Technological Solutions for Energy Security and Sustainability

Paul J. Werbos, Room 675
Directorate for Engineering
National Science Foundation[1]
Arlington, Virginia

1. Introduction

The United States and other energy-consuming nations face three major energy security challenges:

(1) Transportation fuel security: How can we make our transportation sector robust enough to be able to survive the possibility of a major price shock – with crude oil rising to $200/barrel or $400 or even more – at the soonest possible time?
(2) Daytime electricity: How we eliminate the need for us and our allies to import natural gas in growing quantities, in order to generate daytime electricity, as soon as possible?
(3) Baseload electricity: How can we help the world escape the grave long-term costs of expanding any of the three well-established options for providing the majority of the world's baseload electricity, as oil and gas become too expensive for that application: coal, nuclear fission with enrichment, or solar farms costing >$5 trillion/year more than what we now pay for electricity?

The next two sections of this chapter will propose a strategy for achieving each of these three goals, in this order. The third section will take a broader look and ask – what about the oil producers? What are their optimal strategies and stakes in this game? In the rest of this introduction, I will make some general comments about the background and approach.

This paper is basically an updated version of a previous paper on global energy sustainability (Werbos 2003) in the *State of the Future 2004*. The *State of the Future* is the most widely used annual report on long-range global trends and possibilities, produced by an international network of analysts linked by the United Nations system. That paper, in turn, was stimulated by international discussions in 2003 hosted by the Mexican national oil company, Pemex, on future strategies for the oil-producing regions of the earth. Ismaili El-Shatti of the Gulf Institute for Strategies Studies (now Deputy Prime Minister of Kuwait) presented a set of long-term scenarios for the Middle East which were far more integrated than what we usually see in the US, very well-argued and credible, and terrifying. During these discussions, we tried to see if we could envision a "win-win" strategy for this very challenging global game, in which the very survival of humanity may be at stake. It also became clear that the optimal strategy for Mexico,

---

[1] The views herein are the personal views of the author, and totally unofficial; however, they do constitute work by a federal employee under government time.

especially, is very close to the optimal strategy for the US consumer. In Mexico, I coined the term “GEM flexibility” for cars which are capable of using any *mix* of gasoline, ethanol (E85) and methanol (M85), with the ability to change fuels from one day to the next.

Why do I stress *technological* solutions here, rather than political or economic or spiritual solutions? In fact, political, economic and spiritual actions end up being a major part of the story here. But the field of energy policy is littered with wasteful, pious good (or self-serving) intentions of little real value to human society in the end (or to self-preservation). So long as the technology deployed on the ground consists of conventional automobiles which can only use one energy source, gasoline or diesel fuel, and so long as our supply of gasoline is conventional oil drilling, then we will be playing a losing game which we will lose in the end, no matter what we do. As I said in my own plenary talk in Mexico – if we become a world of big hungry rats fighting over the last piece of cheese, I would not want to be one of those rats. I would not want to be the cheese either.

Technologies deployed in the real world define the chessboard that we are playing on here. Economic analysis and incentives provide a way of *moving* the pieces on that board. As for political or spiritual actions – “by their fruits you will know them.” If they pay full attention to the economic and technological realities, and move us energetically towards a solution in the real world, then they can help.

Some would question these basic facts of life. For example, some would ask: “Why should we worry, even if gasoline should go to $50 per gallon, and the cars available come from the same menu we see today? Why not just change our lifestyle? Why not take bicycles to work, or use public transportation?”

Bicycles have a lot to offer our health, but they do not really help us solve the larger problems in the United States. (In some parts of the world, continued use of bicycles and motor scooters does buy us time, but the United States is in no position to tell the Chinese and Indians to keep using bicycles forever.) Half of my first job in the federal government, on rotation from university faculty in 1978, was to evaluate the 50 best models of regional economic development, and analyze how one could do better. At that time, Census data showed that the percentage of US workers who *could* get to work by public transport was only about 10%. More recent data (Census 2004, page 3) show that the percentage of Americans getting to work by public transit is only 4.7%. From 1990 to 2000, the number working at home has risen from 3.0% to 3.3%, but that is not even close to changing the general situation. Perhaps more important – 88 percent of American workers got to work by car, and 84% of American workers take more than ten minutes to get there. If a price shock or supply interruption kept half of these workers from getting to work, the domino effects on the US economy would be devastating. It would be devastating even if we initially relied on the free market to distribute the pain as efficiently as possible. Conversely, if we all end up driving electric cars powered by renewable energy sources, individuals who choose to drive large or fast cars would be hurting no one but themselves by doing so.

If Americans all moved out of houses into apartments close to their jobs, and never changed their jobs, then the need for cars would be reduced dramatically – but so would their standard of living. In any case, this is not really feasible for a very long time to come. It would not be a feasible way to respond to a major price shock. It would not be feasible politically *before* such a price shock. On the other hand, once we deploy the technologies that we need for true energy security, we can continue to build houses as big as we choose, without any need for constraints beyond the discipline of the free market.

Why not rely on the market to do *everything* here? Why even talk about technological solutions?

There are two answers to these questions. First, even the market requires that *someone* works out the technological details – from the big picture down to the essential specifics. This chapter does not ask: “What can *governments* do to achieve energy security?” It asks: “What can *we* do – all of us together, including industry leaders and university researchers especially..?” Government has an essential role in encouraging and facilitating the major changes required here, but only industry can supply the new cars and new energy production systems that we need.

Second, *purely* economic market-based approaches to these problems tend to be a meat-axe. For example, if we imagine that we live in a world of truly perfect, precognitive markets, then the perfect way to prevent excess CO_2 emissions would be a massive tax on those emissions. At one time in the 1980’s, I managed the official long-term energy forecasts of the Department of Energy (DOE) published in the *Annual Energy Outlook* (then a volume of the *Annual Report to Congress*). With inputs from all over DOE, I ran a large carbon tax scenario, included in the official report. The results were not encouraging. The impact in hurting the economy was much greater than the impact in improving efficiency. The details were an incredible learning experience – but beyond the scope of this chapter. Here I will still propose market-based strategies, but market-based strategies *informed by* the technical realities. If we understand the condition of the patient better, we can get away with using a scalpel instead of meat-axe.

The strategies proposed here will *not* be the usual bureaucratic kinds of “ten year plan” strategies, attached to six-digit specifications of exactly how much fuel we will use of each kind in every year. Plans like that do not do justice to the *uncertainties*, the *hazards* and the *opportunities* which are the essence of the challenges in front of us. For example, our first goal here is *not* to reduce the actual use of gasoline; it is to reduce the damage that the US economy would encounter *in case of* a major oil price rise. The larger goal is to maximize the *probability* that the human species as a whole attains a secure, sustainable energy system, while we still can. Tiny “incremental improvements” which do not help us make this transition are mostly worse than useless, because they distract us from what we need to do..

The oil industry learned long ago that we can’t even do a good job with conventional oil, unless we learn to think in *stochastic terms*. Tools like decision tree analysis (Raiffa 1968) are needed to guide rational oil exploration and wildcat drilling. Our recent work on the engineering side (Werbos 2004) has led to a new understanding of how we can extend that kind of optimal, adaptive, stochastic decision-making to much more complex challenges – like the larger challenge of energy security.

