Green Car Congress
Energy, technologies, issues and policies for sustainable mobility

Using the PHEV (Plug-In Hybrid Electric Vehicle) to Transition Society Seamlessly and Profitably From Fossil Fuel to 100% Renewable Energy

17 July 2015

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Abstract. The alternative-fuel car evolved to reduce exhaust emissions and other problems derived from burning fossil fuels. The PHEV (Plug-in Hybrid Electric Vehicle), a subset of the electric car, combines a primary electric motor with a much smaller back-up engine fueled with a hydrocarbon/biofuel mix. (In this paper PHEV refers solely to the long-range PHEV of 60 miles (100 km) electric-only range.) The PHEV does not require the heavy, costly batteries required by other electric cars, nor does it suffer from a limited range or poor freeway performance.

Though the PHEV combines the two types of energy and power, it is not merely a temporary “transition” between gasoline and diesel cars to pure electric cars. It is much more than that. It offers the solution to several significant transitions we need: moving society from burning fossil fuels to substituting renewable resource fuels such as solar, wind and biofuels; and from using fossil materials as fuel to using them for other recyclable uses.

At present, PHEV technology alone is equipped to improve the current electric grid. The car can refuel during periods of low demand on the grid, and if equipped with a bi-directional charger, can actually replenish the grid with excess energy gleaned from a renewable resource. It solves the storage problems faced by the electric utility companies in absorbing and adapting to

the highly variable power and energy generated by solar and wind. Since it can refuel from a standard household outlet and from a gasoline station, it needs no new infrastructure.

If PHEVs became the major form of transportation, the use of fossil fuels would be cut dramatically. The average PHEV uses $1/10^{th}$ the amount of liquid fuel needed by a conventional car a year. Since it can operate on 100% biofuel, it is the means for achieving new goals recently set for reducing the use of fossil fuels and cutting the net emission of CO_2 to zero. In fact, the PHEV is the only existing technology that acts as a vector for transitioning our society to exclusive use of renewable resources.

We have written a short paper of about 22 pages suitable for a general audience, pulling out more technical information into a series of appendices. Since some readers might read only one appendix, some information has been repeated.

About the authors

Prof. Andrew Frank is a significant industry dignitary credited as being the "Inventor" (or "Father") of the modern day Plug-in Hybrid Electric Vehicle. Prof. Frank has spent more than 30 years in breakthrough vehicle development, during which he received two world records for vehicle fuel economy, designed nine generations of PHEVs, and was a four-time winner of US DOE Advanced Vehicle Design competitions.

He holds more than 35 patents (12 of which belong to UC Davis), has published more than 100 papers, and is an internationally recognized subject matter expert.

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She edited the *New England Sierran*, which in a few years grew from ~3000 subscribers to more than 30,000, and moderated a weekly radio show ("Earth Crisis") hosted by MIT and Boston University. As one of the planners for the first Earth Day in Cambridge Mass., she transcribed and edited Ralph Nader's speech. She taught English literature, grammar and composition for more than 30 years.

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Introduction : Addressing the Earth Crisis

Human culture, with its voracious desire for heat and energy—combined with a population expanding exponentially—poses a catastrophe without historical parallel. The combination of harvesting whole forests and burning long-sequestered carbon sources such as coal or oil has impaired the Earth's carbon cycle at an increasing pace. Excess CO_2 in the atmosphere creates what has been called "the greenhouse effect," raising the temperature of Earth's air, lands and oceans. Increasing temperatures pose a direct threat to human survival, fueling the force of hurricanes and tornadoes, and facilitating the proliferation, size and intensity of fires. Fires result in more CO_2 as well as destroying the plant mass necessary to restore the balance that enabled the biosphere to flourish in the past. It is a terrifyingly destructive cycle that we humans have instituted, but it is so entrenched in our habits, economy, and convictions that it sometimes seems impossible to reverse.

To restore balance we must protect the oxygen-producing biomass of Earth and reduce the amount of carbon emissions. Since the burning of fossil fuels produces harmful hydrocarbons, particulates, and other cancer-causing chemicals as well as CO_2, it is especially important to end our over-reliance upon coal and oil energy, methodically replacing them as soon as possible with renewable energy sources such as solar-, wind-, hydro-, electric- and bio-fuels.

Electrically-powered vehicles called plug-in electric vehicles, (PEVs), can shift us from exclusive use of gasoline and diesel to offer a pathway to a future of burning no fossil materials. Electricity can be generated from non-CO_2-creating energy sources like those listed above. Since the energy density of liquid fuels is unchallenged by any other form of energy carrier we have today, we will have to continue to use liquid fuel to support our society as we know it. This is especially true in air, sea, and some ground transportation as well as in industrial processes. So the PHEV can simply use a small amount of this needed liquid fuel in the future.

Engineering Advantages of the PHEV

The plug-in hybrid electric vehicle (PHEV), a subset of the PEV, uses electricity plus a different energy source (at present gasoline or diesel) to run its second engine. This engineering solution allows versatility. Unlike the vehicles fueled entirely by battery which must carry the weight of enough batteries to attain a desired range, the PHEV simply switches automatically to an efficient, non-electric engine using an energy-dense fuel when greater range is occasionally needed. Gasoline/diesel fueling stations to replenish the liquid fuel for these engines are readily available.

In contrast, except for the PHEV, the alternative fuel vehicles—such as hydrogen, natural gas and battery electric vehicles—pose problems and limitations due to their single energy source and the lack of infrastructure for high-power energy distribution of their individualized fueling needs. (See Appendices (A - C))

The word “hybrid” is misleading. It may suggest a crossbreed of limited utility—like the mule—which offered a gain (great strength) in exchange for new limitations (sterility). The PHEV, in contrast, is a whole new paradigm—without limitations. It offers a range of elegant solutions to a number of problems. Some of these, like the need for more efficient use of the current electric grid have not been addressed by other technologies. We will soon discuss this need in detail. The use of the electric grid for energy transfer is not well understood, much less addressed by designers of other electric and alternative fuel vehicles. The potential is enormous because the current grid has sufficient energy capacity to supply every vehicle in the United States if every one of them was a PHEV. To ignore this potential is wasteful and foolish. As will be discussed later, only the PHEV is equipped to make use of this excess electric grid capacity. (For an extended discussion see Appendix C).

The PHEV does not suffer from the “range anxiety” that limits other electrically-powered vehicles. The pure electric vehicles, for reserve, must carry heavy and expensive batteries—which add expense as well as weight—and must have access to high-powered recharging stations[1]. Every electric energy consumer, not just the relatively few electric-only vehicle owners, will be asked to pay for the expensive hardware for these high-power charging stations. Nor are these stations likely to use renewable energy directly from solar and wind.

On the other hand, the PHEV can use the existing electric distribution and gasoline dispensing systems with minor or no change. These energy transfer systems are already everywhere in the country. Furthermore, even the older version PHEV can recharge at a slow rate using local solar, wind, water-derived or other net zero CO_2 fuel. With this charge it can travel an average daily distance of about 30 miles (50 km), which is often enough to serve most consumers’ needs.

When the PHEV electric range is exhausted during a long trip, the vehicle simply automatically switches to its liquid fuel engine which can use a bio-fuel blend (or all biofuel in the future) to attain ranges well over 400 miles (650 km). This synergy of the electric and liquid fuel allows for a much lighter and smaller combustion engine (perhaps one fourth the conventional size) than what must be used in a vehicle exclusively powered by gasoline or diesel.

Though the engine is smaller, the PHEV’s performance can be much better due to the electric power and energy on board for short-term bursts of power. All of this means a PHEV uses much less liquid fuel (as little as 10% of a conventional vehicle’s averaged annual fuel consumption), saving money and extending the miles per gallon of gasoline or alternative liquid fuel. These examples of versatility explain why we call the PHEV a new paradigm.

It is alarming to see comparisons of the Chevrolet Volt PHEV with battery electric cars when the comparison focuses only on the electric range and ignores the other important differences. The California Air Resources Board, CARB, is now considering incentivizing “e-miles” covered by a vehicle. (“E-miles” is a term denoting the distance covered by a particular vehicle over a one year time frame using only electricity.)

The impetus for this change came from a study by the US Idaho National Lab[2]. Its published results showed the average Chevrolet Volt PHEV drove 9100 miles a year on electricity compared with the average Nissan Leaf all-electric car driving 9500 miles a year on electricity alone. On the face of it, this experiment would suggest that the all-electric car, which does have a greater electric range, contributed 400 more e-miles than the Volt. But the real story is yet to be told.

Both owners drove an average of 12,000 total miles in the year. A thinking person should ask, “How did the Leaf owner travel the unaccounted miles, the ones that were not e-miles?” The answer is he or she would have to have access to a second, gasoline–powered vehicle to use for trips that exceeded the 80-mile range of the Leaf. This undisclosed factor completely changes the way the experiment should be evaluated.

The 2900 miles traveled by the Volt, drawing upon its combustion engine, produced far less CO_2 since the Volt uses a small and more efficient engine. In contrast, the Nissan Leaf owner would switch to a conventional gasoline car with a much larger, less efficient engine to satisfy longer distance travel needs. Thus evaluation of vehicles by e-miles alone omits important consideration of annual emissions. More information on e-mile comparisons is given by Reference Nº 2.

Another strikingly different concept evidenced by the PHEV is that it is essentially a large, portable battery that can store energy gathered during one part of the day, and then use it later to power not only itself but also the vehicle owner’s home. Its potential as an electric energy storage facility means the PHEV can be used to even-out the vast energy inefficiency of the current grid, as well as to store intermittent solar and wind energy, a process which we will soon explain.

Perhaps most important, the PHEV allows a seamless transition from the current use of fossil fuels to renewable electric and biofuel energy sources. It can do this with little disruption to the way homes and industry purchase and use energy today. Essentially, no new energy distribution infrastructure will be needed as we transition to all-renewable energy. This adjustment can be accomplished gradually and seamlessly, by replacing old worn-out vehicles with PHEV's. The transition can be sped up with proper incentives from government or other sources.

We must act quickly as the planet is warming due to CO_2 production from burning fossil fuels. In order to accomplish this transition in a timely way, we must start the mass manufacturing of PHEV vehicles and renewable energy generation and distribution systems now.

