The Electric Car

What does the Future Hold?

There is a massive undercurrent of change in our society to remove dependence on oil as an energy source. This topic has been tossed around for decades, starting with the gas shortages of the 70s. Today, however, the situation is very serious.

In 40 years, if projections are correct, our lives will drastically change. Our dwindling oil reserves will dictate lifestyle adaptations. And are we sure that we even have 40 years? Recent US actions include canceling zero emissions mandates and shifting to low mileage SUVs. The explosive growth of China's manufacturing economy has accelerated the consumption of oil, and introduced a new urgency to the problem.

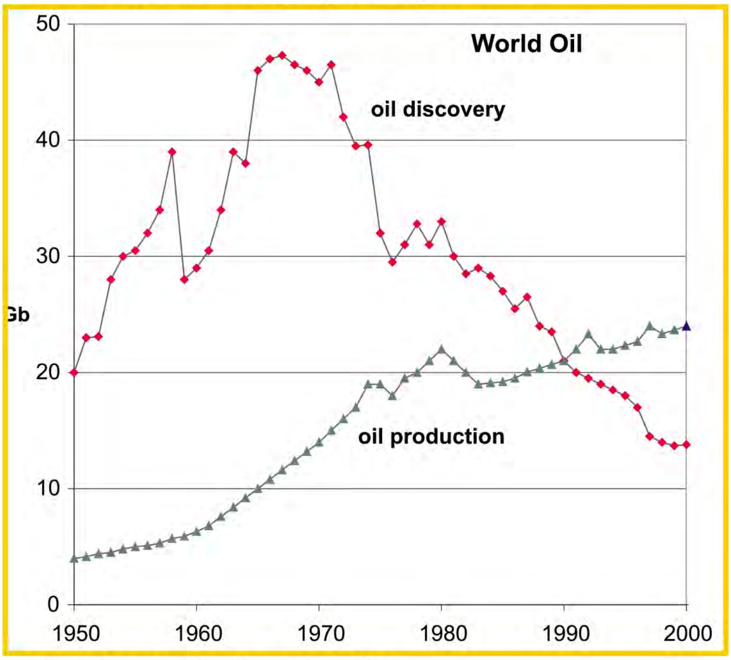

Fig. 1: The world's oil supply decline.

According to Colin J. Campbell of the M. King Hubbert Center for Petroleum Studies, "The US has to somehow find a way to cut its demand by at least 5 percent per year. It won't be easy, …but the alternative is even worse"[1]. The actual date when demand exceeds supply will lead to economic turmoil. We'll stay out of that debate, but we will take a closer look at proposed changes in oil consumption.

In just 20 years, we will need to adapt to a new transportation behavior. There is a dim public awareness of this fact, but it has not become a tangible issue for most.

The foundations are shaking in three industries–automobile manufacturers, oil companies, and utility companies. The topic of alternative fuels can threaten their existence or empower them, depending on how the pendulum swings. The politics involved are extremely complex, while these three powerful industries struggle to maintain control over their domains.

The massive political and economic push that is receiving media attention today is the theory of conversion to a hydrogen economy. In this article, we will discuss and challenge this theory.

Hydrogen is just one alternative. Recent events and achievements in the power electronics industry may open other doors of opportunity to either supplant the need for, or complement, hydrogen or other alternate fuel systems. We will also see later that the efficiency of proposed hydrogen-based automobiles cannot compete with the all-electric vehicle.

The Electric Car of the Last Ten Years

Ten years ago, many companies were looking at the electric car very seriously as a future product and tremendous sums of money were spent to investigate the technology and develop prototypes. At General Motors alone, $1.3 Billion was spent on producing 1000 fully electric vehicles. Development was driven largely by California's mandate (since rescinded) requiring 10% of all cars in the state to be zero-emissions by 2005.

GMs EV1 was definitely a step in the right direction, and was featured in our second issue of Switching Power Magazine in 2000[2]. While leasors (none were ever sold) of the electric car loved the product, the prototypes produced by car companies all suffered from issues that simply could not be overcome at the time.

Fig. 2: A step in the right direction: GM's EV1 was a fast, fun car that turned heads everywhere it went, but ultimately suffered from range and recharging issues.

It doesn't mean that the money spent on research was wasted. In fact, much was learned about the power electronics design that allowed the electronics to shrink and coexist with a conventional gasoline engine in the present hybrid drive technologies.

Why did the EV Fall Short?

In the most recent generation of modern electric cars (electric cars were first invented in the 1800s), there were two major obstacles to widespread acceptance of the technology - driving range, and infrastructure for charging. The cars themselves were actually attractive, safe, fast and fun to drive. It was the 50-100 mile range on the massive pack of lead-acid batteries that made it difficult to reach the next charging station. This is a result of the battery technology, and, our favorite topic, the power electronics.

First, we will look at the battery technology. The lead acid battery has been around since the birth of the automobile, and has changed very little. Incremental improvements in capacity, longevity, safety, and maintenance have not removed the fact that it is simply too heavy and bulky to work in the electric car and be practical. This was an issue that the car companies hoped would be resolved, but did not happen in time for the projects to continue being funded at the necessary level.

Then there was the issue of charging methods. This was the subject of much debate in the car industry in the 1980s. Two approaches were considered, one was direct connection to an electrical outlet. The other was something that looked much more like a common fuel pump as it exists today, utilizing a "paddle".

Supporters of the direct connection method pointed out that a simple universal plug connection to charge a car was a better solution. Opponents of this system claimed that the heavy-duty plugs required would be unreliable and lend a perceived safety problem to the public. While this may be the right solution, the car companies could not all agree on the seemingly simple concept of what the connector should look like. As a result, Ford, Toyota, and others each had their own power connector, and none of them were compatible.

