Review of the 2008 APS Energy Study, *Energy Future: Think Efficiency*

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Shortly after the oil embargo of 1973-74, the American Physical Society played a significant role in advancing U.S. energy policy with its study, Efficient Use of Energy (AIP Conference Proceedings 25, 1975). Now we have reached another crisis time, when US security is threatened by its heavy dependence on imported oil (an issue that contributed to Gulf Wars I and II); when urban air has improved but could be better; when U.S. oil imports cost $250 billion/year (2% GDP at $50/barrel); and when concern grows over carbon-induced climate change. The APS study examines energy use in buildings (36% of US carbon emissions) and transportation (32% of US carbon emissions).

The time was ripe for the APS to take a fresh look at energy efficiency. An APS panel has just produced a report, Energy Future: Think Efficiency, which will be published in the Reviews of Modern Physics and it is now available at www.aps.org/energyefficiencyreport/index.cfm. This APS study was chaired by Nobel-Laureate Burton Richter with a distinguished committee of knowledgeable physicists and engineers. The study examines energy use in buildings (36% of US carbon emissions) and transportation (32% of US carbon emissions). The report stresses that "making major gains in energy efficiency is one of the most economical and effective ways our nation can wean itself off its dependence on foreign oil and reduce its emissions of greenhouse gases." I am comfortable with the APS study conclusions given below. One can really only debate the timing of events. That is, one can ask when (not if) will the lithium battery propel autos at a competitive cost? The future cost of gasoline is as important as the future cost of batteries in this calculation. The day of economic competitiveness for journeys of forty miles is not far away, and it will be hastened with large-scale production economics.

Energy Efficient Cars: Automobile efficiency improved by 20% (from 36 to 43 ton-miles/gallon) over two decades (1985-2005, Figure 6; Figure numbers refer to the APS report).

But, over the same period of time auto fuel economy (FE) stagnated at 28 miles/gallon (mpg). The APS study finds that improved internal combustion cars and hybrids could obtain 50 miles/gallon by 2030 by weight reduction and engineering (p. 33). Perhaps this is too cautious a time frame. If we reduce the weight of cars and remove the special regulatory status of SUV's, considerable progress can be made. Car weight dropped from an average of 4100 pounds in 1975 to 3200 pounds in 1980, but sadly it returned to the former 4100-pound level in 2004. What happened is that improved car efficiency and reduced mass easily satisfied the Corporate Average Fuel Economy (CAFE) standard of 27.5 mpg by 1985. But then further progress in fuel efficiency was dedicated to increasing the engine mass (horsepower) to reduce acceleration time to 60 mph from 14 seconds to 10 seconds.

The APS study notes that "a 10-percent reduction in weight, for example, yields a 6 to 7 percent increase in fuel economy." Thus, reducing car mass by 22% back to 1980 levels increases fuel economy by 15%. The 1.15 factor gain in fuel economy translates to reducing fuel consumption by 13%. Energy savings is not proportional to fuel economy (miles per gallon), but to the inverse of fuel economy (gallons per mile). Consider the case of two cars with fuel economies of 10 mpg and 20 mpg. If the two cars travel 20 miles each, one consumes 1 gallon and the other consumes 2 gallons for a total of 3 gallons. The forty-mile trip consumed 3 gallons, for a fleet average of 13.3 mpg. Note that the fleet average of 13.3 is lower than the numerical average of 15 mpg, closer to the guzzler at 10 mpg than the car at 20 mpg. This makes good physics sense, and that why CAFE standards impose limits on fuel economy rather than fuel efficiency.[1]

