and news about hybrid cars
http://www.hybridcars.com

Information on hybrids sponsored by the Union of Concerned Scientists
http://www.hybridcenter.org/

Society for Automotive Engineers
http://automobile.sae.org/

Green Car Journal
http://www.greencar.com/

National Renewable Energy Laboratory
http://www.nrel.gov/

MathWorks Simulink for model-based system design
http://www.mathworks.com/products/simulink/

Renewable Fuels Association
http://www.ethanolrfa.org/

The World Wind Energy Association
http://www.wwindea.org/home/index.php

American Solar Energy Society
http://www.ases.org/

Home Power Magazine
http://www.powerhome.com

The Steam Automobile Club of America
http://www.steamautomobile.com

The California Cars Initiative on plug-in hybrids
http://www.calcars.org/

Alternative Fuels Data Center – U.S. Department of Energy
http://www.eere.energy.gov/afdc

Fuel economy data, federal tax incentives and hybrid car and alternative fuel information – U.S. Department of Energy
http://www.fueleconomy.gov

Hybrid car information and information exchange opportunity
http://www.greenhybrid.com

Information by and for hybrid owners
http://www.mixedpower.com

National Institute for Advanced Transportation Technology
http://www.webs1.uidaho.edu/niatt