The new methods for optimal decision-making learn to compute the correct *value functions*, the measures of progress, called “J” or “$\underline{\lambda}$”, which measure our real progress towards our long-term goals, and provide guidance for what we need to do immediately in the here and now. Often these value functions depend on things we cannot measure directly; in those situations, it is essential that we adaptively update our estimates of those things. For example, in energy policy, it is essential that we continually update our understanding of the upside potential of new technologies. One of the new decision-making methods which I have developed, Dual Heuristic Programming (DHP), has led to a new controller for electric generators which can withstand disturbances three times as large as what the best previous technology could handle (Venayagamoorthy 2003). Slightly modified, it has been used to reduce NOx emissions from diesel engines by 98%, and improve efficiency in conventional cars (Sarangapani 2007). It can also improve performance in wind energy systems and in electronic control of the power grid (Qiao 2007). Optimal management of the entire power grid or global energy systems requires a kind of third generation of this technology (Werbos 2007) which has not yet been deployed in engineering technology – but it does underlie my thinking here.

My real goal here is not to propose a specific set of actions – though I will do so, as much possible at this time. Rather, my goal is to address the question: what is the optimal strategy of action, when our goal is not to make incremental improvements but to get to true energy security, as soon as possible and with maximum probability? Energy security and sustainability are not enough by themselves to assure the future survival of the human species, but they are a large and necessary part of that larger challenge.

2. Transportation Fuel Security: How can We Zero Out America's *Dependence* on Oil at the Soonest Possible Time?

2.1. Context

We all know that our growing *need* to import oil from unstable parts of the world is a central challenge to US national security. If world dependency on those regions continues to grow at the present rate, in 20-30 years the costs and the dangers could grow to be ten times as large as they are now. Clearly we need to take very strong action, if we have any hope at all of changing these trends. It is a matter of life and death.

This section will talk about serious ways that we might change these trends. It will present a strategy for zeroing out our *need* to use gasoline, as soon as possible. This is also an essential part of a larger strategy for how to zero out world emissions of CO_2 as soon as possible. Notice that the goal here is not to minimize *actual gasoline consumption* in 5-10 years; rather, it is to build up an ability for the US to survive a worst-case scenario, 10-20 years from now. Survival under the worst case scenario is a matter of national security, a legitimate area for strong US government action.

US oil dependency and US CO_2 emissions are mainly due to the limitations of the technologies we now depend on. Thus we have to understand the technologies and what they really offer. The best information on automotive technology is not something you can find in an authoritative hundred-year-old encyclopedia or government agency report. In fact – the engineering community (represented by societies like IEEE, ASME, SAE, etc.) is the best source of front-line current information.

One of my major sources of information here is the IEEE-CIS Alternate Energy Task Force, whose members are listed here:

Chair: Paul Werbos
Vice-Chair: Anya Getman, Caterpillar
Rajashekara, Rolls-Royce (former Delphi hybrid leader)
Danil Prokhorov, Toyota
Ken Marko, ETAS/Bosch

Lee Feldkamp, Ford
Hossein Javaherian, GM
Pierro Bonissone, GE
Georg Zimmerman, Siemens
Fei-Yue Wang, Chinese Academy of Sciences
Pablo Estevez, U. of Chile
Toshio Fukuda, Nagoya U.
J. Sarangapani, Missouri U. of Science and Technology
G. Venayagamoorthy, Missouri U. of Science and Technology
Derong Liu, U. of Illinois

Nothing I say today will represent the task force as a whole – but people on this task force have been very helpful in keeping me from getting too far off track. The people on this list include the world's leaders in intelligent adaptive engine control, one of the two key requirements for maximum fuel flexibility in any kind of car. It is also essential in maximizing fuel efficiency and minimizing pollution.

2.2. Why the Challenge Is Difficult

Can we cut our *need* to use gasoline or diesel oil by 50% or more in 20-25 years, by which time this flexibility will be very badly needed?

The main problem here is that new cars stay on the road for an average of 15-17 years after they are purchased. Trucks last even longer. Thus in order to achieve 50% or more gasoline-independence in 20-25 years, we have to change half the new cars and trucks being sold in a mere 5-10 years. By 2015 or so, we would roughly require that half the new cars and trucks must be able to operate without any use of gasoline at all, if necessary.

It turns out that this goal *is* achievable, but only if we have tremendous will power and focus on the problem. Money will be required – but not so much money as was already given away in the Energy Act of 2005. The critical resource here is brainpower, determination and honesty, not money.

If we do it all right – we have a serious chance, on the technical level, to reduce our dependency on the Middle East dramatically over the next 20-30 years while paying the world back for the entire cost of the effort and even clearing a profit in the end. But it is only a hope, not a guarantee. If we were venture capitalists, we would say that the new energy technologies are highly risky. But in order to survive, some of us need to think about risk in a different way. From a national or global viewpoint – the most serious risk is what happens if we do nothing. We need to work harder in order to *reduce* the huge risks that we are already facing. We need to ask our R&D review panels to focus discussion on this other kind of risk -- the risk of what we lose by inaction.

2.3 Long-Term Options for Cars Which Do Not *Require* Liquid Hydrocarbons

There are four proven ways to carry the energy needed to power a car, other than liquid hydrocarbons:

(1) Alternative liquid fuels, which could be ethanol, methanol or more exotic liquids like P-series biofuels, corrosive Fischer-Tropsch liquids, mixed alcohols, hydrazine hydrate, or dimethyl hydrazine;
(2) Electricity stored in batteries;
(3) Gaseous fuels like natural gas (methane) or hydrogen;
(4) Compressed air.

In addition, there are three further serious possibilities today:

(5) Electricity stored in new types of ultracapacitors with high energy density;
(6) Wind up cars, similar to wind-up toy cars with large rubber bands;
(7) Heat batteries, or "thermal storage units."

In 1994, at the National Science Foundation, I proposed and managed a new topic for NSF's Small Business Innovation Research (SBIR) on enabling technologies for next-generation vehicles. Proposals were received and evaluated in depth in all of these areas, *except* for the new types of ultracapacitors (a new technology) and heat batteries for cars (not yet on the horizon).

Tata Motors, the big automobile company of India, has announced near-term plans to mass-market compressed air cars. This may do well in India, but would have difficulties in the US market because of the limited driving range and lack of suitable infrastructure.

Any of these technologies could be used in principle to give us a transportation system able to run without hydrocarbons. However, it is not realistic to imagine that half the people buying new cars in the US in 2015 would be willing to buy cars which cannot be filled up from an existing nationwide infrastructure – gas stations, the electric power grid or (arguably) the natural gas grid. Automobile company research (Nichols 2003) has concluded that the fuel for a car must be available in at least ten percent of the local gas stations, before a normal consumer would be willing to buy the car.

In general, liquid fuels allow twice the driving range or more, compared to electricity or gaseous fuels, under today's technology with cars that a consumer could afford. Electricity offers at least twice the overall energy efficiency and an easier fit with renewable energy sources. (I will give more of the details below.) Even in the long term, if Americans continue to demand a driving range of 300 miles, if liquid fuel prices continue to rise but battery prices do not fall beyond today's best market price, the optimal long-term sustainable solution may actually be similar to the near-term approach proposed below. However, that near-term approach has the advantage of opening the door to more rapid development *both* of alternative liquid fuels *and of* electricity storage; it would be a very important steppingstone to a different long-term future, if either of those is better.