How the PHEV Provides Smooth Transitions: From Fossil Fuel to Renewables

Though popular as energy solutions, wind and solar power are not constant energy sources. The hourly and daily generation of power from wind and solar renewable energy varies dramatically and changes from one location to another and from day to day. These variations must be managed by adding a great deal of electric energy storage in order to work on a mass scale.

Of course, wind and solar sources could be supplemented by fossil materials as fuel to fill in the energy gaps, but that runs counter to our objective of reducing the use of fossil fuel. For example, resorting to a fossil-fueled electric generator whenever the wind stops blowing is not a good solution. In addition, huge energy storage farms using lithium and other chemical-based batteries are being proposed to store the excess wind and solar energy in order to supply electric demand continuously without interruption. We are suggesting that the variation in power and energy from renewable sources can be managed much more easily and economically with the batteries in PHEVs when they are plugged into the grid with a low power connection.

Only the PHEV can share energy with the grid without stranding the driver. Battery-only vehicle owners are disinclined to share because the BEV has only one energy source and owners tend to hoard the energy from its expensive and slowly-charged batteries. In contrast, the PHEV with a bidirectional charger can feed some of its surplus energy back into the grid using that energy to power other needs than transportation. In order to accomplish this, the total energy system needs to be properly controlled and monitored. (Appendix C will discuss in more detail how such monitoring and control may be accomplished). The figure below shows how these goals may be achieved and integrated.

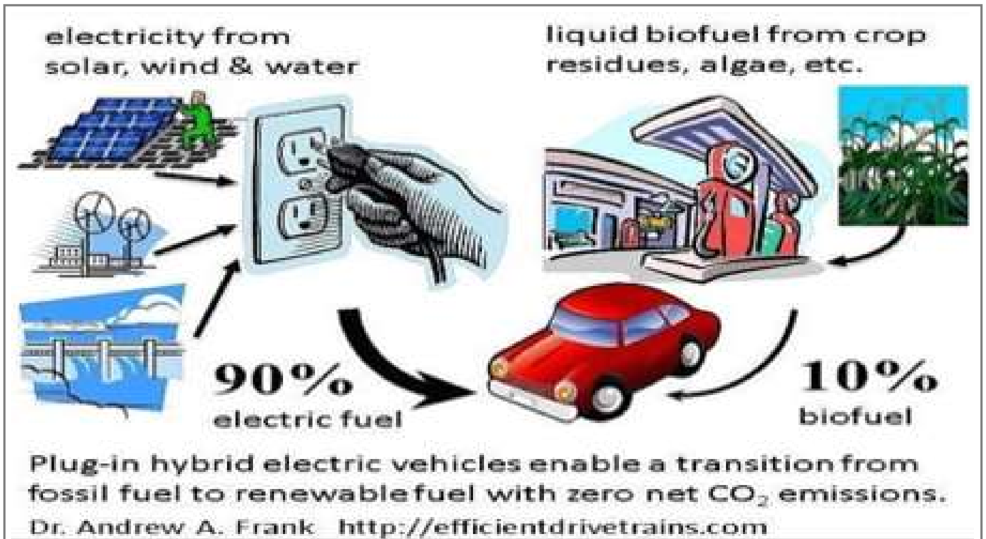

Figure 1. Averaged over the year, 90% Renewable Electricity and 10% Biofuels will provide zero net CO_2 emissions[3]. Click to enlarge.

As shown in Figure 1, for electricity, the PHEV can plug into a standard existing electrical outlet, and for supplementary power it can fill its tank from a standard, ubiquitous and familiar fuel station. Thus no new energy distribution infrastructure is needed. As biofuel becomes a greater percentage of the total fuel mix, less fossil fuel is used.

Furthermore, the PHEV uses only 10% of the liquid fuel that a conventional gasoline car uses and most liquid fuel sold today is already 10% biofuel. Thus, using the PHEV, the source of energy for transportation can be changed seamlessly from fossil fuels to renewable electric and biofuels. The transition process begins by gradually increasing the percentage of renewable electricity and biofuel. These can be supplied by our current energy distribution and dispensing network without changing the infrastructure. The objective is to create the technology which would allow us to use, on the average over a year, 90% renewable electricity and 10% all-biofuel to power and supply energy for transportation.

To clarify: Assume that 100 conventional cars over a period of time use 1000 gallons of fuel, which today consists of 100 gallons of biofuel intermixed gasoline. Fifteen years from now if conventional cars are replaced by 100 PHEVs, then the total liquid fuel used will only be 100 gallons. Since PHEVs can use 100% biofuel, then the liquid fuel can be 100 gallons of biofuel without any gasoline. This means 900 fewer gallons of gasoline used! This change in vehicles and fuel would provide our sought-for zero net CO_2 fueling or energy system. In addition, we need no more biofuel than what is currently in production now. All we really need in addition to fleets of new paradigm vehicles are additional solar and wind generation sources. We already have sufficient biofuel sources since the PHEV uses only 10% liquid fuel.

In designing improved PHEVs, the engines should be flex-fuel capable meaning they should be capable of using any blend of fossil to bio fuel mix.

In addition, with the new all electric range (AER) for the PHEV of 60mi (100km), enough electric energy could be stored to power the driver's home and supply the energy to drive 30mi (50km) a day with energy left over. And even greater ranges can be expected soon. Furthermore, the batteries in a PHEV are generally smaller than those in any other electric vehicle constructed today and the battery savings in the PHEV from a pure BEV can easily make up for the cost of the small liquid-fueled engine, resulting in a lower-cost production vehicle for mass distribution.

The question now is: Will we have to dismantle or rebuild the current electric grid to accommodate the alternative fuels? The answer is that no such radical change will be necessary with the PHEV since it allows use of low demand time on the grid to recharge cars at a low power.

To clarify, in order to use solar power at night, the energy gathered during the day must be stored. PHEVs' batteries can be used as the storage medium. After charging during the day, energy not yet used for transportation may be transferred back to the grid for night usage or redistribution. The vehicle can also be used to transfer the energy to another location—for example, from a solar charging station at work to the vehicle owner's home or from a home solar set-up to a vacation dwelling or to a jobsite in a commercial setting. Though this sounds like speculative fiction, these applications are already in use.

One PHEV company, Efficient Drivetrains Inc., has constructed prototype PHEV trucks for electric utility companies which can deliver energy to power an entire neighborhood during maintenance or repair when there is a power outage[4]. (Also see Appendix E and Reference 1.)

We need a plan to transition from gasoline and Diesel to biofuels. For a more detailed discussion of biofuels see Appendix G.

A Smooth Transition From Burning to Recycling Fossil Materials

Fossil material is not evil in itself; it is vital for the production of medicine, space age plastics, and other advanced materials. It is wasteful and destructive to be burning this versatile molecule; we must stop. But use of petroleum will continue.

Even more new uses will be discovered in the future. Some examples are the use of fiberglass, carbon fiber and Kevlar substituting for wood and metal in vehicle parts, appliances and furniture products. This industry can be greatly expanded and improved to absorb all fossil material. Thus, as new renewable energy sources such as solar and wind are integrated, the fossil-material-as-fuel industry can be replaced by a fossil-material-product industry, thus preserving the oil and coal industries and creating new business opportunities. Then as solar, wind, water and other non-fossil fuel industries ramp up, the fossil material industry can shift to different but more lucrative customers.

These new applications can be both more profitable and more ecologically responsible since the materials can be recycled and retain their value. The recycling process for these materials has to be considered in the design process, using primarily heat from solar, wind and other renewable energy for product recycling. No revolutionary change in the economic infrastructure will be necessary. Our society will continue to need more of these products in the future.

In addition, many roads are currently built with asphalt, a fossil-derived material; future asphalt can be improved to be even more durable than reinforced concrete. As another example, some 2x4s used in construction are already made from fossil materials. The chemical processes necessary to do this already exist. The designs can be greatly improved to be more cost-effective. The lumber companies would need to be absorbed into this business plan as well since they have the distribution and manufacturing facilities for the construction industry. Ultimately all wood products could be replaced by recyclable plastics that could be in use for thousands of years. Thus we can also begin to repurpose the world's depleted forests to their original functions such as maintaining the natural carbon/oxygen cycle and preserving Earth's habitat for humankind.

The basic technology for all these new uses of fossil material already exists; the application simply needs to increase many-fold. No longer burning fossil materials for energy or power means liberating no more of the stored and environmentally harmful CO_2.

Adjusting the usage of fossil materials also eases economic transition. As discussed above, the fossil extraction industry can change its business plan.

How the PHEV enhances the Electric Infrastructure

Today's electric grid was designed by Nicolas Tesla and Thomas Edison with help from Westinghouse and General Electric some 100 years ago. It has served us well up to now—unchanged. Globally, billions of people are using this ancient grid as installed, but the enormous potential of the grid is untapped—we could be getting much more energy from it. Today, the utilization factor (UF) of the grid, its energy-carrying capacity, is very low. In contrast, the power capacity is high. Everywhere in the world the UF is less than 10% since all grid-carrying capacity is sized to handle peak power demand which may rarely, if ever, occur. Therefore, a great deal of the electric grid's energy capacity lies dormant.

In order to supply millions of electrically-powered cars, conventional wisdom would expect that the peak grid power capacity must increase. We imagine you objecting: "Oh no, we'll have to build lots more power plants!" This misconception arises from a misunderstanding of the way electric utilities operate.

The only time a power plant does not have enough power is when there is a surge in power demand. Such surges are not common. Most of the time, consumers of electricity use far less energy than the utility could supply in a pinch. The electrical system has perhaps 85% excess capacity most of the year which means we are wasting money in excess electric generation and distribution infrastructure and resources.

Appropriately using the slow-charging option available to all PHEVs, we can greatly increase the UF of the grid. In essence, the PHEV can plug into the unused energy transfer potential of the grid. The grid then becomes more efficient, thus reducing the cost of delivered electricity to everyone. (In contrast, the fast-charging required by battery-only electric cars will decrease the UF and increase the cost of electric energy to everyone.)