The “paddle” method involved inductive charging, where the power converter for charging the car was essentially split in the middle of the transformer. The primary circuitry and primary windings of the converter lived in a fuel pump, and components in the car completed the transformer construction and provide the secondary part of the circuit. This became a fascinating challenge to the power electronics researchers– how to split a 50-100 kW converter in half and make it work. The solution involved resonant power conversion to accommodate the relatively high leakage of the transformer, custom designed ferrite cores, and sophisticated mechanical interlocks to hold it all together reliably.

The next critical issue was the power electronics, and choices made here were crucial. The motor drive systems that GM and others developed were, in a word, superb. Several generations of power electronics drives shrunk the size and cost to the extent that it could miniaturize a 100 kW power supply to coexist under the hood with a standard gasoline engine in the present hybrid car. This is a phenomenal achievement.

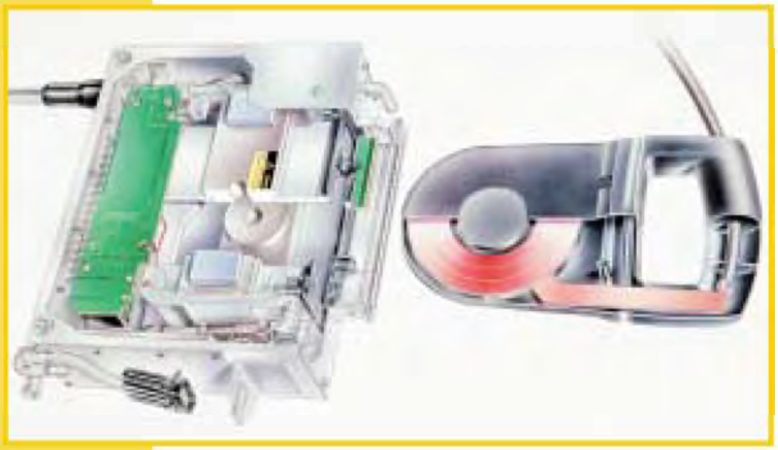

Figure 3: The inductive charging system used by GM split the charging electronics in two pieces. The primary of the transformer, in the "paddle" was driven by a resonant converter in the fuel pump. The transformer was completed when the paddle was inserted in the car.

Ultimately, the charging infrastructure needed was far too complicated and expensive. All charging stations, for example, would require expensive "pumps" that required maintenance. This is where the move toward this style of infrastructure stagnated.

Although millions of dollars were spent on installing public EV charging stations in California and Arizona, the goals of available, convenient charging for EVs were never met. In addition, EV1 drivers had mixed experiences with inductive charging. The floor-mounted chargers had a very high failure rate, and service delays were inevitable.

GM's EV1 was recalled in 2000 and the all-electric car from GM died with this recall. The distinct feeling in the industry given at the time was that the all-electric vehicle was not a practical car, and was fraught with problems. The subject of the recall was the charging system. The charging system was, from day one, a huge engineering undertaking. Many researchers in the power electronics industry thought it could not be done at all. Any undertaking like this is bound to have failures that lead to improved design, but should it have killed the EV programs?

According to Tom Gage, President of AC Propulsion, GM car users started carrying their home charging stations in their cars as the reliability of the charging systems became a serious problem. Essentially, they implemented the fully on-board charging system that, in hindsight, should have been part of the vehicle from the very beginning.

Following along with GM, all of the electric vehicles shown in Fig. 4 have been discontinued. This happened soon after California's mandate for 10% zero-emissions in the fleet of vehicles was lifted. In the midst of the need for better ways to manage fuel, we have returned to the gas-guzzling ways of 20 years ago, under the guise of research for better fuels.

What Crisis?

There is a common misconception amongst the general public that we are in imminent danger of an energy crisis and we will "run out of energy". There is not now, nor will there be, an energy crisis in our world, in the sense of energy *supply*. What we have instead, is an energy *storage* problem. There is plenty of energy falling on the earth in the form of sunlight, plenty of renewable energy such as wind energy, and plenty of high-density energy storage in the form of nuclear fuel. What we lack is a method of storing the energy in a convenient and safe medium. And that is the drive of the future– to find an efficient, safe, and cost-effective replacement for gasoline. But it is not a one-to-one comparison. Gasoline is both an energy storage medium, ***and*** an energy source. The proposed replacements are merely energy storage mediums.

What are the options? We have ***mechanical*** energy storage, which amazingly, has been attempted in the past, even for automobiles. A scheme proposed was flywheel energy, where a carbon-fiber cylinder was spun up to 100,000 rpm in a vacuum, suspended by magnetic bearings. Flywheel energy is fine for short-term power needs-perhaps a few seconds for short line outages. But in a car, the storage of 50-100 kWh in the

Comments from users of electric vehicles
posted to the EV1 web site during March and April 1999:

"It should be mandatory that all electric cars have a built in 120 volt charger. You never know when or where you'll get hung up without electrons."

"The fact that with a 110VAC (115VAC) input to an EV literally makes EVERY home and BUSINESS a filling station really should be re-evaluated. It is extremely important, and should have been incorporated into the new NiMH model"

". . .with the ability to charge with 115VAC, virtually every home, business, and parking structure becomes a potential charging location. So instead of people [complaining] about the number of EV filling stations compared to ICE filling stations, There are 1000's of times more EV refueling stations. A simple point and - no matter how slow the charge, it is a safety blanket. "

". . . I'm going to stick with any EV that allows me some type of interface with a NEMA spec., 110/115VAC wall outlet which has been around for longer than I've been alive. I wouldn't call that a trend, but a fact of modern life."

"There is no infrastructure in this country that is more available than that of a 120 V plug. Why this abundant resource has been ignored is just beyond comprehension."
"The ideal charger, in my opinion, could be programmed to draw a user-specified maximum power from the line. It would also accept either 120V or 240V, and be small and light enough to carry around...or be built into the car..."

"Inductive charging died the minute that Volkswagen decided to adopt the AC Propulsion charging system, which costs (much) less and performs (much) better."

And a final post sadly announced the end of the project to electric vehicle owners.