CAFE Scenarios: In this section I estimate energy savings from the APS study conclusions, placed into a table below, comparing fuel economy, inverse fuel economy and the fractional and barrel savings from 2007 (before collapse) when light vehicle sales were 50% cars at 28 mpg and 50% SUVs, minivans, and light trucks (SUV+) at 22 mpg. This gives a 2007 fleet average fuel economy FE of 24.6 mpg, much closer to SUV's (22 mpg) than cars (28 mpg). Next consider the case of the entire light vehicle fleet as having the same fuel economy as cars (SUVs at 28 mpg). Then consider the fleet at 35 mpg by 2020, as mandated by the 2007 CAFE standards (42 mpg in California?). The new fleet might consist of improved internal combustion (IC) engines and hybrids. Next we look at 50 mpg by 2030, a goal that the APS study concludes (p. 33) "is achievable if technological improvements are focused on reducing fuel consumption" with a mix of cars with fuel economies typical of today's hybrids. Then I consider advanced hybrids at 90 mpg by 2030 (p. 32). Lastly consider all cars to be plug-in electric vehicles with 40-mile batteries, saving 60% of vehicle miles (Figure 37). Since the miles saved are urban miles, we arbitrarily raise this to 65% savings. In the table below we obtain the steady-state (after 10-20 years) savings by multiplying the fractional savings times the light vehicle consumption rate of 9.3 Mbbl/day. The results show that the US can save more than 50% of petroleum used in cars. This could be done with plug-in electrics or very good gasoline hybrids.

Mass and Safety: The mass, momentum and aggressive design of a Hummer can severely inflict damage on a Prius in a crash. But, a Prius hitting a Prius, with good engineering and ample "crush zones," is similar, to first order, to a Hummer hitting a Hummer. From conservation of momentum, we know that a light car with half the mass of a heavy car experiences twice the velocity change (twice the deceleration and twice the force on humans) of the heavy car. The APS study points out (p. 35) that "the linkages among fuel economy, vehicle size, weight, and safety are manageable and are more a function of smart vehicle design than any other single factor." Some researchers conclude that "reducing vehicle weight while maintaining the key dimensions of wheelbase and track width could decrease the total number of fatalities." The increased volume of crush-zones reduces deceleration and increases safety.

Plug in Electric Cars: If all cars had 40-mile batteries, 60% of vehicle miles would be powered by electricity and not gasoline (Figure 12). The savings in carbon emissions would be less than 60% since 50% of US electricity is generated from coal. APS recommends (p. 41) the following: "Time-of-use electrical power metering is needed to make charging of batteries at night the preferred mode. Improvements in the electrical grid must be made if daytime charging of electrical is to occur on a large scale or when the market penetration of electrical vehicles becomes significant." Thus, in the near term, the smart grid is not needed, but it will be needed in the future with more electrical cars and with more solar and wind renewable power that varies during the day. The plug-in electric car is a good fit with the grid since it can use wasted electricity from base-load power plants operating at night, and it can use wind power, since charging is not concerned with fluctuations of wind power. A smart grid of the future could vary the rate of charging batteries, helping to stabilize the grid from the fluctuations of wind power.

Chevrolet Volt: The Chevrolet Volt is scheduled to enter the market in 2010 with the capacity to drive 40 miles on electrical energy stored in a lithium battery. The Volt is a plug-in, series-hybrid electrical vehicle (PHEV) that is propelled only with its electric motor, the first forty miles on electricity from the grid and successive miles from gasoline converted into electrical energy. The Volt it is not a plug-in parallel-hybrid

Situation	**fraction at FE**	**fleet FE**	**fleet 1/FE**	**Savings**	**(%, Mbbl/day)**
2007	fi = 0.5, 28 mpg fi = 0.5, 22 mpg	24.6 mpg	0.0406 gpm	0	0
SUV = car	fi = 1, 28 mpg	28 mpg	0.0357 gpm	12%	1.1 Mbbl/day
2020	fi = 1, 35 mpg	35 mpg	0.0286 gpm	30%	2.8 Mbbl/day
hybrid std.	fi = 1, 50 mpg	50 mpg	0.02 gpm	51%	4.7 Mbbl/day
hybrid(2030)	fi = 1, 90 mpg	90 mpg	0.0111 gpm	73%	6.8 Mbbl/day
all PHEV	fi = 1, 40-mile battery			65%	6.0 Mbbl/day

that is propelled by both the motor and the IC engine. After its battery has been drained, the Volt only uses its three-cylinder IC engine to recharge the battery. The advantage is that the IC engine operates only at its optimal operating point (RPM and torque), which has a reasonable efficiency at that point. IC engine efficiency drops quickly when operating away from its optimal point. Electric motors have a much broader region of high-efficiency operation than do IC engines. The Prius battery has a capacity of only 1.3 kWh, to drive but 4 miles without being recharged. The 40-mile Volt battery has a capacity of 28 kWh, which is twice the minimum size to prevent deep discharging of the battery. Today, this battery costs about $20,000, but it is generally believed that increased production rates will cut the cost to $10,000.