Water delivery provides a useful analogy for electricity and the way it works. For example, we build our hydraulic systems with pipes of ½-inch to ¾-inch diameter designed to deliver water faster than we normally need so that we can, for example, fill a swimming pool quickly. More often, however, we are filling a bucket or a glass of water. In contrast, the electric grid uses the equivalent of a 1/8 inch pipe, so that it is not suitable to provide quickly the energy needed for daily driving by a standard vehicle powered by batteries alone. It can, however, provide the amount of energy needed for a day's driving for a PHEV or for some BEVs.

We can take advantage of this simple fact of the grid's excess capacity for energy and improve the utilization factor of the grid by "intelligently slow charging" the batteries at times when the grid is greatly underutilized: such as at night. In actual fact, the owner of an electrically-powered car can charge the car during the underutilized hours of the grid at any time during the day or night. To do this, the owner must rely upon the utility-grid operator to turn the car charger on or off according to the grid's needs at any point in time. The vehicle's battery actually prefers the intermittent low-powered charge for longer life and capacity due to less heating and the inherent electrochemical processes. In this way, the current grid can be used "as is" to provide the necessary energy for PHEVs. (For more about the batteries and the advantages of slow-charging, see Appendix E.)

In addition to improving the grid for its own purposes, the PHEV can also be used to store and transport energy to serve the larger social matrix. To allow the PHEV to power a house, a bidirectional charger is required. A low power intelligently-controlled bidirectional charger, 1-2 kW, can be economically integrated into every passenger-sized PHEV sold and connected to the grid through an ordinary 2 kW extension cord if it has a standard ground fault interrupter (GFI) outlet. The local electric grid can then use the electric energy to and from these vehicles to increase the UF of the grid's wires. This energy flow can be managed by the local utility companies through wireless communications networks already installed everywhere.

The significance of this advantage cannot be over-emphasized given the current inefficiencies of the system[6]. For example, the current electric system for a typical house has an installed capacity of 20kW. (This is the maximum amount of power available to power everything in the house simultaneously. In terms of our earlier analogy, this maximum capacity is like a firehose—it is an amount of power unlikely ever to be needed.)

In fact, the average daily use is on the order of only 2kW to 3kW. This means the grid wires are utilized at only 10% to 15% of their installed energy transfer capacity. Or their UF=10% to 15%. This grid inefficiency at the level of domestic use is typical all over the world.

If in addition to normal electric use in homes such as lights and appliances, we charge the PHEV cars at 2 kW at the appropriate times, we could increase the utility factor of the already-installed wires in homes to more than 25%, still leaving plenty of safety margin and capacity. More detailed energy management can increase the utilization of the installed wires further, as microcomputer control technology improves. This new technology simply avoids charging the batteries if the house load demand is higher than normal or the grid is being stressed highly at a given moment.

During these high demand periods a little longer time is needed to charge the batteries, but the batteries are being charged at times when the vehicle is parked many hours anyway. Typical vehicles are parked for over 20 hours per day. As long as a standard 1.5 kW to 2 kW plug is available at home and at work, both the battery electric vehicles (BEV) and PHEVs can be charging at any time during these 20 idle hours.

In addition, the grid could ask for energy back from the batteries of a PHEV if the house or neighborhood need is at a high level for a short time. The electric utility companies can easily send a signal to the car charger indicating the demand, and the car's computer can negotiate its needs automatically with the utility company. (This negotiation between a non-sentient vehicle and its fuel supplier sounds like it is taken from science fiction. Again, this is why the PHEV represents the start of a new paradigm.)

If one vehicle cannot give or take energy due to the state of its batteries, another nearby vehicle can be queried by the utility company's controller. Because the PHEV has both liquid and electric fuel, it has the best capability to allow bidirectional energy flow. Since its electric range is not an issue, it has energy to spare if there are enough batteries on board. The exchange of information between the vehicle and its energy supplier can be made much better and more convenient by installing a wireless 2-part inductive charger with grid communications installed on the stationary part of the charging station located in the parking spot. This would be like a wireless electric toothbrush where the charger has a part plugged into the wall and the other part is in the toothbrush itself.

A simple rule for energy exchange can be set by the grid operator—for example—never to take more energy from the PHEV batteries than the equivalent electrical energy generated by 1 gallon of liquid fuel from a particular vehicle. (One gallon of fuel equals one-tenth of the tank, or about 30 miles of electric range. For an electric car that is a huge sacrifice, for a PHEV not so much.) In this way, all the needs of home and transportation can be satisfied together, allowing us to integrate the energy systems into one comprehensive and much more efficient system.

The battery-only electric vehicle, on the other hand, may have an issue with the grid using its battery's energy since it already suffers from range anxiety. (Since the Tesla car has a 300-mile capability on one charge—a huge overcapacity since it normally needs around 30 miles a day—one might think the Tesla could be used as a supplemental battery). However, Tesla owners do not pay twice the cost of a PHEV in order to share their energy with the world.

This energy exchange capability applies just as well to industrial PHEV vehicles such as trucks and buses. The significance of this opportunity is immense. For example, studies by the US National Laboratories (Battelle North West and others) have shown that the currently installed domestic electric grid can supply the energy for almost the entire fleet of light duty vehicles—cars and small trucks—in the United States with no change in electric grid or generating capacity—in other words, no new investment in electric infrastructure is needed for many years into the future as we transition from conventional fossil fuels to renewable energy using PHEV concept for all existing vehicle classes.

Distributed Solar and Wind with the PHEV

The PHEV plays a vital part in integrating renewable energy sources because it allows for distributed energy distribution from small generation systems. The advantage of solar and wind energy is that it can be effectively generated in a small and distributed fashion, such as from rooftop solar installations, as well as from centralized large solar and wind farms. In fact, it may be much more cost effective to have a few thousand low-power distributed solar and wind energy generators on homes than to build large high-power but remotely-located generators such as a solar farm spread over a large but remote desert. The energy generated by rooftop systems can be transferred to a PHEV as well as used directly to power the home. Integrating the PHEV as a moveable battery is an important part of the new paradigm.

Moveable batteries (the PHEV) replace the need for expensive and inefficient high-power transmission lines cluttering our visual space and wasting energy. Huge remote installations have been proposed by many electric utilities around the world. However, to supply a million homes spread out over 500 square miles or more from large wind or solar farms requires high voltage transmission lines and distribution stations. On the other hand, solar rooftops do not require transmission lines since the power and energy are used right under the roofs and the connections are simply the existing low-power wires already in the house.

This efficiency is another benefit of distributed energy generation since it results in better electric grid usage. Because there is no need for large scale electric transmission lines for energy distribution, the local UF can be further increased. Also the present electric utility industry can shift its business model to managing many small distributed energy sources as well as the large concentrated sources so that everyone is properly supplied with energy on demand. This also allows the utility industry to expand its value and grow its business adapting to the fast-improving communications technology. (For more on Solar and Wind See Appendix G.)

All the technology for electrification of transportation and generating renewable energy is already available. But to seamlessly transition out of fossil fuels we need to scale up the manufacturing and use of the available technologies. In particular, we need to commit to the PHEV: to its production and use on a wide scale, and to the development of renewable biofuels and electricity.

The engines in the PHEV should be flex-fuel capable meaning they should be capable of using any blend of fossil to bio fuel mix. In the past the auto industry has responded to incentives and guidelines set by government agencies and reengineered their product to meet this requirement. Similar processes can be followed again.

Government agencies and others are already talking about change, but not with a vision of how it can be accomplished in a timely and coordinated fashion. For example, California has promised it will increase the use of solar and wind to 35% of all needed electric energy. The State also plans to be powered by renewable energy for at least 50% of its needs by 2035. However, this progress will require battery electric energy storage that does not presently exist. The good news is that this storage could easily and simply be provided by PHEV cars and trucks as discussed above. What is now needed is for governments and other responsible entities in business and manufacturing to create the road map for this coordination.

A good start: have all government vehicles be PHEVs. (See Appendix G for a speculative picture of how a 15-year transition from fossil fuels to renewable energy in Hawaii can be accomplished.) We can set a goal to have every new vehicle purchased be a PHEV. This does not mean that you will not be able to buy that Cadillac or Corvette you have been admiring. Virtually any car, truck or bus can be made or redesigned as a long-range PHEV. It is only a matter of economics motivated by incentives or taxes. There are trucks and buses being converted commercially today. Already Porsche, Mercedes and other high-end automotive manufacturers are making such PHEVs because of the availability of low-cost electricity from wind and solar and the availability of government incentives which make them competitively priced in the beginning.

In addition to giving every vehicle PHEV capabilities, we need to provide enough solar or wind generation to power vehicles, homes, and industry. The owners of the PHEVs would be well advised to add or support the construction of a solar installation or windmill close to where they park their vehicles. These installations will need to produce about 3kW to 4 kW of peak solar or wind power per car. This effectively means that the owner of a new PHEV can buy a new vehicle and most of its fuel for the next 20 years.

If a driver travels 12,000 miles per year in a conventional car getting 30 miles per gallon, that would use 400 gallons of gasoline yearly. At $3.00 per gallon, that would cost $1200, adding up over 20 years to $24,000. This is much more than the cost of a solar or wind generator for this much energy today. If the cost of gasoline rises, the economic advantage will be even greater. Also using the excess energy to power the home would save even more money. Thus we will be able to drive our cars and power our homes much more economically, leading to a more affluent society.

Responsible communities are already providing free charging stations for electric vehicles. As more charging stations are added by these and other communities, planners should be aware that Level 1 (slow-charging) stations[7] cost about 1/10th of the cost of Level 2 (faster-charging) stations. Level 2 stations currently cost $1000 each including installation, while Level 1 stations may be less than $100 each since they can consist of a simple waterproof GFI outdoor plug rated at 1 to 2 kW. Thus for each Level 2 station proposed there could be instead 10 PHEV Level 1 plugs widely distributed in society.

Conclusions

Long electric range PHEVs (vehicles which travel at full performance about 60 miles (100 km) on electricity only, like the new 2016 Chevrolet Volt) can integrate all three essential electric power system elements: the grid, the loads, and the new intermittent renewable energy sources. They can, first, provide the energy storage necessary to smooth out the energy peaks and valleys that occur in renewable energy generation; second, they can handle variable load demand in a home or industry; and third, they can manage all the variable distance demands of vehicle travel. This greatly increased utility is only possible if certain rules are followed. The PHEV must be consistently connected to the grid when it is parked and its batteries must be charge-managed appropriately by the grid and the vehicle owner. The main ingredient needed is energy management hardware and software (a computer energy management program) and a social commitment to insure that everyone benefits technically and economically. Thus we can end up with job creation for manufacturing, installation, management and support by simply using the PHEV as the base technology for all vehicles.