"Tomorrow we will formally announce that Edison EV will cease operations in the near future -- most likely within the next six months. While we believe in the long-term viability of EVs, we have concluded that the market is growing too slowly to sustain a stand-alone business at this time. "

form of mechanical energy is simply not a safe thing to do. In the event of a crash, all the mechanical energy must be released almost instantaneously. While mechanical storage proponents may debate this, we do not believe it is a safe process.

Then we have ***chemical*** energy storage, which covers a wide range of possibilities, including hydrogen fuel, ethanol, and batteries. In all batteries, the energy is stored in a chemical medium, either lead-acid, or some other technology such as lithium-ion.

Direct ***electrical*** energy storage is not yet practical on any large scale. Electrical can either be stored as an electric field (in a capacitor) or magnetic field (lossless inductor). Supercapacitors have advanced

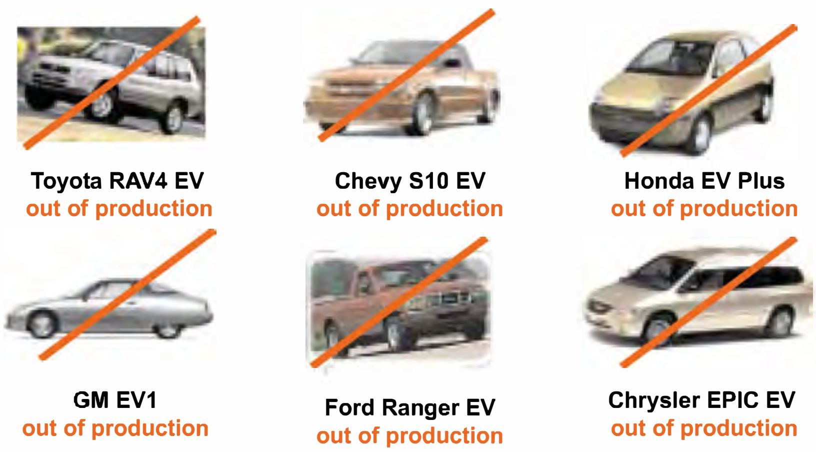

Fig. 4 The status of electric cars today - all of the production vehicles have been discontinued and/or recalled.

tremendously, but cannot yet provide the energy storage needed for automobile use. They are useful for temporary storage, and for filtering peak power requirements to reduce the draw on other power systems.

Now we will look at where today's research is headed. First, we will explore hydrogen fuel, and where the technology stands as it relates to the hybrid car. Then, we will discuss the reemergence of the all-electric car in a new package.

Hydrogen Fuel Cell Technology

The politics, money, and marketing today are revolving around the hydrogen fuel cell. Oil companies, automobile companies, and governments are behind a massive effort to develop the technology, and convince us all that this is the way to go. And the surface assessment of fuel cell technology can be very misleading.

The typical car engine runs less than 20% efficient today. The ideal fuel cell is, according to thermodynamic principles, 83% efficient.

And that's as far as most analysis goes when touting the hydrogen economy. It's four times more efficient, there's plenty of hydrogen around in common water, and it burns cleanly to produce water vapor. The fact that you need to make and store the hydrogen safely and efficiently is a detail that's overlooked in most industry marketing.

An article in the Atlanta Journal and Consitution February 11, 2005 edition states, "The 2005 concept car generating the most buzz in the auto industry is General Motors' hydrogen-powered Sequel." Later in the article, it says, "Shell Oil company, which produces 7,000 metric tons of hydrogen daily, believes fuel cell cars are clearly in sight. Shell has the only hydrogen refueling station in the country in Washington, D.C., but said it will build another refueling site in New York city, with the goal of providing one more somewhere in between to create an East coast hydrogen corridor." This is very reminiscent of the early days of the electric car where a few dozen fuelling stops were installed, with the hope of an infrastructure that never materialized.

It makes sense that Shell Oil, a major player in a very finite resource, would get involved in alternative fuel such as hydrogen. They are producing large amounts of hydrogen from the process of refining oil into gasoline. By using both, this marginally extends the current energy resources derived from oil. What happens when the oil is gone? Perhaps by then, other methods to produce and store hydrogen will be in place. If an infrastructure is in place, it will allow us to continue buying fuel for our cars much like today. This is great for the fuel companies and their future, but what about the consumer?

Hydrogen Storage and Safety

The first perceived problem with hydrogen vehicles is safety. When most people think about hydrogen energy storage, the Hindenburg disaster of 1936 comes to mind. While this seems an obvious reason not to put large amounts of hydrogen in a moving vehicle, there has been a concerted PR effort recently to clean up hydrogen's negative image.

According to the National Hydrogen Association, a group dedicated to promoting hydrogen as the energy storage medium of the future, the Hindenburg disaster was NOT caused by hydrogen fuel, but by a highly flammable varnish on the dirigible. While this may be true, there will still be a tremendous public relations effort needed to get people to accept hydrogen tanks in their car and houses. And, when the first accident

Figure 5: Proponents of the hydrogen economy envision a happy, pollution-free system where fuel is plentiful, clean, and based on the same traditional methods of distribution and usage as today's gasoline vehicles. Their arguments are very convincing, but flawed.

occurs, with injuries due to fire, it will be difficult to forge ahead. It doesn't necessarily mean that hydrogen is less safe than gasoline, of course. If gasoline were invented today, the gas-powered car would probably be unacceptable to the public.

Researchers are trying to find hydrogen storage alternatives such as metal hydrides, nanotechnologies, and glass beads[4]. All of these technologies add weight, cost, and inefficiency to the fuel system, and it is too early yet to assess the economic or technical viability of each. Right now, the only functional solution for hydrogen storage for fuel-cell cars is in the form of compressed gas or liquid hydrogen.

Hydrogen looks like a great storage medium when you look at its energy storage density, which is about three times that of gasoline, by weight. But we have to also assess the volumetric storage density of hydrogen. While it has 2.6 times the energy storage of gasoline per unit weight (33 kWh/kg versus 13 kWh/kg), the inherent lightness of it makes it take up far more volume– it is in fact about 11 times lighter than gasoline when in liquid form.