2.4. How to Zero Out the *Need* for Gasoline In Most New Cars By 2015-2020

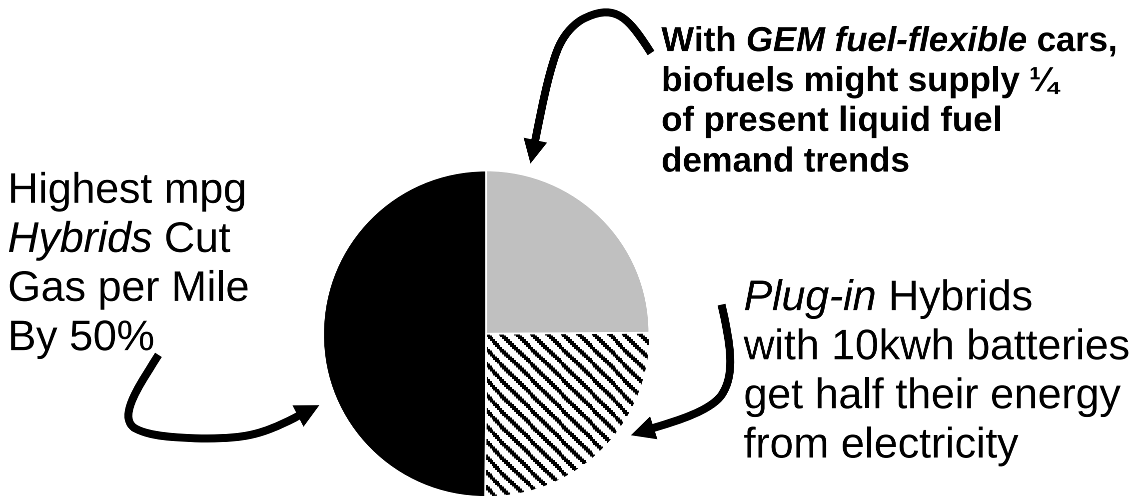

Figure 1. Best Near-Term Option to Zero Out *Need* for Gasoline

This chart is based on numbers and detailed analysis in the recent IEEE-USA white paper on plug-in hybrid vehicles (IEEEUSA 2007). Before discussing strategy, I need to explain some of what you see in this chart:

(1) Today's most established hybrid car, the Toyota Prius, recently showed a reduction in gasoline per mile by 47% compared with the conventional version of the same car, according to EPA mileage estimates. EPA mileage estimates have been adjusted downwards *both* for conventional and hybrid cars, but the comparison is generally correct. As other companies catch up with Toyota in hybrid technology, similar gains should be expected. Hybrid technology is still improving even at Toyota; for example Prokhorov (2007) has reported a new software controller which can improve the mpg of the Prius hybrid by more than 15%, with no change in the hardware of the car.

(2) A *plug-in* hybrid electric vehicle (PHEV) is essentially just a hybrid car or truck with two things added: (a) a larger battery, so that the car has a significant all-electric driving range; and (b) a plug, so that the battery can be recharged by plugging the car into an electric outlet at your home or at a parking lot. IEEE Spectrum magazine (2005) has estimated that a typical consumer, if given a PHEV with 32 kilometer all-electric driving range, would use electricity to replace about half of the gasoline he/she would have used with the usual hybrid.

(3) GEM fuel flexibility formally means that a car can use gasoline, ethanol (E85) or methanol (M85) in any mixture, from one day to the next, without voiding the warranty of the car. In practice, GEM flexibility requires two key inexpensive upgrades of a car *at the factory*: (a) use of corrosion-resistant gaskets, hoses, engine materials, etc.; and (b) use of adaptive engine control, so as to optimize performance for any mix of fuels. These upgrades also allow the use of more exotic liquid fuels. GEM flexibility was a well-established technology for conventional cars by 1990, but is easier in hybrid cars and can be improved by use of new technology.

The core strategy here is simply to accelerate the arrival of GEM-flexible PHEVs as much as possible, for the sake of national security.

More precisely, the four measures of progress which all of us should try to maximize here and now are:

(1) The market penetration of GEM-flexible highway vehicles, fuel-efficient hybrids, PHEVs, and – best of all – GEM-flexible PHEVs;

(2) The development of technology which improves the quality and reduces the cost of GEM-flexible cars and PHEVs, such as better batteries, better battery management systems, adaptive engine control and the development of supply chain systems which accelerate the use of the best available technology;

(3) Likewise, the technology (and its penetration) for supplying alternate liquid fuels, both from biological and nonbiological sources, to be selected by market forces with proper incentives for sustainability in biofuel production and proper correction for net production of greenhouse gasses; this includes GEM-flexible gas stations;

(4) The penetration and technology for connecting PHEVs to the electric power grid, both at home and in parking lots, so as to provide maximum value to the electric power grid across different times of day.

Again, please remember that these values are *not* designed to minimize the actual use of gasoline. That is not the long-term goal which they represent. The goal here is to move us away from an insecure *monopoly* situation, where the consumer has no choice but gasoline (or diesel fuel) to use in his/her car. The goal is to open up a new *market competition* between different forms of energy, so that a user can decide on a day-to-day basis which fuel to use, and how to make the tradeoff between driving range (always best with gasoline or advanced liquid fuels) versus cost (best with electricity). If we believe in the power of market competition and consumer choice, then this approach is far better than *today's* policy of enshrining gasoline as the one and only government-backed "winner."

More precisely, this strategy aims to serve four longer-term goals: (1) to create a *resilient* system for transportation energy, able to adapt quickly and efficiently to changing conditions of price and availability of fuels and electricity – continuing to use gasoline *so long as* gasoline is affordable enough as judged by the consumer; (2) to improve efficiency in the production and use of fuels and electricity; (3) to improve the efficiency of the electric power grid itself, by providing additional storage available to the grid and making better use of night-time transmission capability; and (4) as a byproduct of competition, to create a transportation system which can respond quickly and efficiently to incentives or taxes based on environmental conditions.

All of this assumes that GEM flexibility and PHEVs are in fact viable technologies. The next two subsections will provide more information on these two technologies. I will also discuss gaseous fuels, which I do not propose as a national priority at this time.

As this books goes to press, China has moved ahead on an ambitious plan to produce such cars and produce methanol. (See http://www.werbos.com/E/PlugIns.pdf and http://www.setamericafree.org/Dolan041608.pdf for details.) Chery has begun to produce a new generation of GEM flexible cars. BYD Motors will be mass-producing PHEVs later in 2008. This is by far the most serious and effective program to reduce oil dependency in the world, but optimization calls for us to work even harder to accelerate the progress even faster. More precisely, in order to minimize the probability of economic disaster, we need to move as fast as we can, because the risks we are facing are both growing and accumulating with time. Above all, we need to take advantage of new possibilities for US-China cooperation and changes in the US, so that US resources can be mobilized more effectively, to make the transition faster and more secure. Other nations also have important unmet opportunities to accelerate this transition.