Simple Economics of Electric Cars: Let's use the APS study's results for some basic economics. I am on a list to buy a Chevy Volt. I am not sure if I will buy the Volt at the projected cost of $40,000, but I plan to buy if it costs $30,000. Because of my interests I have carried out some basic economics below. Let us assume travel of 10,000 miles per year in urban traffic at 40 miles/day, five-days per week all year. The APS study states that the off-peak electricity costs in California are about 3 cents/mile (p. 38), or $300/year. We will ignore the cost of this operating electricity since a typical IC car has this magnitude of expense because of its many moving parts. At 33 mpg, a car consumes 300 gallons a year, which costs $600/year at the current price of $2/gallon, or $1200/year at $4/gallon (a year ago), and $1800/year at $6/gallon (in Europe). These savings on gasoline must be compared to the cost of buying the battery pack (and associated equipment) and the interest paid during the lifetime of the battery. At tomorrow's battery price ($10,000), the capital recovery rate at 5% interest on a 20 year loan is 8%/year.[2] The annual cost is then 8%/year times the cost of the battery of $10,000, or $800/yr. Of course, the battery may only last 10 years, then the capital cost recovery factor grows to 13%, raising the annual cost of $10,000 battery to $1300/year. Let's also double these figures for today's batteries at $20,000. Let us take the favorable case first: The all-electric car with a $10,000 battery with a 20-year life costs $800/yr. That's only $200.year more than the cost of operating an IC engine at $2 gasoline ($600/yr), but it is $400/year less than the cost at $4 gasoline ($1200/yr). The 10 year battery at $10,000 is a very good deal for Europe. Things look darker with the present $20,000 battery, costing $1600/yr (20 yr) and $2600/yr (10 yr). Will the future bring a 20-year battery life? I would bet that in two decades, the price of gasoline will be considerably higher than today's $2/gallon in 2009 dollars and also higher than last year's $4/gallon. Recall, we used an IC engine car at 33 mpg. If we had used a more likely car at 25 mpg in the city, we would have consumed 400 gallons/year, raising the cost of the IC car by 33% to $800/yr ($2/gal), $1600/yr ($4/gal) and $2400/yr ($6/gal). Thus, an all-electric car looks like a safe bet once the "bugs" are out of the system. This conclusion is very scenario dependent. For those that drive 30,000 miles/year it should be very attractive, but recall that the battery drives only 40 miles/day on electricity from the grid, and then the Volt efficiently uses gasoline for the other 80 miles/day. For those who drive 5,000 miles/year, it is less attractive. Some will make the investment for sake of our local planet. Do we have to save all of our money for our children?

Cost of Conserved Energy: Another approach to determine the economics of saving energy is to calculate the cost of conserved energy (CCE), which is the annual cost of the capital investment divided by the annual fuel saved. This approach has the advantage that we do not speculate on future fuel costs, but merely determine what cost of gasoline would be needed to break even. We will not add in the $300/yr for electricity since we have avoided the maintenance of the IC car. The annualized costs are $800/year ($10k battery, 20 yr), $1300/yr ($10k, 10 yr), $1,600/yr ($20 k, 20 yr), and $2,600/yr ($20 k, 10 yr). We divide these figures by 300 gallons of gasoline/year, and obtain CCE of a gallon of gasoline of $2.70, $4.30, $5.30 and $8.70. At 25 mpg and 400 gal/yr, the CCE per gallon is 25% lower at $2.00, $3.25, $4.00 and $6.50. Remember, this is the cost of gasoline over the future 10 and 20 years. I estimate that the first three scenarios will be cost effective over that time period. It is only the expensive, short-lived battery at $8.70 and $6.50/gallon that would fail in the market place. There was a very nice debate in the letters section of APS News (p. 4, January 2009): Robert Levy wants the APS to be more bullish on the lithium battery, stressing that any problems with them are legal and political, not technical. The APS study chair, Burton Richer, responds that he thought the report clearly stated that the study group regarded plug-in electric vehicles as "one of the most important developments in the automotive industry to reduce both gasoline consumption and emissions." He goes on to say that "the batteries for the Chevy Volt…. are the first generation of a new Li-Ion battery and as such are not likely to be good enough for the FULL span of all the light vehicles on the road."