The increased volume is made clear by the picture of a proposed hydrogen-fueled plane in Figure 7. The gas crisis may have a big impact on car design, but that is nothing compared to the impact it will have on the aerospace industry. Even today, we have alternatives for the car that could be implemented very quickly. We do not have good alternatives for air transportation. There is a case to be made for conserving our limited supplies of gasoline for the industries that really need it, such as aerospace, long-haul ground transportation, heavy equipment, and petrochemicals.

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Storage of hydrogen and range is something that is not talked about much by the proponents of the hydrogen economy. Liquid hydrogen needs four times the volume to store the same amount of energy as gasoline. And, a liquid hydrogen tank would need to be a cryogenic container that would require insulation. As heat leaks through to the insulated container, the hydrogen liquid must be allowed to boil off to maintain the low temperature, resulting in hydrogen leakage of about 2% per day. That is not acceptable in a home environment.

Fig. 6: Recent studies have shown that the Hindenburg disaster was not caused by hydrogen, and would have happened even with helium aboard. Whether this helps make the public more accepting of the technology remains to be seen.

A compressed gas tank is even larger. At 5,000 psi, the Honda FCX needs a 40 gallon fuel tank to run just 170 miles (about 4 kg of hydrogen). Researchers are looking for ways to increase the pressure of the tanks to 10,000, or even 20,000 psia to increase the driving range. The additional energy needed to compress hydrogen will consume more renewable resources, and reduce efficiency. The hazards of storage and technical difficulties of making containers are topics that consume much of the present government funding.

Hydrogen Efficiency

The other achilles heel of hydrogen is efficiency. The theoretical fuel cell efficiency is 83% in converting hydrogen fuel back to electricity but actual numbers are considerably lower. Numbers in the 40% range are actually achieved in automobile use[6]. This is not the high-efficiency number that has been promised– in fact, it's no better than modern diesel engines.

Fig. 7: The Cryoplane would run off liquid hydrogen, cooled to -253 degrees Celsius. Liquid hydrogen is essential for energy storage density, but even then, the new fuel tanks above the fuselage add substantial volume to the plane design. The fuel storage tanks need to be four times the volume of gasoline fuel tanks.

According to a May 2004 presentation by Teledyne Energy Systems[5], the goal for hydrogen generation from electrical energy via the process of electrolyis is 58%. This is to pressurize the gas to 5,000 psia, required for reasonable fuel density.

The Honda FCX requires 4 kg of hydrogen (about 132 kWh) to drive just 170 miles, confirming the current fuel cell efficiency numbers. In contrast, the all-electric Volvo 3CC concept car travels the same distance on just 50 kWh energy storage.

The big problem is this: the overall efficiency of generating the hydrogen fuel, compressing it, and burning the hydrogen in a fuel cell is projected to be about 20-25%. If the source of the hydrogen energy is to be the power grid, then 75-80% of the power will be wasted in creating the hydrogen and burning it.

The net amount of energy needed from the utilities to fuel a hydrogen car will be 300-600% higher than that needed by the all-electric car. Given the impending depletion of oil reserves, this seems very impractical.

Let's shift back to the all-electric car and see what has been accomplished with today's technology.

The Ultimate Electric Car Specs

If we are ultimately going to run cars from the power grid, it makes much more sense to store the energy in batteries for efficiency. So the question is, can an electric car be built on batteries with acceptable range, performance and recharge options?

Let's suppose you could have an electric car with the following performance specifications:

Top speed: 85 mph

Acceleration: 0 - 60 mph in 4 seconds

Driving Range: 300 miles

Cost of Refill: $4-6 (2004 dollars)

Weight: <2000 lbs

Charging infrastructure: Already established

Charging stations: Any Electrical Outlet

Anyone looking at these specifications in 1995 would have regarded them as impossible. Investment in such a vehicle, if it existed, would have exploded, and we would be on a very different path to the present.

Unbelievably, this has all been achieved in a single car designed and built by AC Propulsion's[7] Alan Cocconi, who designed the prototype electronic drive system for the first GM electric car. He was working for Hughes Aircraft, which later became a part of GM. The first all-electric car that he worked on used lead-acid batteries and Mosfet switches.

As GM picked up the technology, Cocconi felt the need to remain part of a smaller autonomous company, and he also disagreed with the inductive charging philosophy adopted by GM. He believes that this is one of the factors that led to the ultimate demise of the infrastructure to support the EV.

He then started his own company, AC Propulsion, which has persistently pursued the goal of the all-electric vehicle. In a stroke of marketing genius, he realized that the best way to get the public's attention was to produce a car that was all about performance– the tzero.

The tzero has literally trounced the competition at alternate fuel car events around the world. It accelerates faster than the top class Ferrari, and can be charged from standard electrical outlets, at a small fraction of the cost of gasoline. And it can drive 250-300 miles with ease.

Despite this, there has been little more than sporadic interest from the big automakers in pursuing this product. One of the reasons is a reluctance from carmakers to go back to the all-electric car after denouncing it as a failure. It seems that the big companies abandoned the electric car programs just before they became truly viable.

Lithium-Ion tzero Power Electronics

The electric power of the tzero comes from lithium-ion cells identical to those used in modern laptop computers. The cells are packaged in the sidewalls of the car. Figure 9 shows the parallel assembly of 68 of these batteries into modules. 100 modules are connected in series to form the power pack for the tzero, with a total of 6,800 cells. The battery assemblies combine to give between 330 and 420 volts at up to 500 A. It sounds like a lot– but for each battery cell, it equates to a small current no more than 10 A under full power.

The battery pack of the tzero is probably overkill, designed to reach the magic number of 300 miles range, which matches the gasoline-powered car. In reality, half this range is probably sufficient, and only 3000 cells are used in the Volvo concept car, described later.