2.6. GEM Flexibility – The Nearest-Term Option

Let me start with a quick summary of key points which I will elaborate on, in order:

* GEM flexibility is much more than the widely publicized gasoline/ethanol (GE) flexibility;

* GEM flexibility was already a proven technology in 1990 (Nichols 2003), much less expensive than hybrid cars or gaseous fuel capability, let alone pure electric or fuel cell cars today

* Methanol is already an inexpensive merchant fuel, currently in excess supply. A quick, rough calculation suggests that US consumers might have saved hundreds of billions of dollars per year by 2005 if we had adopted GEM flexibility already in the 1990's. The calculation actually shows a doubling of US revenue to distribution companies like Exxon, but a deep reduction in oil import bills.

* Conversion to GEM flexibility in all new cars could be accomplished in 2-4 years.

* GEM flexibility offers greater efficiency in the use of coal-based liquid fuels, and something like a doubling in the sustainable potential contribution of biofuels.

* Greater methanol availability *would have* offered the optimal path to widespread use of fuel-cell cars, but progress in other technologies has lowered the importance of this benefit.

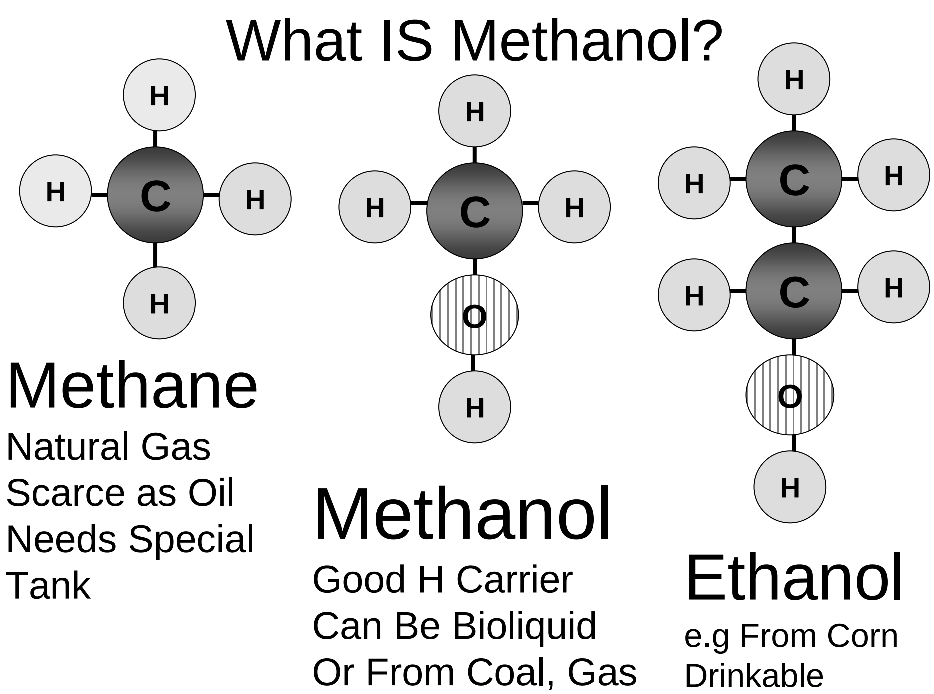

Figure 2. Methanol Versus Ethanol and Methane

To begin with, it is important to be *very* clear on the differences between ethanol, methanol and methane, illustrated in Figure 2. We are not proposing the use of *pure* ethanol or methanol as a fuel for cars; that would have many problems, well documented in the literature. Roberta Nichols, who led the fuel flexibility efforts at Ford for many years, has explained how a *blend* of methanol and other fuels – 85% methanol – overcomes those well-known problems. (Nichols 2003). That blend is called M85. In practice, GEM flexibility also allows use of other liquid fuels as corrosive as M85 or less.

In the 1980's, Ford worked hard to promote GEM flexibility. Meetings were arranged between Nichols and the White House. In his 1988 campaign speech, George Bush Senior said: "ALCOHOL FUELS: Detroit is ready now to -- make cars that would run on any combination of gasoline and alcohol -- either ethanol, made from corn or methanol, made from natural gas or coal or even wood. Cars produce less pollution on alcohol fuels, and they perform better, too. Let us turn away from our dependence on imported oil to domestic products -- corn, natural gas, and coal -- and look for energy not just from the Middle East but from the Middle West." (Source: George Bush 1988 Campaign Brochures, www.4president.org.) Working with Boyden Gray, Bush did enact new blending requirements which were intended to substantially increase the use of methanol as a component of gasoline; however, oil industry legal forces managed to change the requirement to MBTE in the legal system. Nichols concluded her review of the Ford experience with a brief explanation for why the effort failed at the time: lack of cooperation from anyone in the oil industry. (Low gasoline prices in the 1990's were clearly a major factor as well.)

How much money could we have saved if we had adopted GEM flexibility over the 1990's? In 2005, I did a very rough back-of-the-envelope calculations for a meeting organized by Congressman Inglis of South Carolina. The calculation is certainly *not* an accurate forecast – but it does give a feeling for how much is at stake, and the assumptions are easy to see.

The quick calculation showed that we would have paid $324 billion for transportation fuel if we had used methanol instead of $540 billion with oil. I assumed 216 billions gallons of gasoline, equivalent to 418 billion physical gallons of methanol; this came by starting from the EIA/DOE number of 27004 trillion BTU of petroleum in transportation, converted at 5.253 million Btu per gallon of gasoline (Appendix A of the EIA report) and 42 gallons per barrel. (This should probably be reduced by about 20%, since ground vehicles other than trains are not the only users of petroleum in transportation.) I assumed gasoline at $2.50 per gallon. (The savings would certainly be more at today's price of gasoline!) For methanol, I estimated the wholesale price as $220 per metric ton, from the listing at the Marathon oil web page, which noted that the $220 price in 2004 was a very strong (high) price. I then went to the EIA Primer on Gasoline Prices, and assumed that the distribution cost per physical gallon of methanol would be the same as the distribution cost per physical gallon of methanol; this implies almost doubling the revenue to the distribution sector. I also assumed the same taxes per BTU of methanol as for BTU of gasoline. In summary, the consumers would have saved many billions, yet the US distribution system would have doubled its revenue. Reduced spending on crude oil would have been the real source of savings.

How real is this calculation? Certainly, the price of methanol would have changed if demand had increased this much. Yet the excess supply of methanol capacity today (due to the outlawing of MBTE made from methanol) should be able to meet a respectable share of US fuel demand – on the order of 5-10% -- with *more savings* per gallon than the calculation above. Recent project plans from Canaccord on the web show that new methanol projects using remote natural gas (not suitable for pipeline use) can turn a very nice profit even if the methanol is sold at $164 per metric ton. Many quadrillions of BTU of remote natural gas, located near oil wells, are still being vented and flared today; with a market for methanol, oil producers would be able to use that gas to expand the methanol supply still further. In summary, if cars could use M85 as a fuel today, we really could be achieving huge savings, across a very large fraction of our fuel use. Large immediate benefits would be possible – *in addition to* the benefits of being better able to use coal-based liquids and biofuels.

How long would it take to convert all the new cars in the US to GEM flexibility, and how much would it cost? In the 1980’s, Ford deployed thousands of GEM-flexible Taurus cars in California, at no additional cost compared to conventional cars. Nichols, representing Ford, estimated that it would cost $300 per car to add this capability to all new cars, in mass production.