We have also discussed how all elements of current high volume manufacturing can be preserved, changing only their business model. This change is unlikely to happen unless the proper marketing forces and new industries are created. Regulations which benefit every business entity and especially the people of the country and planet will be required to motivate business to move quickly. This change may be accomplished more easily than it sounds when the profitability of the PHEV and its benefits are fully realized.

We have also shown that the PHEV is the essential new paradigm that will enable the necessary short transition time from fossil to renewable fuels. From the above discussion it is also clear that a number of social elements—government, industry, and technology—have to come together. The better the government-driven coordination and management, the faster the transition can occur. One key element is to try to keep all critical elements of industry innovative, cooperative and profitable.

High-volume manufacturing of long electric range PHEVs is a good start. In fact, (in our humble opinion) all new vehicles should be PHEVs, and each PHEV or fleet of PHEVs needs to be sold with a comparable number of solar or wind generators. In effect, each passenger car needs about a 3kW to 4 kW renewable energy generation system to serve both the transportation and household energy needs of the owners. Then the package-purchaser of a PHEV linked with a solar or wind generator has essentially bought a vehicle and its fuel for the life of the vehicle. The solar or wind fuel can power his house for the next ten or more years as well by cycling through the PHEV's batteries. The convenience and low cost of this concept alone merit attention.

The planet and people of the world are waiting for us to act.

Appendix A: Comparative Use of the Battery Electric Vehicle (BEV) with the Plug-in Hybrid Electric Vehicle (PHEV) in a zero net CO_2 society

Most drivers of BEVs will need two cars: the electric car for economical short range commuting, and a separate conventional liquid-fuel internal combustion vehicle for long distance travel. No matter what the BEV's range, it will not be able to compete with the energy content of liquid fuel in volume or weight. So most people who drive BEVs will need to have available an additional conventional gasoline vehicle for long distance travel. Even Tesla BEV car owners with 300 miles of electric range will use a conventional gasoline car or a PHEV for the very long distance trips they need to take a few times a year.

In contrast, the PHEV can be used for both short and long distance travel with the same or better convenience than our current gasoline and diesel cars. Both BEV and PHEV can operate at zero net CO_2, so the criteria for comparison becomes cost, resource allocation, utilization and finally efficiency. The PHEV provides the advantage in all these criteria. In fact, the optimized PHEV is much more efficient as a long range liquid fuel vehicle, because the engine is downsized. Smaller and lighter, it requires less liquid fuel. Yet it can have better performance than any conventional car because of the efficient long-range battery pack and high-power electric motors which can be used for performance on the highway if the PHEV system is properly designed. In addition, the transmission can be much simpler than in a conventional car with equal performance. (The battery pack is larger than that of a Hybrid Electric Vehicle, HEV, with little or no electric range, but smaller than that of a BEV.)

For these reasons, the PHEV not only provides the technology for fossil-fuel-to renewable-energy transition, but is the final technological solution when solar and wind generation capacity match the created demand. The PHEV allows the use of all-renewable energy when the electricity is from renewable sources and the liquid fuel is a pure biofuel. In addition, the small engine of the PHEV uses the biofuels much more efficiently than do conventional gasoline or diesel vehicles, thus driving the vehicle farther for each gallon used.

It also emits far fewer emissions. The total emissions will be near negligible and there will be zero net CO_2. New emission evaluation criteria are needed to motivate the proper designs for the next biofuel engine advances needed to realize all these benefits. One transition scenario for moving quickly to renewable energy is to sell each new PHEV with a solar array to be put where the user chooses, probably where the car or truck is parked most days. The array would be large enough (3 to 6 kW, for cars and larger for trucks) to provide energy for the driver's daily travel and domestic home needs. This would be similar to selling a car along with its fuel, and also selling a source for the owner's domestic electric needs for the next ten to fifteen years or perhaps the vehicle's lifetime.

This PHEV system is not hampered by variations in wind and solar activity. If sun is unavailable on a particular day due to rain or other weather conditions, then the owner can use a little biofuel from the local gas station or, if the house is still connected to the grid, use some standard grid electricity.

These concepts can all be integrated by broader design concepts. For example, we are talking about integration of home and transportation energy use patterns and energy generation sources under the user's control. The PHEV provides the best means of reaching the goal of reducing liquid fossil fuel use to zero. Already the Chevrolet Volt is moving us in that direction. In fact, the Idaho National Labs reported to the US Department of Energy that the present fleet of Chevrolet Volts in the USA has been shown to use about 80% electricity and 20% gasoline when averaged over the year.

These PHEV Volts have a 35 mile (56 km) AER. If the AER of the Chevy Volt were increased to 60 miles (100 km) as suggested in this paper, it would be able to reach the suggested average annual energy consumption of 90% electricity and 10% liquid biofuel use shown in Figure 1, achieving the goal of zero net CO_2. (The good news is that the 2016 Volt will come out with 50 miles (85 km) AER.) In addition, with bi-directional chargers, we could use the excess energy stored to power the domestic needs for energy as well. Such an improved Volt also can help level grid energy and greatly improve the efficiency or UF and energy transfer of the conventional grid resulting in the utilities selling or managing more energy resulting in higher profits.

Many parts of the world already sell E10 gasoline and B20 Diesel fuel. These fuels are 10% ethanol for E10 and 20% biodiesel for B20. In fact, use of these fuels is required by law in many states of the USA. It is also required in Thailand, Brazil and many other countries around the world. So the biofuel production technology, manufacturing process and distribution system have already been developed. Therefore, it will be possible to sell much higher concentration biofuels for vehicles as the nation's liquid fuel needs are reduced due to PHEV adoption.

The PHEV will use only 10% of the amount of any kind of liquid fuel used by the conventional car. As the biofuel usage of PHEVs increases due to PHEV adoption, the total amount of liquid fuel used everywhere will be proportionally decreased. Thus, if we simply maintain our present production level of biofuels, we can gradually ramp down the fossil fuel percentage as the proportion of PHEVs increases. This reduction will then increase the percentage of biofuel in the liquid fuel mix when the smaller amount liquid fuel is demanded. Thus little or no increase in biofuel production is needed to achieve a zero net CO_2 society. This is illustrated in Figure 2.

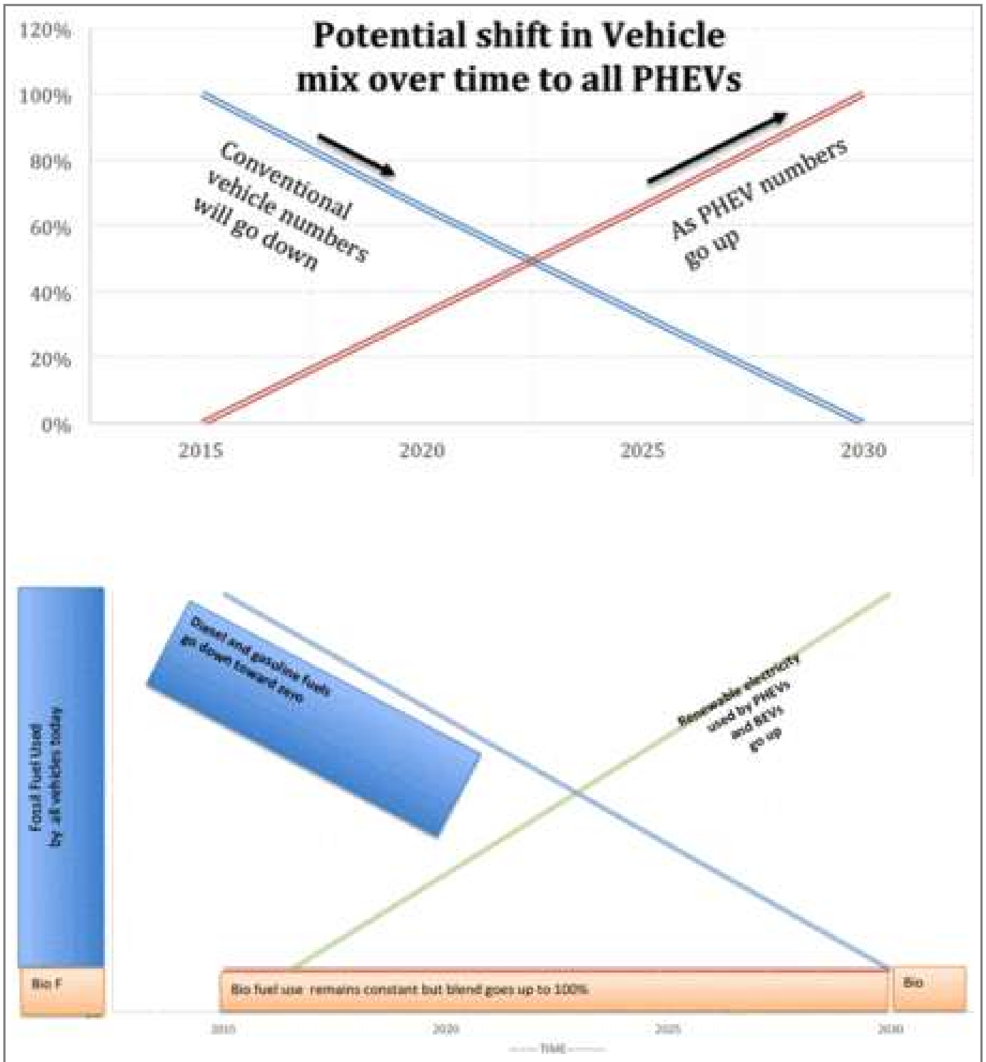

Figure 2. A 15-year transition from fossil fuel to electricity and bio-fuels. Click to enlarge.

The important requirement during the transition is that the total biofuel use remains constant until no fossil fuel is used by the PHEVs after the transition period.

Most paradigm shifts run into the natural human resistance to change. However, if habitual practices remain unchanged, much less resistance is encountered. For example, we can begin the PHEV transition from conventional gasoline and diesel vehicles by requiring our government fleets to replace them in their current fleet with PHEVs. We must also require government-installed local solar and wind generators and the installation of conveniently-located but wireless low-powered charging systems (1 kW to 2 kW).