A conventional three-phase motor drive topology is used, as shown in figure 10a. Amazingly, the tzero uses standard TO-247 packages for the main drive switch. Twelve 600 V, 85 A IGBTs from International Rectifier are connected in parallel to form a single power switch, as shown in Figure 10b. The second set of twelve switches in this figure complete the power switches for one phase, and three of these modules complete the drive. Each driver board contains current sensing, protection logic, and transformer-isolated gate drives for robust performance.

Fig.8: AC Propulsion's Li-Ion tzero provides all the range and performance specifications that could not be achieved with the first go-around with electric vehicles.

This use of multiple parallel switches is a trend we see all over the power electronics world in the most advanced systems. Thermal load spreading, RF layout improvement and individual protection can be achieved with smaller parts. This approach works much better than the typical brute-force designs that use large modules for power switches.

The schematic of Figure 10a shows two additional contactors, K1 and K2, which allow the drive system to double as a charger for the battery. K1 is closed and K2 is open for normal motor drive operation.

When charging, K1 is opened, and K2 connects the circuit to the input power line. The switches of the main bridge are then used to run the charger. The motor windings are cleverly used as the power inductor of a single-phase PFC boost converter, operating directly from the AC line. This allows charging at up to 20 kW (more would be possible with a three-phase feed, and increased control complexity) with almost no additional cost in terms of parts, weight, and size. Using the motor windings saves considerable size and weight, and the only penalty is that the motor windings need to be suitably insulated.

The main drive motor, shown in Figure 11, is a custom-designed and built, 90% efficient, copper-rotor induction motor weighing 50 kg (110lbs). It produces 225 N-m (165 ft-lb) of torque from zero to 5000 rpm.

First Test Drive of the Li-Ion tzero

Excerpted from a report on the AC Propulsion Web page

"Wednesday, August 27th, 2003, the Li-Ion tzero was driven for the first time. The 90-mile test drive included climbing to the top of Mt. Baldy road, a 40-mile loop including a climb to 6000+ feet elevation, and a 35-mile highway loop at 70-75 mph. At the end of the test drive less than 1/3 of the measured battery capacity had been used. During the test drive, the tzero battery exhibited excellent voltage uniformity, excellent temperature distribution and control, and high discharge rate capability. The Mt. Baldy trip gave the highest regenerative energy recapture ratio that we have ever observed, demonstrating the high cycle-efficiency of the cells.

The weight of the tzero is reduced to under 2000 pounds, providing significant improvements in acceleration, handling, and efficiency. As a complete car, the Li-

Fig. 9: AC Propulsion's Li-Ion battery pack components for the tzero. 6,800 cells are used in parallel-series combinations to provide the needed energy storage.

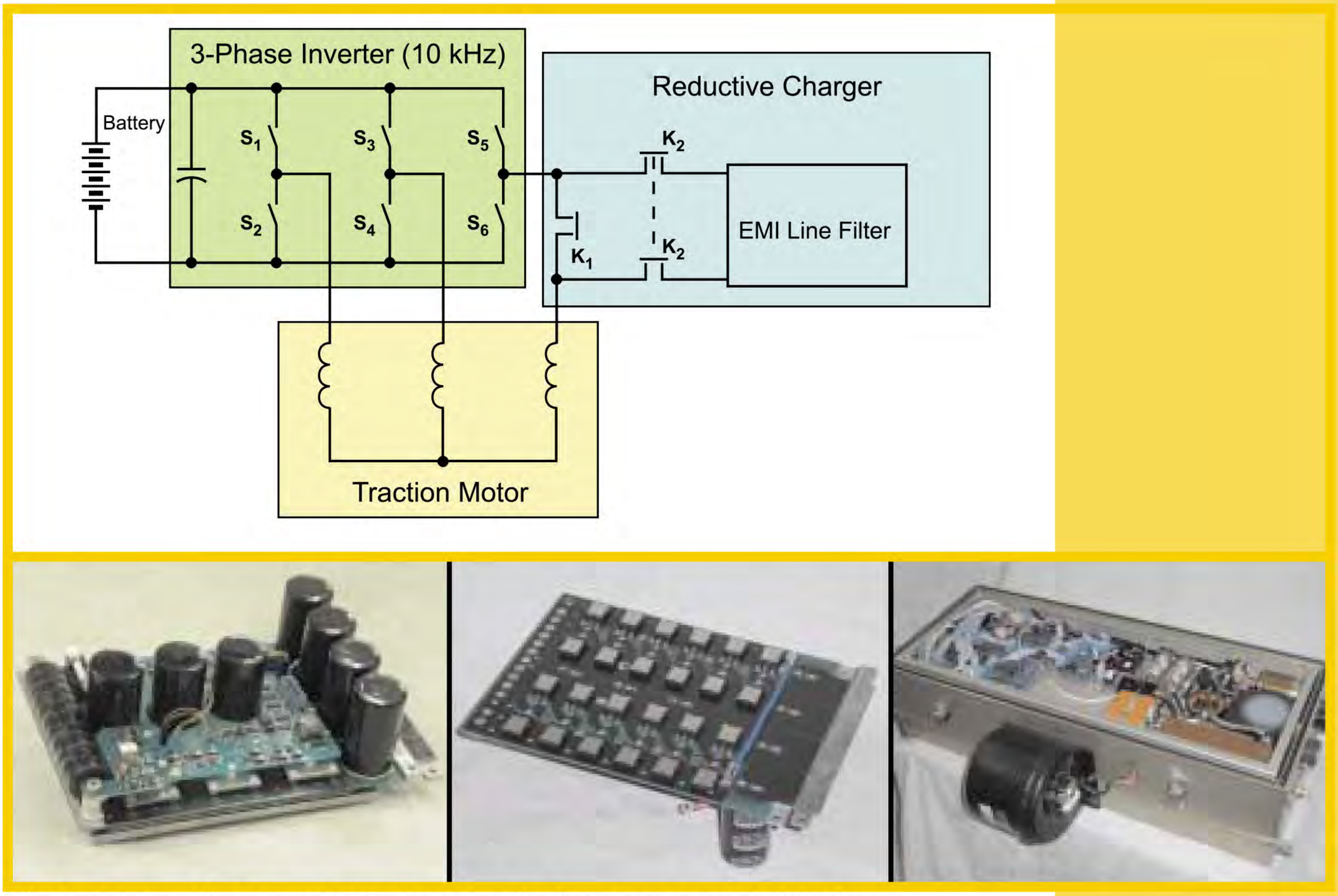

Fig. 10: AC Propulsion's Power Electronics Design. The three-phase motor drive is implemented with 12 parallel IGBTs in TO-247 packages for each of the switches, S1 - S6.

ion tzero has higher specific energy, in Wh/kg, than the Toyota RAV4 EV battery pack alone.