A major part of that estimate was the cost of better control, and the cost of a more corrosion-resistant gas tank. Because of environmental regulations, stronger gas tanks are now already in use. Advances in computer chips have lowered the cost of control. Auto industry sources have informed me that the cost would be about $200 per car now (a rough estimate); some estimate only $100. Professor Steven Paul of Princeton has even identified specific part numbers for gaskets and hoses available from Dupont today that would provide the required corrosion resistance. Auto industry sources have told me that it would take only about two years to convert auto production to GEM flexibility *outside* the US; in the US, it would take an additional two years for legal delays unless, of course, the law was changed to speed up the process.

These facts may seem surprising to some; therefore, some empirical data may be in order.

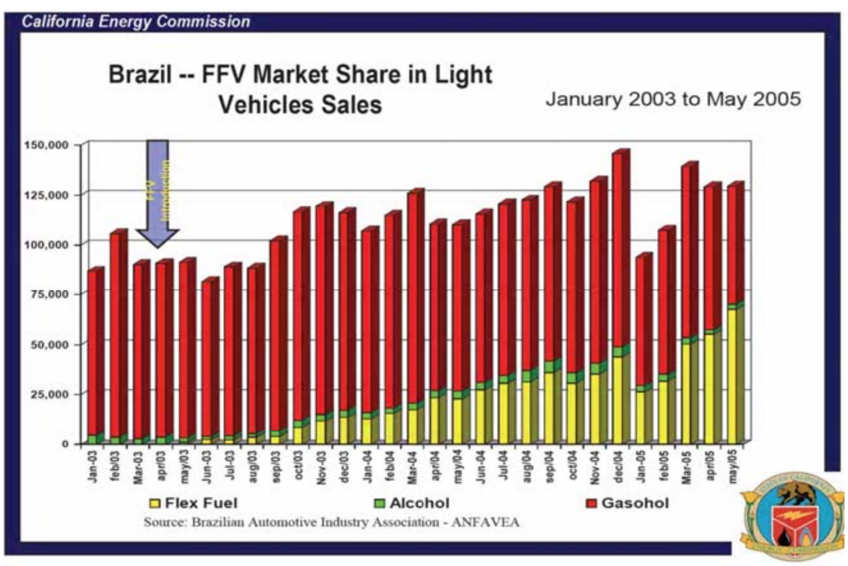

Figure 3. Speed of Conversion to GE Flexibility in Brazil

From January 2003 to May 2005 – about two years – the share of GE flexible cars rose from zero to a majority of the new cars sold in Brazil. Current statistics are about 85%. The technology for GE flexibility is essentially the same as GEM flexibility (though a bit weaker). Furthermore, the companies selling these cars in Brazil are the same as the companies selling cars in the United States; they already have the experience of GE flexibility well-assimilated, as a starting point.

What about the benefits to coal-to-liquids technology and biofuels?

So far as I know, the most promising coal-to-liquids technology is still based on oxygenated gasification. In 1981, at DOE, I commissioned Ed Merrow and Horvath of the RAND Corporation to analyze cost escalation in the construction of synfuels plants, which were very popular at the time. His report (Horvath 1982, Merrow 1981) showed relatively promising numbers for the "Texaco" or "Cool Water" technology of oxygenated gasification. In recent years, GE purchased this technology from Texaco, and is promoting it as the best "Clean Coal" technology. In China, Shell has agreed to build major new methanol plants (to produce transportation fuel) based on oxygenated gasification. These kinds of plants *can be used to produce hydrocarbons* – but at a cost. Higher efficiency and lower cost (and lower waste of resources and less emissions) can be obtained by going to methanol instead of hydrocarbons. Even lower costs can probably be obtained by doing even less processing of the liquids stream coming out of the Fischer-Tropsch process at the heart of these plants; a GEM flexible car could also use these more general Fischer-Tropsch fuels.

Likewise, GEM flexible cars would allow the producers of biofuels to produce more fuel from the same biomass, while wasting less energy in the process. It would also allow them to use a far larger set of biomass sources. Thus they would make more money and contribute more to society at the same time.

At the present time, there is great excitement about developing new technologies for *cellulosic ethanol* – converting sources of cellulose like switchgrass or wood or the husks of sugarcane plants into high quality ethanol, as required by GE-flexible cars. But moonshiners (and Tennessee Eastmann) have been making mixed alcohols out of wood and cellulosic plants for many decades! There are well-established processes here, far less expensive that some of the new high purity distillation schemes. The alcohols are not so pure, but with GEM-flexible cars we can live without purity. Waiting for purity – and paying for it – simply makes no economic sense here. If the pure ethanol producers really can do better than expected, GEM cars would certainly open the door to their product too; however, those of them who doubt whether they could really compete in an open market may be worried about the competition that GEM flexibility would bring.

Finally, I should note that I was initially attracted to methanol (in the 1980's) because of an exciting new technology which is no longer as new or exciting as it once was – the fuel cell automobile. The initial plans for the Proton Exchange Membrane (PEM) fuel cell at Los Alamos and the early GM funding efforts were driven by the hope that methanol could become very widespread in gas stations, first, opening the door to mass production of fuel cell cars carrying methanol in the fuel tank. Methanol, *unlike* gasoline or natural gas, is an excellent carrier of hydrogen. This would have solved the famous "chicken and egg" problem with fuel cell cars. But because of stubborn unsolved problems with hydrogen peroxide formation, and because of new opportunities with competing technologies, I no longer see the PEM fuel cell as a serious part of the story, short of a long series of required breakthroughs. Even the more promising carbon-tolerant alkaline fuel cell (Urquidi-Macdonald 2005) would provide marginal benefits at best, compared with a GEM-flexible PHEV using new types of engines and liquid fuels such as optimal Fischer-Tropsch liquids.

2.7 PHEVs

Section 2.5 has already shown how plug-in hybrid electric cars (PHEV) could benefit energy security in the transportation sector. But it still leaves open some important questions:

* Could the world automobile industry scale up to providing enough hybrid cars or PHEVs to supply half or more of the new car buyers by 2015-2020?
* Could the electric power grid supply the required electricity? How much would it cost to the grid?
* What are the implications for CO_2 emissions?
* Do the extra costs of the new vehicles outweigh the benefits?

The first question is the most worrisome issue here by far. Toyota has announced that most of the new cars it produces will be hybrids within ten years – in part because of very strong market pressure and high gasoline prices in most of the developed world. For several years, Toyota has succeeded in doubling its production of hybrids every year (NAIST 2005). In the absence of any other near-term alternatives (except for the *complementary* technology of GEM flexibility), we simply need to accelerate this transition as much as we can, and hope for the best. Scaling up to produce PHEVs does not add much additional difficulty here, since a PHEV is basically the same as a hybrid except for the battery. Battery manufacturers are generally optimistic about their ability to scale up quickly – given enough demand and financing, and good enough battery designs. Some automotive consultants have argued for years that hybrids will never make it on the market, that Toyota's plans are leading them into deep financial troubles, and that Toyota should learn from the much more secure strategies they have persuaded Detroit to adopt. I hope Detroit has learned by now how much to disbelieve that species of consultant. The economic bottom line has become overwhelming by now. It will be a major challenge to make sure that the US automakers survive and contribute their share of this global transition.