Lithium batteries: The APS calls for a more balanced portfolio "across the full range of potential medium- and long-term advances in automotive technologies, including plug-in battery electric vehicles." Lithium batteries are the only significant technical barrier to the wide-spread adoption of plug-in electric cars, which would be a significant improvement over the electric hybrids of today. We have adored our lithium batteries in our laptop computers, but yet we know that the $100,000 Tesla, which uses computer batteries, is too pricey for us. The good news is that lithium batteries are getting better and will, hopefully, power the Chevy Volt in 2010. The bad news is that Asian battery manufacturers appear to be doing better than the American counterparts. Recently, General Motors awarded a big contract for lithium batteries to a Korean firm and not to a US firm. This is one of the reasons why the APS study recommends (p. 38 and 88) increased funding for research and development.

Lithium Details: The APS report prints a schematic (Figure 16) from Venkat Srinivasan of Lawrence Berkeley National Laboratory, which compares the specific energy, specific power and acceleration for several vehicle power sources, including the lithium-ion battery. Srinivasan's Figure 17 gives estimates for the success factors for eight key parameters for lithium batteries. To discuss these parameters is useful, but most of us lack the details to understand fully their true meanings. For example, the efficiency of charging a battery decreases as its state of charge (SOC) is raised from empty to full. On the other hand, the efficiency of draining a battery decreases as it is drained from full to empty. Thus, there is an optimal point to operate the battery. A hybrid that continually drains and fills a smaller battery, keeping the SOC near 50% capacity, can do this better than a car with a 40-mile battery for a 40 mile trip. But if we want long range from a smaller battery pack, we would need to discharge the battery deeply, operating it in its less efficient mode. How much do deep discharges hurt lithium batteries? We have all occasionally emptied the battery of our laptops without noticeable damage. But on a daily basis is this wise? You can see that this discussion is just beginning. And are the 28-kWh lithium battery packs safe? (I believe they can be made safe in collisions, but this needs to be proven.) Will large amounts of lithium be available beyond Bolivia and China? Srinivasan's 2007 data is listed below in terms of the percent of goals achieved: Specific power (W/kg) is 100%; power density (W/m^3) is 100%; specific available energy (Wh/kg) is 80%; available energy density (Wh/m^3) is 80%; cycle life (cycles) is 70%; calendar life (years) is 60%; production price ($) is 55%; operating temperature range is 43%.

Hydrogen cars: The APS study gives a death blow to the hydrogen car which was part of the "Freedom Car" partnership between DoE and US automobile companies (2003) to promote high risk research on light cars to use less oil and generate fewer harmful emissions. The study group concluded the following (p. 39): "Hydrogen fuel cell vehicles are unlikely to be more than a niche production without scientific and engineering breakthroughs in several areas. The main challenges are durability and costs of fuel cells, including their catalysts, cost-effective onboard storage of hydrogen, hydrogen production and deployment of a hydrogen-refueling infrastructure." I am even more pessimistic about hydrogen cars than the APS statement. Clearly hydrogen from natural gas is not reasonable since natural gas is valued for other uses and is in relatively short supply. It takes electrolysis at about 50% efficiency to produce hydrogen energy, and then the fuel cell makes electricity at about 50% efficiency to propel the car. This approach is much less efficient than batteries charged from the grid. Charge/discharge efficiency can be 90%, but it will be less with a fast charge and it depends on the SOC of the battery. The APS POPA study, The Hydrogen Initiative, clearly pointed out these problems in 2004.

APS Facts on Energy and Buildings: Buildings (2005) account for 36% of US greenhouse gas emissions related to energy use and they consume 72% of the nation's electricity. But the buildings sector has little impact on imported oil. The four largest end-uses of primary energy in residential buildings are space heating (32%), air conditioning or space cooling (13%), water heating (13%) and lighting (12%), totaling 70%. For commercial buildings, the four largest end uses of primary energy are lighting (27%), space heating (15%), space cooling (14%) and water heating (7%), totaling 63%. Energy codes adopted in California since 1975 have resulted in energy savings of more then $30 billion, more than $2,000 per household. The energy needed to cool a new home declined by two-thirds to 800 kWh per year, although homes are about 50% larger than in 1975. The energy program at Lawrence Berkeley National Laboratory on advanced window coating and electronic fluorescent ballasts has saved consumers $23 billion, as well as additional savings from computer simulation modeling, house doctor technologies, new types of insulation, infiltration mitigation, passive solar and day-lighting technologies.