This first drive confirms the benefits of Li-ion batteries, demonstrates the usability of small, commercial, off-the-shelf Li-ion cells for automotive applications, and increases our confidence in the techniques we have developed for assembling them into automotive packs.

Testing and development of the Li-ion tzero continue. The results so far justify our moving forward with plans for design and development of other vehicle applications for this technology."

Fig. 11: AC Propulsion's 200 hp Traction Motor. Total weight is only 50 kg. and the motor is 90% efficient. The cost advantages of implementing this type of motor in place of a conventional gasoline engine are obvious.

Racing Against the Best

Cocconi took his tzero to Silicon Valley to demonstrate to entrepreneurs and investors the concept of a high-performance, environmentally-sensible, silicon-intensive automobile. AC Propulsion's tzero out-accelerated a Ferrari F355, a new Corvette, and a Porsche Carrera 4 in a series of impromptu 1/8 mile drag races. The 200 hp tzero accelerated to 60 mph in 4.1 seconds, demonstrated a fuel efficiency equivalent to 70 mpg, and zero emissions. After numerous impromptu races with different drivers and cars, the tzero began to attract signifi-cant attention.

Battery Technology

The major turning point in the development of the practical electric car was the change from lead acid to lithium-ion batteries. This dropped the weight of the tzero by 500 lbs, while tripling the driving range.

Lithium-ion batteries have been optimized for computers and other small electronics devices. They have an aging problem, however, about which most manufacturers keep understandably quiet. After a year, some degradation is noticeable, regardless of whether or not you use the battery. After 2-3 years, the battery fails.

The lifetime issue needs specific research, especially as it pertains to the electric vehicle. It will typically be called upon for power less than 1 hour a day, and usually charged slowly over a period of 8 hours at night. Right now, research focuses more on cost reduction and size reduction, since the actual lifetime of 2-3 years for most electronics is already acceptable.

Figure 14 shows progress on the storage capacity and price of lithium-ion cells suitable for the electric vehicle. While the energy capacity seems to be reaching a plateau, the cost continues to be driven down linearly. It remains to be seen how low this will go in the limit.

The cylindrical, 18650 cell (18 cm diameter, 650 mm length) is the most effective choice of lithium-ion batteries in terms of cost per energy storage. It's the cell used by AC Propulsion in their car.

If battery lifetime is improved, and capacity is almost resolved, there is still the issue of cost. Time will tell how effectively these can be solved, but the technical difficulties and margins of improvement needed are nothing compared to the challenges faced in moving forward with a hydrogen economy.

Making and storing electrical energy is much, much easier, safer and interchangeable. It may be charged and discharged as needed. The infrastructure is in place. We just need better batteries. While we don't anticipate transformational breakthroughs, it would seem that in the next 5 years, with sufficient funding, it would not be unreasonable for the price to drop another factor of 2 with mass production, and energy density to climb by perhaps another 50%, with a 2:1 lifetime improvement.

Fig. 12: The tzero out- accelerated a Ferrari F355, Porsche Carrera 4, and Corvette.

Fig. 13: dual AC Propulsion Drives powered this car to set the electric land speed record at 245.5 mph in October, 1999.

Efficiency of the battery-powered vehicles has never been an issue. It is relatively easy to get numbers in the 90% range for charging and discharging the battery directly from the grid. This is far better than the number for the hydrogen economy. The numbers have been proven in EPA testing, where overall energy efficiency for production prototyped have measured four times better for the battery vehicle than the hydrogen vehicle.

The final advantage for battery storage comes in the form that we can all understand easily enough-price of refueling. Figure 15 shows the cost of different fuel sources, based on present energy prices. (Note that the cost of hydrogen fuel does NOT include the cost of transportation and infrastructure.)

Integration of the Electric Car with the Electrical Grid

The usefulness of the battery electric car does not stop with energy efficiency. AC Propulsion proposed using the car as part of a massive distributed energy storage system to alleviate power line problems in parts of the country that are power limited.

For short periods of time, even a modest fleet of vehicles, connected to the grid, and under the control of the utility, could alternately provide additional energy when needed to supplement the grid, and recharge when power demand reduces. Not only could cars provide a massive reserve of energy when needed during peak demand periods, but they could also be used as local regulating units.

Normally, regulation of the power grid is done by issuing commands to one generator or another to produce more or less power. Response time is very slow, and this gap could be filled with the rapid response of the distributed generating capacity of cars.

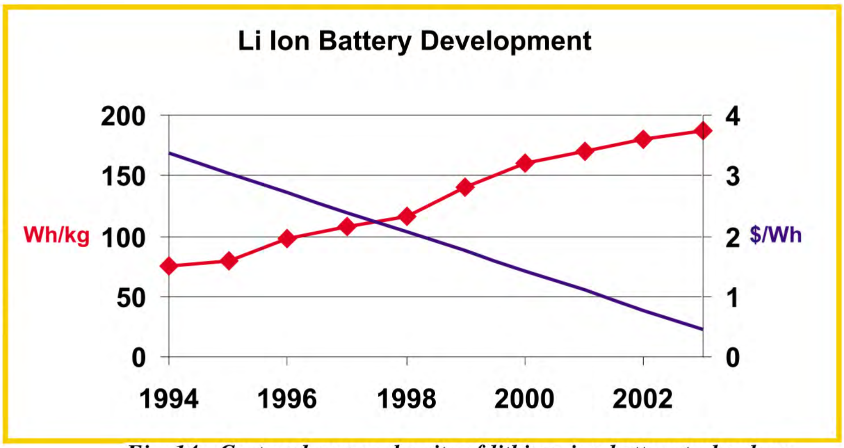

Fig. 14: Cost and energy density of lithium-ion battery technology.