In the electric utility industry, it is generally understood that a widespread use of PHEVs would be a *net benefit* to the grid, not a net cost. This helps explain the strong interest in PHEVs from the electric utility industry (IEEEUSA 2007). At the September 2007 workshop on PHEVs led by IEEEUSA, Commissioner Wellinghoff of the Federal Energy Regulatory Commission discussed in detail what a boon the PHEV could be for the management and efficiency of the grid. Wellinghoff particularly stressed the potential of "vehicle to grid" (V2G) technology (Kempton 2005a,b). DOE's Pacific Northwest National Laboratory (PNNL 2007) has estimated that 84% of US cars, pickup trucks and SUVs could be PHEVs powered by the existing electric power system, without any increase in generation or transmission capacity. A major reason for this conclusion is that the electric transmission grid is now used at less than 50% capacity during the night, when most people would be recharging their PHEVs. The National Renewable Energy Laboratory performed a similar study, concluding that “there is no need for additional generation capacity, even at 50% PHEV penetration.” (NREL 2006, p.15.)

How could so much gasoline be replaced by so little electricity? Part of the reason is unused nighttime transmission capacity. But the biggest reason is efficiency. IEEE has pointed out that the small gasoline engine at the heart of the Prius hybrid is only 30% efficient. (IEEEUSA 2007.) The car as a whole outperforms conventional cars, mainly because conventional cars spend most of their time operating far away from the point of maximum efficiency and because they lose energy during braking (unlike hybrids.) But when natural gas (a fuel similar to gasoline in cost and scarcity) is burned to make electricity in large electric power plants, efficiencies as high as 60% can be achieved; thus the PHEV is basically twice as efficient as a regular hybrid and four times as efficient as a conventional car, when it is running on electricity. (Old car batteries also had a 30% loss in the charge/discharge cycle, but the new batteries for PHEVs are much better.) Of course, the electricity can also be supplied from less expensive or renewable sources, which makes the situation still better for the driver.

This high efficiency explains the recent finding by the Electric Power Research Institute and the Natural Resources Defense Council that use of PHEVs could reduce total greenhouse gas emissions substantially, across all nine scenarios they considered, using different assumptions about where the electricity comes from. In its independent official position (EPRI/NRDC, p.v), NRDC concludes:”NRDC does believe that with sufficient emission controls in place PHEVs have the potential to improve air quality and to substantially contribute to meeting our long term GHG reduction goals of 80% below 1990 levels by 2050.” In other words, PHEVs can improve other dimensions of air quality, *in addition* to the CO_2 benefits, so long as the cars are properly controlled. With adaptive engine control, this should be straightforward.

What about the bottom-line costs and benefits to the ordinary consumer?

Because of the high efficiency of PHEVs operating on electricity, we should probably believe the widespread claims that the cost of electricity to the consumer is less than $1 per gallon of gasoline equivalent. (IEEEUSA 2007.). In total, then, the savings to the average consumer would only be slightly less than ¾ of what he or she spends on gasoline. But the main benefit to the consumer and to the nation would be *increased security* – a kind of insurance, to protect against the possibility of gasoline becoming unavailable or unaffordable. (If gasoline prices had to rise high enough to accommodate a 50% reduction in supply, then gasoline would of course become unaffordable for half of the present market. Even a bad hurricane in Houston poses this kind of threat.) But if all American workers had access to a PHEV with a 40-mile driving range, and if all parking lots at work had plugs, then it is clear that >90% of the workers would still be able to get to work and back (Census 2004), so long as the electric power grid stays up.

Unfortunately, the conventional hybrid car is a borderline investment for the average consumer. With the Toyota Prius today, at $3 or $4 per gallon, the additional cost of the hybrid car is slightly more than the benefit of the fuel savings. For the Prius, the additional cost of the hybrid is about $3,000, of which $1,800 is said to be for the battery and $1,200 the ancillary equipment. Only the increased security or insurance benefit –

and tax incentives that reflect that benefit – really justify the purchase. This is why strong incentives will be needed and justified for many years to come.

The PHEVs available today are retrofitted hybrid cars, using upgrade kits which cost well over $5000 (Spectrum 2005). Using batteries from the historic large and powerful US battery manufacturers, it is difficult to do much better. Studies which rely on such sources tend to be very pessimistic.

Fortunately, there have been major breakthroughs in batteries in the last decade, due to the electronics industry and to research groups outside the usual orbits of the usual Washington "stakeholders." As an example, Thunder Sky (www.thundersky.com) of Shenzhen, China, is now able to supply the 10kwh batteries needed for a PHEV for a cost of $2000 each in quantity – only $200 more than the usual estimate of the battery cost for a conventional hybrid. The manufacturing plant itself (which I have visited) is totally nonpolluting, and the recycling issues are easier to deal with than the recycling issues for ordinary lead-acid batteries. The cost per kwh is less for larger batteries. A123 in the US also has a modern lithium-ion battery used in Black and Decker tools, and a new relationship with GM. Soloway of MIT has explained how the "periodic table" of new materials for batteries might well allow new batteries with ten times better performance even than Li-ion, if only someone would fund the right kind of systematic research to explore the possibilities. If batteries suitable for PHEVs can truly be made at a cost similar to the battery cost for conventional hybrids, then PHEVs will become a value proposition for the consumer better than conventional hybrids; however, strong incentives could be important in getting us to that point. (For purposes of this strategy, new ultracapacitors with high energy density are just another important new battery option.)

In its Volt program, GM has announced that it will mass-market a PHEV with a 40 mile all-electric driving range, using a 14 kwh battery, within just a few years. Still, this will be a very challenging effort. The success of that effort should receive very strong support from all those who truly care about energy security and sustainability – and the very survival of our economy.

2.8 Gaseous Fuels

Several nations have experimented with cars carrying special fuel tanks capable of holding gaseous fuels such as natural gas or hydrogen. I will not say much about these options, and do not include them in the strategy here, for several reasons. First, natural gas – especially *pipeline* natural gas – is a scarce and valuable fuel, no more plentiful than oil itself. Second, the upgrades cost on the order of $1000, and cost a lot of space on the car. PHEVs cost more, but they offer larger long-term reductions in fuel cost, and a stronger pathway to using renewables as the ultimate source of energy. Hydrogen is even more expensive, as a fuel, and does not provide as much efficiency as electricity.

2.9 Transportation Fuel Beyond Cars and Trucks

Oil-based fuels are used in more than just cars and trucks, in the transportation sector. They are also used in busses, off-highway vehicles, trains and airplanes.

Because the bulk of our dependency comes from cars and trucks, we need to focus our energy on cars and trucks until and unless we are truly moving as fast as we can in that sector. Nevertheless, busses and off-highway vehicles can sometimes provide a good market-worthy testbed for GEM flexibility and battery-based technologies. *So long as* we do not take resources away from cars and trucks, these other vehicles do have a place in the strategy of section 2.5.

Trains present a different situation. Most modern trains use highly efficient diesel-electric hybrid engines, and use massive amounts of energy per vehicle. New technologies like JTEC or advanced Stirling (section 3) may allow fuel flexibility in trains, but they are not yet ready for use in that sector, and trains are not the best testbed to start with. Electrification for trains is a known, expensive technology. Lipo of the University of Wisconsin has proposed a new form of magnetic levitation technology, which might allow electricity-based trains to move faster and cheaper, and compete more effectively with passenger jets dependent on liquid fuels. This is an exciting possibility for nations like China which already make heavy use of passenger rail and have not yet built up their jet fleets; however, it should not be allowed to distract from more urgent life-or-death work described in section 2.5.