Zero Energy Buildings: In California a ZEB means a reduction of energy use to zero with better insulation, passive solar heating, solar daylighting and energy storage, plus electricity generated with renewable technologies, such as photovoltaics. The trend is definitely in this direction, but the goal line will still take some effort. APS concludes (p. 56) that "energy demand in the building sector could be reduced from the projected 30% increase to zero between now and 2030." Recall that there is much inertia in the building sector because buildings last for 50 to 100 or more years. The APS study concludes (p. 61) that "The goal of achieving significant levels of construction of cost-effective new zero-energy commercial buildings by 2030 is not obtainable without significant advances in building technology and without the development and widespread adoption of integrated building design and operation practices." The APS study points out (p. 66) that the US spends only $100 million/year for research on energy in buildings, less than the $250 million/year (today's dollars) spent in 1980. The APS study recommends (p. 71) that "Building energy standards, such as those promulgated in California, should be implemented nationwide. States should be strongly encouraged to set standards for residential buildings and require localities to enforce them. For commercial buildings, performance-based standards that rely on computer software to compare a building design with a reference building are implemented only in California. The federal government should develop a computer software tool much like that used in California to enable states to adopt performance standards for commercial buildings. States should set standards that are tight enough to spur innovation in their building industries."

Appliances: The progress has been phenomenal: Since 1975, refrigerator energy use has dropped form 1850 kWh/yr to 450 kWh/yr, saving 50 power plants with improved refrigerators and freezers. At the same time refrigerators have gotten 15% larger. This isn't the only low-hanging fruit, as energy for central air conditions has been reduced by 40% and that for furnaces has been reduced by 25%. And these opportunities are synergistic; a tightly insulated house can downsize its air conditioners. And as the price of electricity rises (as it will), additional improvements are feasible, making energy-savings a renewable resource. On the other hand, standby energy use in California has risen to 980 kWh/year (or 112 Watts), and corresponds to 13% of the state's total residential electricity use in 2006. This wasteful use of energy amounts to 70% of the 1400 kWh/year saved with an improved refrigerator. The APS study recommends (p. 71) that "DOE should promulgate appliance efficiency standards at levels that are cost-effective and technically achievable as required by the federal legislation enabling the standards." Apparently DOE has been slow moving in this area as the APS study comments that "A streamlined procedure is needed to avoid delays in releasing these standards."

Conclusions: The nation has received a thoughtful clarion call for action from the APS energy study. The APS study has examined the advancing technologies to reduce energy use at a profit to the nation. The APS report issues 17 recommendations that should be heeded as soon as possible. They are well-balanced, and based on facts and not hopes. For further technical details on many of these topics, I recommend the APS Forum on Physics and Society's conference proceedings, Physics of Sustainable Energy.[3] I appreciate comments on the draft paper by Jeff Abramson, Ben Cooper, Allan Hoffman, Barbara G. Levi, Peter Schwartz and Richard Scribner.

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Endnotes

1 *The CAFE formula, devised by Allan Hoffman in the 1975 EPCA law, determines the fleet-averaged fuel economy. The inverse of the fleet averaged FE is the sum, over all classes, of the ratio of its fractional population fi divided by the fuel economy of that class FEi, or* $1/\langle FE_{fleet}\rangle = \Sigma_i f_i/FE_i$. *Applying the formula to the case of the 10 mpg and 20 mpg cars, we obtain* $\langle 1/FE_{fleet}\rangle = (0.5/10) + (0.5/20) = 0.05 + 0.025 = 0.075$, *or* $FE_{fleet} = 13.3$ *mpg!*

2 *Capital recovery rate =* $CRR = i/[1 - \exp(-iT))]$ *where i is the interest rate (continuously compounded) and T is the lifetime of the battery. D. Hafemeister, Physics of Societal Issues (Springer, 2007), p. 412.*

3 *D. Hafemeister, B.G. Levi, M. Levine, and P. Schwartz, Physics of Sustainable Energy: Using Energy Efficiently and Producing it Renewably, AIP Conference Proceedings 1044 (2008), p. 438.*