And with the electrified parking pad, workers don’t even need to plug-in the new PHEV car or truck when they park in their designated space. Their behavior need not be changed as they proceed on their daily duties. Since the propulsion system automatically shifts from electric to liquid fuel, the government employee, like any member of the general public, would not be able to tell the difference between a conventional gasoline vehicle and the new PHEV he or she is driving—except for the new positive benefits such as conveniently-located parking spaces for their cars and reduced need to buy gasoline.

If cities and employers also provide free electricity derived from solar or wind to supply these chargers, the general public will quickly warm to the advantage of PHEVs. The positive results including costs, need to be properly published and distributed, creating and accelerating the demand for all classes of PHEVs from small cars to full-size trucks and buses.

These concepts, working together, can then provide a seamless transition from fossil to renewable energy. In a paper published by Sterling Watson at a conference on renewable energy, she has calculated that if we were able to sell only Chevrolet-Volt-style PHEV powertrains for all vehicles sold in the state of Hawaii, USA, for the next 15 years (the life of the car) simultaneously with a coordinated increase of solar and wind electricity generation, the entire state of Hawaii could become fossil fuel free. In addition, the society would become much more affluent and convenient, because the cost of energy would be greatly reduced and fewer trips to the gas station would be necessary.[8]

Recently many international agreements have been signed which set world-wide goals to curb green-house emissions. It is now possible to meet and exceed all these goals.

The will of the people and the direction and management from the government are the only ingredients needed to ensure this success. All needed technologies are available and in use including the all-important energy distribution infrastructure. These basic systems and hardware can all be improved as we move into the future. For example, low power Level 1 charging can inexpensively be made intelligent, wireless and automated so that the driver need only to park on a designated pad to get electric fuel and service the electric grid, and all energy costs and maintenance can be taken care of electronically and professionally accounted. And, as indicated earlier in this paper, the cost of a low-power-charging station is only 1/10th that of higher-power Level 2 charging stations and much less than even higher power fast chargers.

Promoting the PHEV technology also preserves the current investment in the internal combustion engine, so that the current auto industry and parts suppliers will not suffer during the transition. They will have to adapt from making big engines to smaller, more efficient flexible-fuel engines, but the production numbers would remain the same and grow with vehicle demand. The real benefits will be to the peoples of the world as we use this broad concept anchored by the PHEV to ameliorate the negative consequences of burning fossil material as fuel.

In our introduction we stated that many modern ecological problems began when humans began disrupting the very efficient processes which Earth had evolved. We humans have cut and burned forests which formerly had purified our air. We also mined or extracted and burned coal and oil, releasing millions of years of stored solar energy indiscriminately, altering Earth's climate. The temperature of the sea has risen, it is more acidic, and its rising level poses threats to islands and shorelines, especially during the increasing number of serious storms fueled by the rise in temperature. Obviously we have done tremendous damage. However, just as the body begins to repair itself when a person ceases to smoke, it is not too late for Earth to repair itself. If we change the use of fossil materials from fuel to construction products, we may be able to start expanding and restoring our forests and the other natural CO_2-absorption systems.

Appendix B: The Vehicle of the Future

In examining the alternatives for vehicles of the future, it has been tempting for some to look only at the vehicle emissions characteristics. To do so, however, avoids consideration of other steps in the production or servicing of a vehicle which could result in environmental damage. The entire life-cycle of the vehicle affects our world.

We need to ask "How badly—from acquiring basic materials to putting it on the road—does each newly-proposed vehicle contribute to the destruction of the environment?" A vehicle consists of many parts, made from many resources—some of which may be rare, dangerous in themselves, or which may cause problems as they are mined, manufactured and disposed of. Indeed, the choice of a vehicle in which to invest our future is as complex as it is important. Among other considerations, the process of evaluation must look at the pluses and minuses of the fuel it requires. One of the largest costs often buried in the rhetoric of each proposed technology is the production and distribution of the basic energy and its carrier.

The known fuel technologies available today that are being researched and developed, which we must examine, are the following:

1. The Hydrogen car and its issues. The creation of hydrogen, its compression, its transportation for final use in fuel cells for electric generation or directly to produce mechanical power throughout society poses a number of problems.

Though the hydrogen car claims zero emissions, it can do so only by ignoring the process of producing, conditioning and distributing hydrogen. Conventionally, this fuel is derived by splitting hydrocarbon molecules, which emits CO_2 as well as the hydrogen. In fact, as hydrocarbon fuel is cracked to produce the hydrogen, the by-product is 100% CO_2! The process requires heating the hydrocarbons to very high temperatures without oxygen. It is also an extremely dangerous process. This is why refineries often have serious accidents.

In the future there may be a less destructive process for obtaining hydrogen. In their book, *Aerohydronautical Power Engineering*, Max Platzer and Nesrin Sarigul-Klijn propose that water turbines aboard sailing ships could harvest powerful ocean winds and use this energy to break water molecules into hydrogen and oxygen. The hydrogen could then be packaged and transported to the users. Though this idea could be developed in the future, currently it has no existing infrastructure to support it[9].

The process of first creating electricity and then using it to split water molecules is an inefficient methodology. It would be much more lower cost and efficient to use that same quantity of electric fuel to charge batteries instead of splitting water molecules and add all the needed infrastructure for processing and distribution of hydrogen. In fact, based on information from the US DOE Argonne National Laboratory's GREET model[10], we calculate that the best renewable electricity-to-hydrogen-to-a-hydrogen-fuel-cell-vehicle wheel efficiency is no better than the average hydrocarbon-to-wheel efficiency of a standard gasoline car which is about 20% to 25%.

The loss of efficiency is due to the convoluted processes needed to get from renewable electric energy to the wheels of the transportation vehicle. But if the same electric fuel, is used directly to drive vehicles with batteries as in PHEV's or BEV's, the electricity-to-wheel efficiency is on the order of 90% or higher. This means the PHEV or BEV can go 3 to 4 times farther on each unit of electric fuel generated (kWh) than the best hydrogen technology today. In addition, huge energy and dollar costs for hydrogen production and infrastructure are avoided.

Hydrogen needs energy for compression, generation and transportation: processes that require a large portion of the created energy. Fuel cell efficiency is claimed to be high from already-processed hydrogen to the wheels with zero emissions, but that is only one of many parts of the process of getting energy from the source (the well) to the wheels.

If hydrogen could be obtained reasonably from renewable energy sources, then a hydrogen PHEV which uses 90% electricity and 10% hydrogen could be a sensible alternative.

2. The Natural Gas (NG) car and its issues. Natural gas is created from fossil or biological materials. It needs extraction, refinement, transport, compression, and storage before it can be used in vehicles. Using fossil derived natural gas, which is a hydrocarbon, means that CO_2 is generated—in direct opposition to our goals for the climate.

Additionally, many environmental scientists object to natural gas because much of it is derived from fracking as the method for oil extraction. Fracking for natural gas produces CO_2 because of the Diesel-generated energy needed to pump large quantities of high pressure water into the ground to fracture the rock. This energy is wasted. In addition, the inevitable escaped natural gas contributes more severely to warming the planet.

Moreover, as with hydrogen, natural gas must be compressed before it can be used, reducing the efficiency of its production. Natural gas can be liquefied to provide more range and be closer to gasoline or diesel; however, this adds to the cost and reduces the efficiency per unit of produced natural gas. Although not specifically an environmental issue, we should also consider that compression of gases is dangerous to workers and others.

On the positive side, natural gas derived from human-caused wastes and biological sources could be counted as a form of renewable fuel. This fuel can be used in PHEVs. In fact compressed natural gas PHEV's are being demonstrated today in the US and around the world[11].

3. The Bio-fueled car and its issues. The creation of liquid fuel from grown and harvested biological materials and human garbage (Bio-fuel) is part of the solution, but can only play a part. Production will never be able to meet the current energy needs supplied by fossil fuels without jeopardizing the food supply for humanity.

Sufficient production of biofuel is not possible with current agriculture practices and the land and water available. At most, only about 15% of the current fossil energy required to sustain the world today could possibly be harvested from biofuels. Thus our current high-energy-using society cannot be built on such technology alone.

At present, biofuels work best when mixed with fossil fuels to reduce their proportionate usage. The reason biofuel volumes cannot replace fossil fuel volumes is that while both are in essence solar energy concentrated by plants, fossil fuels are much more potent, composed of a mix of animal and plant materials which have been collected, compacted and concentrated for millions of years. This helps to explain the climate changes we are now experiencing. In only 200 years we humans have burned millions of years of stored and concentrated solar energy.

However, we note that biofuels created from recently grown plants is a net zero CO_2 producing fuel and should be a part of the earth's future energy system. This is true since plants absorb CO_2 as they grow and when processed into liquid fuel. Then the biofuel, liberate the same CO_2 when it is burned for energy. Currently, it is possible to produce only about 10% to 15% of the current fossil fuel use from bio sources.

4. The Pure Battery Electric Vehicle (BEV). The conventional all-electric vehicle or Battery Electric Vehicle (BEV) and its issues. The BEV, because of its single source of energy, has to have access to a more powerful electric grid than the one that now serves us due to the fast charging requirement. Designing and implementing a wholly new high-powered electric infrastructure would increase the electric energy costs and lower the efficiency of electricity generation and distribution. The already low Utility Factor (UF) of the existing grid would be even lower. No doubt the expensive and inefficient new infrastructure would be heavily subsidized: in other words, built at the public's expense or at the expense of all electric energy users.

If the BEV's energy is depleted, it will take a long time to recharge the batteries unless this can be done at very high power from conveniently located charging stations—which will be expensive and impractical to build everywhere. In this way, the BEVs promise several substantial problems. First, the push for very high-power charging by the BEV advocates implies expensive grid upgrades; second, the upgrades further decrease the grid's UF and its efficiency. Thus for the benefit of the few BEV's, costs will be increased to everyone who uses electric energy.