While this idea may initially seem far-fetched, it has been shown to be very viable. In fact, the energy savings that the utilities gain from this is something they would actually pay for, and it is not a stretch to have a scenario where cars are interconnected most of the day, helping the grid, and charging of the batteries after depletion from driving could be *completely free*.

Changing the entire US fleet of personal automobiles to battery power seems like a massive increase in capacity needed from the power grid. But, in fact, the increment of power over standard household usage would only be about 10-25%. And with changes in fuelling habits (plug it in at night instead of going to a fast-charge station) there would be little, if any, additional peak capacity needed from the utilities.

Figure 16 shows the variation in electrical power demand during the day. As you can see, the fluctuations are substantial, and the excess capacity at night could absorb charging of batteries with ease. Hypothetically, you could switch 50% of California's cars to electric overnight without increasing peak generating capacity.

Being able to integrate this easily with bidirectional power to the grid is a unique advantage of the battery-powered car. It would not be hard to persuade owners of vehicles to allow the utility to shuttle energy in and out of their battery, especially if it provided them with a cost break on the energy.

It's harder to imagine this being accepted by the owners of hydrogen cars. You can only move the energy in one direction– from the car to the grid, since there is no practical hydrogen generator possible on board the car. Interfacing with the grid, and helping with peak power requirements would require additional trips to the fuelling station for the car owner.

AC Propulsion's Tom Gage sees cars as coming standard with the following in the year 2020:.

- Most new vehicles come equipped with standard grid power connection
- Vehicles connected to grid from home and workplace
- Peak grid power needs are met with vehicle-based generation and/or storage.
- Vehicles provide valued ancillary services to the grid, offsetting operating costs
- Vehicles provide high-reliability power for businesses and uninterruptible power for homes

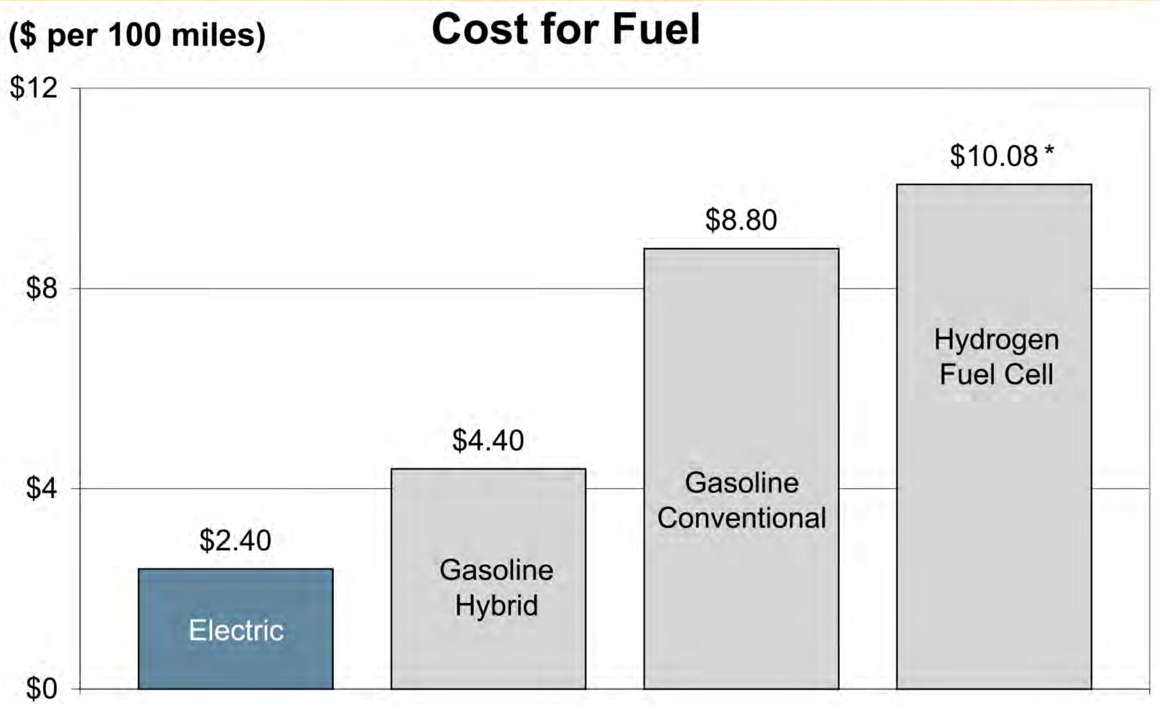

Fig. 15: Cost and energy density of lithium-ion battery technology.

* does not include transportation and infrastructure cost for hydrogen

Integration by Car Companies

Not all car companies have lost interest in the electric car. Volvo showcased the all-electric 3CC concept car at the 2004 Michelin Bibendum Challenge in Beijing, China[8]. Volvo's car showed that the ideas proposed by AC Propulsion can indeed be turned into a realistic product. Despite the success of this concept car, Volvo does not have any immediate plans for production. Perhaps the venue for the showcase of the Volvo was significant. China is set to enter the US car market in

2007– perhaps an enterprising Chinese company, unfettered by political pressures, will be the first to produce a mass-market electric vehicle. The elegant Volvo 3CC is shown in Figure 17.