Aviation is also quite different from cars and trucks. Aviation is basically stuck with liquid fuels with very high energy per kilogram. Fuels with high energy density are usually more difficult to work with than low density fuels like ethanol or methanol, because high energy density implies more possibility of explosions and fires, when all else is equal. On the other hand, professional commercial airlines and government aerospace operations can adhere to safety procedures more systematically than the average car-driver can. Therefore, fuel flexibility in using high-energy low-carbon fuels like hydrazine hydrate or dimethyl hydrazine represent our best hope for hydrocarbon independence in this sector. These two fuels are just examples -- but both are easier to handle than hydrazine proper. Kordesch (1996) has explored the use of hydrazine in high-efficiency fuel cell cars with relatively long driving range.

2.10 Possibilities for Implementation

For many reasons, this is not the proper venue for me to present a comprehensive set of actions to implement the strategy of section 2.5. More effective R&D is clearly one of the major needs here. In 2007, Basic Energy Sciences of DOE announced a new $5 million program in battery research which is a very important step forwards – but there is still a lot more that needs to be done. We also need to think hard about why the investments of the past in the US have been less effective in this area, so that we can do better.

In addition, GEM fuel flexibility offers a very interesting possibility. What would it cost to *require* that all new cars (starting in 3 years) should be GEM flexible – and to pay a $200 incentive payment back to manufacturers to compensate them for this? If 15 million new cars are sold each year in the US, this would work out to a cost of $3 billion per year – much less than the potential savings discussed in section 2.6, even when long-term national security benefits are not accounted for.

Some lobbyists have labeled this idea a “government mandate.” But really, this is closer in spirit to the Open Standards for Digital Television which Congress has ordered, starting in 2009. The goal is not to mandate a choice of fuel, but to establish a new kind of open standards for competition in the fuel market. The new standards for the television industry are estimated to cost much more than the $3 billion I am talking about here, but it has been agreed that the value of open competition in the television industry is large enough to justify the cost and the standards. Is high digital television really more important to national security and the US economy than our dependence on oil from OPEC?

3 New Technologies for Electricity Generation

3.1 Context

For practical purposes, there are two very different markets for electricity – the daytime market, peaking a few hours after noon, and the 24/7 market for steady base-load power, day and night. In the United States, daytime electricity is supplied more and more by consuming natural gas. Natural gas is more expensive than coal or nuclear fuel, but the low capital cost of natural gas generators makes them attractive as a source of electricity which only gets turned on a few hours every day. Higher effective interest rates for electric power investment projects because of deregulation have also tended to favor natural gas in recent years.

Section 3.2 will discuss hopes for new solar technologies to compete with natural gas for the daytime market worldwide. Section 3.3 will discuss energy from space (ES), which is the only really definite alternative to coal and fission+enrichment in being able to supply enough continuous baseload electricity to allow a reduction in both of those two established technologies, which are now poised for rapid growth.

A rational energy strategy should also include efforts to support early research on breakthrough energy concepts which show some hope of being able to produce as much energy, sustainably and affordably, as coal or fission. These concepts have fluctuated a lot through the years, and are beyond the scope of this chapter.

A combination of better batteries, thermal storage and a true, adaptive time-shifting "brain-like intelligent power grid" (Werbos 2004) would allow us to use daytime solar energy to supply the baseload market, or energy from space to supply the daytime market, or wind energy to supply a larger fraction of the baseload market. But in all three cases, there is still a major cost premium involved. The rational strategy is to develop the three core new technologies here in parallel – novel earth-based solar power, energy from space, and the intelligent grid. All three core technologies offer large unmet opportunities to make progress many times faster than is happening as yet anywhere in the world today. Batteries are also important, but were already discussed in section 2. New solar power technology and energy from space must first become established in their natural core markets before we can seriously consider them for time-shifting to the other markets.

Rooftop solar, using new low-cost solar cells, could be an excellent testbed for inserting new intelligent control technology into the power grid. Well-established traditional control methods simply have not allowed us to "pay" solar power providers the full value of what their electricity would be worth, in an optimal power grid. I will not say more about this here, because rooftop solar – useful as it is – is not likely to produce enough electricity to replace the need for natural gas in electric utilities. Also, there are sensitive issues of intellectual property in the new technology needed to make it work, including patents pending.

From basic physics, it is easy to calculate that solar farms and energy from space both have the potential to generate something like 100 times the world's total use of electricity, even if the solar farms are deployed only on desert land. They are enough by themselves, if only we did the things we could do to make them more affordable. As this book goes to press, evidence is becoming more convincing that the US, China and several other nations also have enough raw wind resources to meet all their needs, *if only* the storage and intelligence in the power grid could be improved in the ways we have proposed. It still seems likely that solar farms and energy from space could provide a lower cost solution, if fully developed, but wind provides an immediate opportunity of equal importance. Still, the social and political obstacles to a true intelligent grid are just as serious as the technical obstacles to cheaper solar farms and energy from space. A rational strategy would give roughly equal weight (high priority) to overcome these key obstacles in all three areas.

Claims have been made for wave power which sound similar, but serious sources like EPRI currently suggest less serious potential. Likewise, claims have been made for many types of technology which drill very deep into the earth (or process shale oil formations), all of which pose risks for greenhouse gas emission which may be even more serious than what we face today with coal. It is unfortunate but understandable that advocates of those technologies do not always provide an objective account of those risks.

3.2 Challenges and Opportunities in Cutting the Cost of Earth-Based Solar Farms as Soon as Possible

There are two different technologies available to electric utilities in building "solar farms" to provide daytime electricity: (1) photovoltaics (PV) or "solar cells"; and (2) solar thermal systems, which concentrate sunlight to provide heat, which is then converted into electricity. The key strategic goal here is to build solar farms cheap enough that they can compete with natural gas in generating daytime electricity *nationwide*, *as soon as possible*.

California utilities are the leaders in developing solar farms in the US, in part because they pay a high price for daytime electricity from natural gas, and in part because the Mojave desert gives them a source of steady sunlight large enough to meet all the electricity needs of the US (day and night) if we could afford to use it. *Business Week* (September 12, 2005) reported a new contract between Southern California Edison (SCE) and a new company, Stirling Energy Systems (SES, www.stirlingenergy.com). SCE stated they had agreed to buy up to 500 megawatts from SES, at a price "well under" the 11.3 cents per kilowatt-hour (kwh) they now pay for daytime electricity from natural gas.

The SES technology is a form of solar thermal power, pioneered by the Sandia laboratories of DOE, using moveable "dishes" made up of mirrors to track the sun. Because photovoltaics are more expensive than mirrors, and because they require a large investment in "balance of system" technology and installation, they are not likely to get under 11.3 cents per kwh total cost in the foreseeable future. Our best hope of displacing natural gas nationwide at the shortest possible time lies with solar thermal power.

Beyond the United States, the World Bank has led the world's efforts to develop cost-effective solar farms. They have published a number of comprehensive assessments of solar thermal technology. (World Bank 2006.) Historically, they have focused on older more proven technologies, like the large-scale solar "trough" technologies or heliostats, which focus light onto a liquid like water. These technologies collect hot water from a large area, so that they can use large efficient systems to convert the heat to electricity. SCE has also funded projects to try that kind of technology in California, but the full costs in the US have been in the neighborhood of 20 cents per kwh. The World Bank has reported costs as low as 12-13 cents in other parts of the world. Since labor costs and installation are the main cost for any of these solar systems, it is not surprising that the cost is higher in the US than in Africa. Because the trough technology is a large-scale technology and relatively mature, I do not now believe it is our best hope for beating 11.3 cents in California, let alone competing across the entire US. The best hope lies with the newer if riskier dish technology.