The range limitation of the all-electric car effectively means the vehicle owner needs two cars to cover both daily short-range transportation as well as the occasional longer trips. To travel from San Francisco to Mexico in a BEV would involve many long-time (several hours) battery charges assuming the charging stations will even be available. In addition, the second car will likely be a conventional car burning more fuel and creating more CO_2 per distance traveled than a long range PHEV because of the greatly downsized and more efficient engine in the PHEV.

Amazingly, plans are afoot to ask taxpayers and other electric energy users to fund new expensive electrical infrastructure of high-power quick-charging stations strung out across the world.

An alternative plan that has been proposed and rejected, which suggested batteries that could be removed from the car like a spent lightbulb and replaced at the gas station by a newly-charged one. This idea did not work because all car manufacturers would have to adopt a uniform battery structure. This is not possible because of the wide variety of shapes and sizes of vehicles across all manufacturers. In addition, the chemistry of the batteries is still evolving. Also from the point of view of the vehicle buyer, the price of such a car will not really include the costs of the battery. In addition to the purchase price of such a BEV, there will be rental (of a newly-charged exchange battery) and/or charging costs. Thus the costs associated with the battery could be more than double the already expensive battery. Because of the problems described above, accommodating this kind of BEV is expensive and not at all seamless.

In contrast, the PHEV instead of requiring a change in the grid, improves the grid's currently low efficiency, and thus, lowers the cost of the existing electrical infrastructure and energy costs. It does this because it can be charged at times when the electric grid is in low use and charged slowly due to its dual fuel nature, increasing the grid's UF and lowering the cost of electricity to everyone.

BEVs could make sense for very small passenger cars and bicycles. (Most electric bicycles in a sense are already PHEVs: The secondary engine is the rider and the fuel is the food they eat.) BEV technology does not make sense in long-haul trucks and buses due to the weight of the required batteries and even more serious, the lack of electric fueling infrastructure.

One outstanding characteristic of all electric cars is the silence of the engine. While this may be a problem for a blind pedestrian who cannot hear an approaching car, truck or bus, it is a welcome convenience for deaf passengers who normally have difficulty participating in conversation.

5. The so-called Extended Range Electric Vehicle or EREV or BEVx. This concept is basically a PHEV with a smaller “range-extended liquid-fuel-powered electric generator.” The BMW-i3 and the Renault Kangoo are examples. These vehicles have a battery pack large enough for city driving but a very small gasoline engine and generator just large enough to recharge the batteries but not large enough to maintain full performance of the vehicle especially at highway speeds.

Unfortunately, this concept has some major drawbacks.

- It is much less efficient than a properly-designed PHEV when using liquid fuel.

- It will likely be abused by the user since he will now suffer from range and performance anxiety and would likely try to run the engine-generator constantly to keep his vehicle fully charged so his performance and range are not affected. Over-use of the gasoline engine will reduce his grid energy use, defeating the goal of promoting more grid use. On the other hand, there may exist some unique areas such as retirement communities for which the BEVx could make sense. However the purpose of this paper is to focus on universally practical vehicles.

EREV (now being officially referred to as a BEVx) is actually a poorly designed PHEV; however, the car manufacturers will build whatever concept can be sold to their customers since they are profit and regulation motivated. Therefore, it is likely the lowest cost practical car that provides the benefits of moving toward zero net CO_2 that will be a clear choice. The government’s job then is to properly incentivize the best ideas. Sometimes this is difficult to do until the vehicles are built and distributed. Then vehicle use-patterns can be evaluated, and ideas used badly should then be rejected or dis-incentivized. Thus, the incentive rules made must be flexible so that we are not locked into bad technology.

6. The improved gasoline car. The current all-gasoline car is less efficient in fuel consumption than the PHEV because a large gasoline engine is needed for acceleration, performance and top speed. In contrast, the PHEV can have a much smaller liquid-fueled engine for much higher efficiency with no loss of acceleration and performance. Hopefully we will be transitioning swiftly away from the conventional car.

However, the number of engines manufactured per year as we move forward with the PHEV would remain about the same and thus be essentially seamless to the engine manufacturing industry. The big advantage of the PHEV is the reduced material usage and higher thermal efficiency realized by the much smaller engine. Also the transmission system in a PHEV can be much lighter, simpler and less expensive.

7. The Plug-In Hybrid Electric Vehicle (PHEV). The PHEV exploits the potential of both electric energy and liquid fuel. Both these fuels can be gradually and seamlessly transitioned to be fully renewable[12].

As stated at the outset of this paper, the long-electric-range PHEV constitutes a new paradigm. Its access to two fuel forms solves the “range anxiety” problem of all the above alternative vehicles. Since the electricity it uses can be produced from any of the currently available renewable resources, it is a vector for the transition away from fossil fuels. It also can be used as a battery on wheels to transport energy from one place to another. Significantly, the PHEV can be used to ameliorate the variability of power from solar and wind generation, a problem not addressed by any of the other proposed vehicles.

The PHEV, using renewable-fueled electricity and pure biofuels, will generate zero net CO_2 emissions and result in the lowest possible energy cost at any time from now and into the future. During the transition period the engines in the PHEVs should be able to burn any mix of fossil and biofuel. These engines have been designed in the past and are called flex-fueled engines. Unlike the other proposed concepts, the PHEV technology can be used for all classes of vehicles today from bicycles to heavy-duty trucks and buses. As we have said, it represents a new paradigm.

In addition, the longer-electric-range PHEV’s excess energy storage capability can be used for transportation, domestic and industrial uses. For transportation, the batteries of the PHEV essentially offset the use of liquid fuel, shifting from fossil fuels to the use of electric energy.

For domestic and industrial electric energy use, a fleet of parked PHEVs can be charged using the downtime of the electric grid system to acquire the energy for driving. The same parked-fleet of PHEVs can also supply or augment the electric energy needs for a factory or for other industrial and domestic uses without having to build new high-power electric infrastructure solely for charging vehicles especially if the parking lot is outfitted with local solar or wind generators. In addition, as pointed out, these parked fleets can also balance renewable electric energy generation systems without the need for special expensive single-use energy storage systems as currently being proposed by many battery manufacturers.

Long range PHEVs will be able to go much farther per liter of liquid fuel because the internal combustion engine can be greatly downsized to perhaps ¼ the size of the conventional vehicle's engine, but the acceleration performance of the vehicle can be better due to the electric energy and power on board. This is demonstrated by the all-electric Tesla car which rockets. More than 20 vehicles based on commercial platforms built by one of the authors over the last 20 years have been PHEVs and they have all demonstrated higher performance than the conventional vehicle and when on the highway more than double the fuel economy.

Shorter-electric-range PHEVs are also possible, but these vehicles will need special high-power charging facilities such as overhead charging systems. This may be like the overhead lines used by electric street cars. High power charging will be necessary in order to meet the goals of 90% electricity and 10% biofuel use. An application of this concept for taxi cabs in China chose the shorter-electric-range PHEVs with overhead-charging systems because of battery costs can be minimized[15].

8. The PHEV concept compared with other alternative-fueled vehicles.
Alternatively-fueled vehicles need to satisfy all existing conditions of travel—short and long distance for small and large vehicles—as we enjoy today with the use of fossil materials as fuel. The PHEV surpasses its alternatives because there is no need for two cars to replace the versatility of our current fossil-fueled cars.

In addition, no new physical technology or energy distribution infrastructures are needed. The main need is for the electric utilities to control the existing grid intelligently and to integrate it with new local and remote solar and wind generators for higher efficiency and profits. This could result in the lowest possible cost and provide the shortest possible transition time from fossil to renewable energy.

In addition, the PHEV running on 100% renewable electricity and 100% biofuel has zero net CO_2 emissions, which is our ultimate goal. So the problem of zero emissions is not only in the vehicles themselves but also must include the energy generation and distribution systems. This criteria for judging emissions must hold for all technologies being proposed. In addition to emissions, energy efficiency of the technologies needs to be compared especially if the energy is to be generated by renewable sources.

Small amounts of the other regulated emissions may be generated by the engines used in the PHEV. The engines can use the technology already developed for conventional gasoline and diesel cars and trucks, but since the annual fuel consumption may be less than 10% of that of the conventional vehicle, these criteria emissions can then be minimal. For example, if the liquid fuel engine is never used below 20 mph (30 kph) then the vehicle emission characteristics will be completely different from that of conventional cars and trucks. Thus regulation and incentives need to include energy generation and distribution as well as the vehicle design and customer use in order to achieve the zero net CO_2, minimum energy use, and regulated-criteria emissions that society requires.

Appendix C: Today's Grid uses very little of its potential for energy transfer

We can make much more effective use of the currently-installed and existing electric grid systems by using it for energy transfer as well as power transfer. If we look at the current electric system installed all over the world including China and the USA, we find that the installed copper grid is highly underutilized. We can use the existing installed copper lines to transfer much more energy, but require very little more power.

We can do this simply by increasing their utility factor (the average power transferred over a daily or weekly period divided by the maximum power capability) thus raising the average power transferred. For example, the average power used by a domestic household is about 2 to 3 kW averaged over a 24 hour period, but the peak power available is 20 kW. So the wires could transfer 480 kWh of energy per day, but typically we use only 48 to 72 kW-hrs of energy per day. Thus the wires are used only to about 10% to 15% of their energy transfer capacity.

With this great a difference between the need and the potential, we already have enough energy transfer capacity in the existing wires to satisfy the needs of homes, factories and road transportation. (This potential has been verified by many studies from the US National Laboratories.)

The good news is that the power generation, transmission lines and equipment for a complete electric society including transportation exists now; we need only to identify the right technology to use this excess energy transfer capability that we have already installed but are not using. The same goes for the power generation side of electricity.

We now have enough peak power capability to cover the most extreme power demand in the country even though this emergency need may occur only once every 5 or 10 years. This power generation capacity exists, but we operate with the generation capacity partly idled, or throttled because we have no storage for the excess. This wasteful restraint lowers the overall system's efficiency and increases the costs. (Any time a central power plant is operated part-load, it is less efficient than when operating at full load.) Without storage, generated electric power must be used; if it cannot be used, it must be dissipated as wasted heat.

We can ameliorate these problems by providing efficient energy storage, but the current technique of pumping water back up the dam has been shown to be inefficient. Tesla and some of its associated solar companies proposes to use banks of batteries to provide storage in order to alleviate grid problems and even to power homes and industries with enormous battery banks. However, these stationary batteries and their high power electronics are immobile, expensive, and not really necessary since all these proposed "new" functions are already available in long-range PHEVs with bi-directional chargers.