The Volvo 3CC has the AC Propulsion drive system, and features front wheel drive, with double wishbone front and rear suspension. The front suspension includes horizontally mounted adjustable coil over shocks that give a low hood line. The rear suspension includes vertically mounted adjustable coil over shocks. The range of this car is about 170 miles, and the acceleration is 0-60 in 10 seconds.

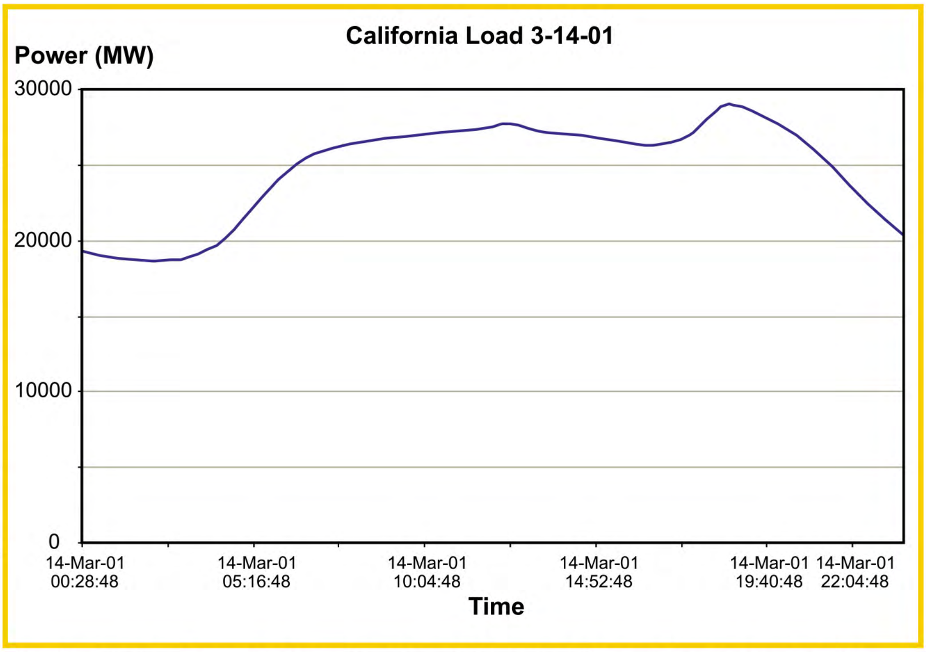

Fig. 16: California power demand for March 14, 2001. The variations in demand show that the present generation capacity is sufficient to power a major shift of the US personal driving fleet to all-electric.

Another specialty car, also with unknown production plans, is the Venturi Fetish.[9] This high-performance sports car, shown in figure 18, also uses the AC Propulsion drive.

For both of these cars, the issue faced is whether the price can be brought down low enough to be attractive.

The fourth and final tzero car, presently in mothballs, would sell for about $250,000 if a buyer comes forward. Making automobiles in small quantities has never been a low-cost venture.

What Does the Future Hold?

To the car companies that participated in the first round of modern electric cars, there is no future for the all-electric car. Production has ceased. Demand for all-electric cars has not ceased, though. In fact, as we are writing this, there is a vigil going on in southern California to prevent the destruction of the last of GMs electric cars.

The mass application of the electric car still hinges on battery issues. Can lithium-ion batteries be made to last longer? Can the storage density be increased? And can the cost of the batteries be made low enough? While we don't know the answers to these questions, the risk seems much lower than trying to shift to a totally new technology such as hydrogen where the technical barriers are far higher, and efficiency is questionable.

The other issue is cost. Any new technology or venture is extraordinarily expensive to introduce, and cost only can be driven down when gearing up to make millions of a product over which the fixed manufacturing costs can be amortized.

Overall, it would seem the both the technological, economic, and environmental issues weigh heavily in favor of the electric car. As a minimum, there should be a balance of investment in hydrogen and battery-powered vehicles. This would provides billions of dollars to optimize the battery technology for long life and energy storage needs. Tom Gage is confident that the issues with lithium-ion can be solved, providing the best alternative for our future.

AC Propulsion founder and president, Alan Cocconi, received his engineering degree from California Institute of Technology.

As an engineering consultant, he developed the drive and solar tracking systems for the GM SunRaycer which won the 1987 World Solar Challenge, a cross-country race for solar powered vehicles held in Australia. He then designed and built the controller for the original GM Impact that was introduced at the 1990 LA Auto Show and which has since evolved into GM's EV-1.

For some early history of Alan Cocconi's connection with the GM Sunraycer and Impact, see Chapter 2 of Michael Schnayerson's book, ***The Car that Could***.

Fig. 18: The Venturi Fetish was showcased at the Paris Auto Show in 2002. This 2-seater also uses the AC Propulsion drive system.

Fig. 17: The Volvo 3CC concept car was showcased in Beijing in September 2004. This car features the AC Propulsion drive system, and has a range of 170 miles. Production plans are unknown.

Useful Online Resources for more Information:

1. Oil production information:
   www.hubbert peak.com/campbell/
2. Switching Power Magazine Volume 1, Issue 2
   www.switchingpowermagazine.com
3. Hydrogen fuel cell investor:
   www.h2fc.com/news.html.
   More political clout behind the hydrogen approach
   www.hydrogenus.com/
4. Hydrogen storage in glass beads
   www.fuelcellsworks.com/Supppage1764.html
5. Teledyne Energy electrolysis generation:
   www.eere.energy.gov/hydrogenandfuelcells/pdfs/review04/hpd_16_cohen.pdf#search='hydrogen%20generation%20efficiency'
6. Hydrogen fuel cell efficiency measurements:
   www.zuyev.com/FCreport.pdf#search=measured%20fuel%20cell%20efficiency
7. AC Propulsion Web Site:
   www.acpropulsion.com
8. Volvo concept car:
   volvocars-pr.com/index.asp?par=conceptcars&pag=overview&model=194&lang=1&flash=0
9. Venturi electric car:
   www.venturi.fr/us/fetish/specs/specs.php3