The *Wall Street Journal* (article published on 4-30-2015) notes that home systems recently introduced by Solar City will be priced at $23,429 for a 5 kWh battery—nearly two thirds the cost of a Chevrolet Volt! Customers who have purchased these refrigerator-sized units and anchored them to their garages will be disappointed: for a little more money they could have purchased a car—as well as the fuel for it and power for the owner's house.

The whole stationary battery plan becomes unnecessary with long-range PHEVs widely distributed, and always plugged in when parked, equipped with intelligent bidirectional chargers. In this case, we would already have enough batteries everywhere for balancing the electric grid. So why not coordinate all these efforts and use the PHEV batteries in parked cars and trucks for multiple purposes as presented in this paper? The more uses we can think of, the lower the new energy system cost, and the more everyone will benefit.

Appendix D: Representative Statistics for Vehicle Driving

The statistics of daily, weekly, monthly and yearly vehicle driving distances by millions of people who own cars can be used to determine the appropriate design for the PHEV. For example, statistics can be used to determine the battery size for PHEVs and its electric range. Statistics also verify engineering success.

However, statistics are only accurate if certain rules are followed. For accurate statistical data the subject cars must be plugged in under the same conditions. The results will differ if the cars are plugged in only at night or if they are plugged in all the time they are parked.

The management of the electric grid to include PHEVs can be analyzed on a statistical basis much as is done today by the electric utility companies for generation and load management if they are plugged-in 90% of the time they are parked. To make the statistics work we have to analyze how people use their transportation vehicles and how the electric system is currently designed and used.

For example, passenger cars—which use perhaps 70% of the fossil material used for fuel or energy today—are seldom in operation for more than a few hours a day. This means they are parked somewhere for over 20 hours a day.

During the few hours of travel, the distance covered on the average, for passenger cars, is about 30 miles (50 km). The amount of electric fuel or energy used for this typical distance traveled in the US, Canada and China is less than 10 kWh. For such a low average total energy usage, the PHEV can be charged at a low level of 1 kW to 2 kW from the electric grid.

To help establish this statistic, the vehicles could be designed to have wireless bidirectional chargers. This bit of advanced technology can be low cost at low power. Many companies are researching such concepts now and waiting for established standards and regulations for production.[13, 14] This means there is no need for fast-high-power and less- efficient chargers as being proposed. Many government and private BEV manufacturers like the Nissan Leaf, Tesla, and other companies are in favor of this course-of-action because they believe it would spur BEV sales for their benefit. But they have lost sight of the main goals of these vehicles, which are to displace fossil fuel with renewable electricity at the lowest possible cost, and highest efficiency and in the shortest possible time.

The key to statistics is that efficient utilization of the grid works only on the average, but every driver's specific use must be accounted for by the vehicle system designer and the customer must be satisfied with a product which is better and lower cost of operation than his current gasoline or diesel vehicle.

The PHEV must be able to do everything these conventional vehicle can do, and more if the claim of advanced technology is to make sense. For example, if a driver goes 100 miles (160 km) in one day, even though his monthly average is 10 miles (16 km) per day, then the car needs much more energy that one day than what it normally uses. This means that to satisfy that occasional use, the owner of a practical BEV must carry around at least 10 times the battery that he needs on the average.

This is the inefficient Tesla model. It is now also being proposed by even more car companies. They are simply adding more batteries for that once-a-month or once-a-year contingent use. They can do this, since most of these cars are being built to satisfy a regulation for fleet-average emissions. Thus there is an incentive to build expensive but not market-sustainable vehicles in order to sell more profitable but dirtier and more fossil-fuel-intensive vehicles. Somehow these ill-advised incentives need to be changed for the common good.

But because, unlike the currently designed BEVs, the PHEV is a dual-energy vehicle, it can take advantage of this capability by automatically basing its transportation plan on initial use of clean electricity, then switching to its much more energy-dense liquid fuel when the batteries are drawn down to their minimum state. Thus it can accomplish the social objectives of using more electricity than liquid fuel by design. The only control policy needed in the design is that it will use electricity first before using liquid fuel.

The statistics of daily driving distance is close to a “Normal Distribution”. Thus if a PHEV has an all-electric-range, AER, of 60 Miles (100 km), and the average driver in the US drives 30 miles (50 km) a day, 50% of the users would drive fewer than 30 miles (50 km) a day and the other 50% would drive more. Then a PHEV with 60 miles (100 km) of electric range would cover the needs of 90% of the drivers in the country using electricity only. (The new 2016 Chevrolet Volt will have a battery pack with 50 miles AER). Since it is a statistical average, some percentage of all the PHEVs would use more liquid fuel but the average PHEV would use about 10% of the average liquid fuel of the conventional gasoline cars.

Appendix E: The PHEV and the electric grid: fast- and slow-charging

Since there is excess energy for 50% of the PHEVs, the PHEV batteries of the cars requiring less range per day than 60 miles, can further be utilized as an energy storage device to balance the irregularity of the grid and cope with renewable energy sources like solar and wind. If the vehicle is properly designed, vehicle operation is not affected whether operating on electricity or liquid fuel.

Thus, many of the longer-range PHEVs in use, in addition to being able to extend their ranges using liquid fuel, could also supply energy for domestic use without affecting either capability. Because liquid fuel energy density is around 10 times more than battery electric fuel or energy, the sacrifice of a little electric range—say 10 miles to supply energy (about 3 kWh for a home)—requires less than a gallon of gasoline. If the PHEV has a 10 gallon tank, this amount of gasoline is generally negligible.

It should also be clear that the batteries should be controlled in PHEVs so they are never drawn to zero state of charge (SOC) because some reserve battery energy is always needed for good driveability and liquid fuel efficiency. Most PHEV designs use this strategy. So there is always a minimum charge in the batteries of the PHEV for performance, hill climbing and driveability needs. (The Chevrolet Volt has a mountain mode to increase this charge reserve temporarily to provide better driveability in the mountains or perhaps when towing a trailer.)

For the features we are promoting, all PHEVs should be plugged into the grid at a low power with a 1 to 2 kW outlet whenever they are parked. This process can be manually operated (using the existing electrical outlets) or better yet, automated wirelessly, like an electric toothbrush. Low-power charging is simple for the PHEV since we are talking about using standard outlets (Level 1) already available everywhere in the world. To make it really seamless and convenient, the charger could be simply an inductive pad in the parking space designed for 1 to 2 kW of power transfer.

Wireless parking pads are being proposed by a number of commercial companies such as the Qualcomm Halo system and the Momentum Dynamics wireless chargers.[13, 14] If these charging pads can be bidirectional and the grid can supply or absorb energy from the vehicle at a low power, the cost of bidirectional chargers can be low and allow the use of the already-installed low-power outlets distributed everywhere in society today.

Another argument for low-power battery charging is that the battery’s internal resistance (Rb) is fixed by the battery’s chemistry and state of charge, meaning the more slowly the battery is charged the less heat is generated and the more efficient the charge acceptance. This loss goes as the square of the current, (I2Rb). This means cutting charge time by four by increases current by four, then increasing the loss by sixteen, and greatly lowering the efficiency of using grid electric energy. [This fact negates the idea of fast-charging batteries.]

The proponents of fast charge have been quoted as saying that fast/high power chargers are more efficient. But this is only true for the charger itself, but not the battery. The battery charge acceptance is the problem. There is also battery temperature rise and loss of battery life, just to mention two other negative consequences often ignored by fast charging proponents. The wealthy owners of battery electric vehicles don't really care about these negative consequences since they are concerned about their convenience and time. We need to be concerned about setting up an electric-charging infrastructure that works for all people and the planet—not just the high-powered few.

BEVs always suffer from range anxiety. Even though a BEV may have 200 miles of driving range and it only uses 30 miles per day on a regular basis, the driver will be anxious because maybe he/she forgot to charge the night before, or the driver may suddenly be called to go on a long trip. The PHEV, on the other hand, with an electric range of about 60 mi (100 km) would have enough energy for daily travel of 30 mi (50 km) a day and be able to supply 10 kWh of energy for the home, and go on the long trip of 400 miles (650 km) at any time, just as in the conventional car. This versatility adds much more value for the owner.

If the energy to charge the batteries is generated from solar or wind, and the PHEV has a bidirectional charger connected to the grid, then when the sun or wind generators become inactive, the PHEV batteries can supply energy back to the grid. We already have available all the hardware and technology needed for collecting solar and wind energy for both car and home use. The only additional technology needed to complete the system is the bidirectional charger to access the energy stored in the PHEV batteries. Thus the grid can have renewable energy storage at only the rental fee paid to the PHEV owner.

This can be realized simply by a lower energy costs for the PHEV driver from the utility company. Thus no new paperwork is required. On the other hand, the BEV used for this purpose will notice the potential depleted range and the concepts discussed above would likely not be acceptable. If the BEV batteries are used for an emergency or routine electric supply, the average BEV user would view it as another dimension to his range anxiety.

A PHEV can use its stored electric energy to power a house for 24 hours on its batteries alone and it can replace a generator or the grid itself if needed.

(For example, Efficient Drivetrains Inc. has designed, constructed and demonstrated PHEV utility trucks which can power a whole neighborhood of 50 houses or more while maintenance and repairs are being made to the grid).[18]

On bad weather days when renewable solar energy is low, the PHEV can use its liquid fuel capability as well, if necessary, with no disruption in service for the car or home. This dual energy capability means that the PHEV can use its batteries for four critical issues of future energy systems: renewable energy storage, grid management, transportation at zero CO_2 and efficient emergency power supply. There only needs to be enough battery reserve on board the PHEV. A 60 mile (100 km) range could satisfy all these applications comfortably on the average.

We have outlined the advantages that can be accrued only by the PHEV with enough battery energy to operate all-electrically for about 60 miles (100 km) at full performance. The new Chevrolet VOLT is close to this goal 50 miles (85 km) AER). This design is the second generation of the Chevy Volt. Its design was dictated by customer preference and demand. So having 60 miles AER is the right number from the customer perspective. As the customers begin to understand the additional use benefits, such as grid balancing and solar and wind energy management, they will want to participate, especially if incentives are correctly administered. For example, the cost of electricity could be lowered to compensate for this contribution. The cost can be further lowered by adding a bidirectional charger and management software. Grid efficiency will be improved and solar and wind energy could be added to the grid. These items add value to the grid.

Appendix F: Biofuel Issues

Currently gasoline and Diesel fuels are blended with up to 10% biofuels. These blends are now being used to reduce oil consumption and for cleaner combustion with fewer regulated emissions. These regulated emissions are nitrogen oxides, hydrocarbons, and carbon monoxide (NO_x, HC and CO). But biofuels could also be used directly in new PHEVs without a fossil fuel blend. As PHEVs replace conventional cars, gasoline and Diesel fuels can be blended gradually using less and less fossil fuel content as time and demand dictate, until the fossil content approaches zero.

Remember that the biofuels are essentially CO_2 neutral since biofuels are produced by plants that consume CO_2 to form hydrocarbons. The biofuel cycle—from seed to plant to harvested fuel—is short and thus does not affect the earth's atmosphere or it results in a net zero CO_2. The fossil fuel cycle, in contrast, requires millions of years. This long-cycle time is irrelevant to the short span of human existence and human progress. We cannot wait for today's trees to turn into oil and coal. The coal and oil we have now are all we will ever have and thus not renewable to human kind. This is why they cannot be called renewable fuels.

The current fossil fuel distribution system could also be used to distribute pure liquid biofuels as well. For example, the same pumps and pipes used for fossil fuel can be re-used to convey biofuels. The existing liquid fuel, manufacturing and distribution systems need to be preserved if the transition process is to be seamless and economically profitable.

Appendix G: Solar, wind energy and grid management using PHEVs

The introduction of solar and wind electric energy is still in its infancy. The current percentages in the USA are small relative to fossil, nuclear, and water plants. California and other states in the country are planning to introduce more solar and wind to replace coal and fossil fuels such as coal, natural gas, and diesel fuels. This transition will take many years to create, build and become reliably operational.

Thus, as time progresses, the fossil fuel component of electric generation will decrease as renewably generated electricity increases. This increase will occur quickly since the PEVs are also being introduced as the load steadily rises from transportation demands. This is illustrated in Figure 3 below.

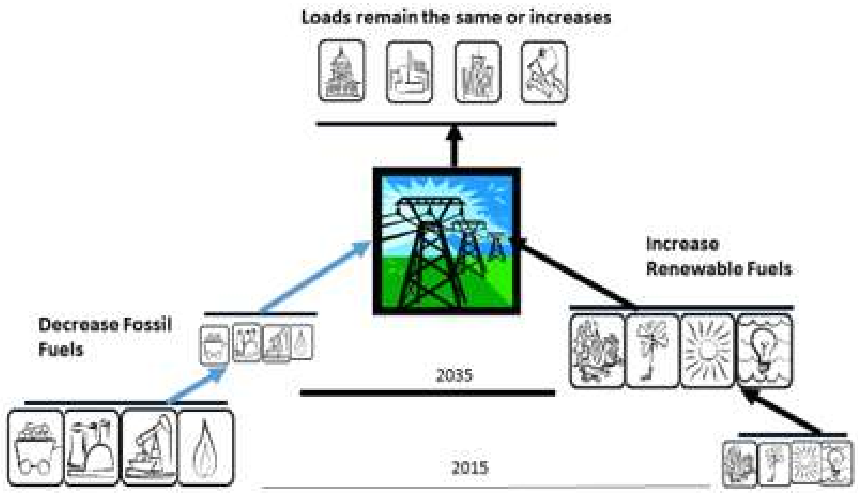

Figure 3. Transition from fossil to renewably-generated electricity. Click to enlarge.

There is some negative reaction to using pure biofuel by people who are generally ill-informed. Supposedly the increased proportion of biofuel will damage cars and void their warranties. It is only the older cars that are not designed for biofuel use that could face a problem. If the vehicles are designed for using biofuel then there should be no issue if the current amount of such fuel remains relatively constant. Since the transition time is 15 years or more these older cars will mostly have been scrapped, so such problems should be minimal. The antique car societies will have their own fuel for their limited use anyway.

Solar and wind electricity, due to their high variability, need energy storage and management to work effectively as shown in Figure 4 below. To take care of this variability, currently the electric grid itself is used as the energy absorber. This means that when wind and solar electricity generation is high, the fossil-fuel generated electricity on the grid is throttled or reduced. This idea works for a small amount of renewable energy. The existing grid cannot support more than about 20% of the grid's energy from variable solar and wind. To go above this threshold requires external electric energy storage of the wind and solar energy. At the same time, these renewable sources are not consistent.

Clearly the sun does not shine at night and the wind can go from maximum to zero in a short period of time as illustrated in Figure 4. The PHEV batteries can be used to absorb some or all of the energy from solar and wind then give it back to the grid efficiently when the renewable energy generators falter due to weather or other factors.

The BEV’s batteries could be used to smooth the solar and wind energy as well if they have enough excess capacity and the driver is willing to give up his reserve energy storage. As discussed above, it may be difficult for the BEV user to part with his energy reserve since he could be left stranded somewhere if he accidentally surpassed the range of the car minus what has taken by the grid that day. Of course it may be argued that high-power charging stations everywhere will fix that, but as pointed out, that comes at great expense to everyone and at the cost of lower electric energy efficiency. [19]

PHEV batteries should be located directly below solar panels or wind turbines for the most efficient distributed generation system. Thus we can avoid high power transmission lines to make use of solar electricity. The same arrangement works for small wind generators (5 to 10 kW per car) as well as for roof-top solar.

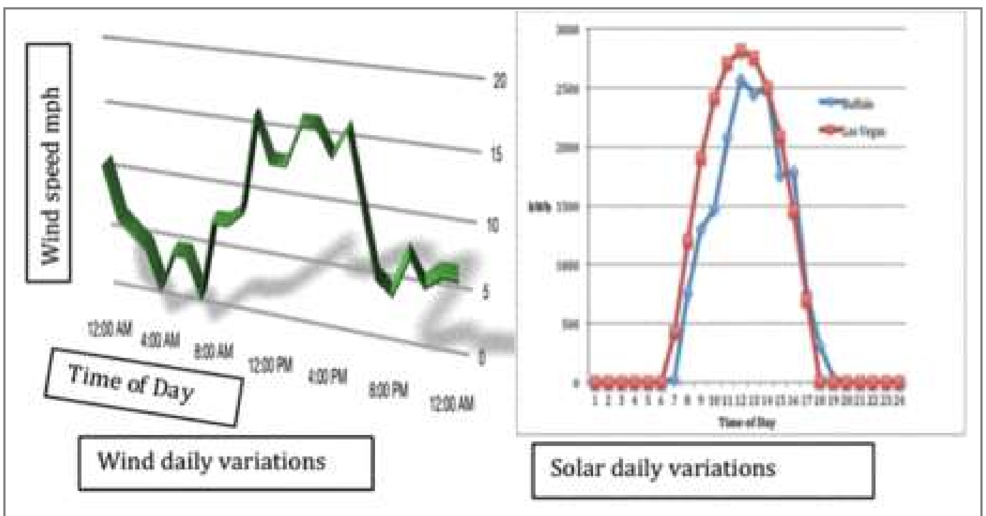

Figure 4. Wind and Solar daily 24-hour variations. Click to enlarge.

The advantage of using the PHEV in these locations is that it is most robust in renewable electric energy management. This advantage is due to the dual-fueled nature of the PHEV and the fact that liquid chemical fuel has 10 times the density of today’s battery energy and likely will remain so into the future. The battery energy is always used first in the PHEV so that electric energy is automatically the preferred fuel.

Currently many liquid fuel stations can be switched easily from dispensing fossil fuels to liquid biofuels. The PHEV used this way with solar, wind, water and other non-fossil sources of energy such as biofuels would be zero net

CO_2 emitting, thus achieving our goal.

Occasionally, we receive through emails beautiful views of the Earth from space, lit up like an ornament. Some viewers perceive more than the lit-up beauty. Astronomers shudder at the spreading of “light pollution,” but also sufferers from asthma, COPD, lung cancer and the like must dread the amount of deadly particulates and noxious gases being emitted by fossil fuels burned to enable the display. Consider, however—if every home and business had a solar array on its roof, and a PHEV charging from it, that whole glowing Earth ornament would be fueled by energy from the sun collected in the PHEVs’ batteries.

References

[1] Infrastructure for EV Battery Charging EAA-PHEV Wiki

[2] How Much Do Plug-In Hybrids Plug In? Volt Has Most Electric Miles, Data Shows *Green Car Reports* 20 May 2015

[3] PHEVs using renewable fuels EAA-PHEV Wiki

[4] More EDI Plug-In Trucks for PG&E - *Fleets & Fuels* 24 Nov 2014

[5] The Electric Vehicle as a Power Plant: A California Utility Shows How it’s Done - Microgrid Knowledge 25 Feb 2015

[6] Whitepapers Microgrid Knowledge

[7] Infrastructure for EV Battery Charging - EAA-PHEV Wiki

[8] Watson, Sterling and Andrew A. Frank (2012) A Fifteen Year Roadmap Toward Complete Energy Sustainability. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-12-35

[9] Title *Aerohydronautical Power Engineering: Is It the Key to Abundant Renewable Energy and Potable Water?* Authors Max F. Platzer, Nesrin Sarigul-Klijn Publisher University Readers, 2011 ISBN 1609274687,

9781609274689

[10] US DOE Argonne National Laboratory's GREET model

[11] *Green Car Congress*: EDI partners with Greenkraft for parallel-series multi-mode Class-4 CNG-PHEV truck; CEC funding 30 June 2014

[12] PHEV Vehicles of the Future - Autopedia Wiki

[13] Qualcomm Halo system

[14] Momentum Dynamics Inc.

[15] More More EDI Plug-In Trucks for PG&E - *Fleets & Fuels* 24 Nov 2014

[16] Watson, Grant and Andrew A. Frank (2012) Electrification of Taxi Cabs in Major Chinese Cities with Range Extended Electric Vehicles. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-12-39

[17] "Grid Storage Data Tracker"

[18] http://www.efficientdrivetrains.com/news.html

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