Sandia has published considerable detail on the dish systems on its web pages in the past, but some of that detail is currently harder to find. They have six full-scale dishes in operation at the lab. They used small Stirling engines to convert the heat to mechanical motion, which is then converted directly to AC electric power. They contracted with several large companies which promised to deliver adequate Stirling engines, but the only ones which worked reliably were those produced by STM, a small company which has recently gone bankrupt for reasons unrelated to the quality of the engines. The former chief scientist of STM, Lennart Johansson, has written a paper on the history and future potential of this technology (Sobey and Johansson 2006). SES is planning to license first-generation reliable Stirling technology from "McDonnell- Douglas" (now a part of Boeing), where Johansson previously brought the technology from Sweden. Sandia has estimated that these dishes will yield solar power at 6 cents per kwh in mass production. At the April 17-19, 2007, DOE Program Review, Chuck Andraka of Sandia stated that dish Stirling is the most efficient solar conversion approach available today, and that purchasing agreements are now in place for 800-1750 megawatts of electricity, involving two large plants in California.

Sandia's efforts today under Andraka are the most promising effort in the world today to beat natural gas on the market, but they face many obstacles at a national level. Most of the United States pays less than California for daytime electricity, and most of the US has far less reliable sunlight than the Mojave desert. For example, the web site of PJM (the largest electric utility system on the East Coast of the US) shows that they pay as little as 8 cents per kwh, on average, for electric power between noon and 8PM, the peak time. If one were to install gigawatt-sized solar farms in the dry and sunny parts of Texas, they estimate that it would cost about 2 cents per kwh to carry that power all the way from Texas to the East Coast. Solar farms *could* compete with natural gas nationwide, if the total cost of generation and power conditioning could be brought down to 6 cents per kwh. But is that really possible?

In order to maximize the probability of success in getting to 6 cents per kwh, I would propose the following strategy:

- Maximum continued support for the existing efforts led by Andraka, SES and SCE (albeit with some fine tuning and augmented funding to exploit new technology opportunities)

- Substantial new efforts to try to develop two promising approaches to double the efficiency in going from heat to electricity. (This could double the electricity output from a given dish, and thereby cut the cost per kwh in half).
- Efforts to retune the design of the reflectors so that they can be mass-produced in existing underutilized factories making body parts for the automobile industry.
- High-risk background efforts to develop construction automation technology to reduce the cost of physically setting up the dishes.

The two promising approaches to doubling efficiency are: (1) fourth generation Stirling engines, as proposed by Sobey and Johansson (2006); and (2) a higher-risk higher-potential new technology, the Johnson Thermo-Electric Converter (JTEC), summarized in Ward (2008).

JTEC is a new general-purpose technology for converting heat differences to electricity. If it works out as expected, and turns out to be inexpensive enough, it could also be used to replace the 30%-efficient gasoline engines in hybrid cars. This would reduce the requirements for liquid fuel by another factor of two. Cost is less of an issue in the solar power application, where the bulk of the costs are for building the dish itself. Fourth generation Stirling is less risky, technically, but presents more challenges in sorting out the legal and business variables.

Sobey deserves credit for proposing the use of auto body factories to make solar reflectors, based on his long experience as a former Division Director at GM, and prior experience at GM Allison including solar power projects.

Because of their modular nature, solar dishes might well be a suitable target for modern construction automation technology. Probably this would require a new partnership between the world's experts in construction robotics in Japan, a US company like Caterpillar capable of building the large robot/vehicles in the US, and leaders in brain-like computational intelligence. It is too early to know whether this is a realistic option, but the potential benefits are large enough to warrant a serious effort to find out what can be done.

Construction automation may also be the greatest hope for lowering the cost of trough style solar farms to compete with natural gas. Nevertheless, dish systems may be a better testbed for construction automation, because they may be easier to assemble.

All of these activities require a highly adaptive approach, of course, as we buy new information about what we can do.

3.3. Energy from Space (ES)

In 1964, Peter Glaser of Arthur D. Little proposed that we could build large solar farms in earth orbit, and beam the power back down to earth by microwave. Ever since then, the proposal has excited very strong emotions, both among supporters and skeptics, which have seriously blurred the analysis of the possibilities.

Until 2002, I myself was highly skeptical but open-minded as a matter of policy. I viewed ES as just another high-risk option. But new information changed the story.

Back in the 1970's, NASA commissioned three major studies – two of them well-publicized – to develop a "reference design" for space solar power (SSP). They estimated that it could produce base-load electricity, essentially 24 hours a day, at 5.5 cents per kilowatt hour. Congress also funded DOE to perform its own evaluation, under Fred Koomanoff of Basic Energy Sciences (BES). As the lead analyst for long-term futures at EIA/DOE, I supported Fred in this analysis. We concluded that the 5.5 cents estimate was unrealistic, and that there were serious questions about whether these reference designs would work at all. *We did not advise against* continued research in this area, because new research could be used to get a better understanding of the problems, and perhaps even new designs; however, Ralph Nader's lobby group did not convey the fine details in its intense efforts to kill the entire area. Of course, this is not the only thing Nader managed to kill, up to and including Al Gore.

In the 1990's, Congressman Rohrabacher arranged funding for a series of "fresh look studies" at NASA, under John Mankins. The NASA SERT program made some major advances here. Using serious tests in hardware, they verified that the earlier reference designs would not have worked – but found new designs that would. They also funded better-documented, more credible cost studies. Nevertheless, the latest cost study – from SAIC in 2002 – showed that the lowest-cost design for SSP would still end up costing 17 cents per kwh, *even on the assumption* that the cost of getting to low earth orbit is reduced to $200 per pound.

In 2000, I worked with Mankins to organize a new workshop, to evaluate whether new technology for intelligent systems might be of value in reducing the costs of space solar power. (Bekey 2000). After the SERT money ran out, I proposed a new joint initiative in SSP through NSF, which Mankins and I then managed (NSF 2002). This was the most recent US government funding effort on energy from space, and we learned many lessons.

For reasons of space, I will not elaborate on the technical details, important though they are. We are now facing several highly credible designs. I myself proposed a hybrid nuclear/solar design (Werbos 2003,2008) which involves some risks, but also offers a serious chance of getting to 5 cents per kwh or even lower, *so long as the cost to earth orbit is lowered to $200/pound*. On technical grounds, $200/pound is clearly an attainable goal, far less risky than most of the technologies I have discussed in this paper (Chase 2006). It has been reviewed and discussed with a wide spectrum of experts. It is also crucial to national security in many ways that have nothing to do with energy. It received strong support from General James Armor, who was recently head of the National Security Space Office, responsible for assuring that the US has the essential responsive space launch capability needed for many applications. But the current politics in Washington have become extremely complex, and there is no light as yet at the end of the tunnel. If the problem is solved in time, before the US loses crucial unique capabilities inherited from Cold War days, then energy from space could be made viable and affordable far sooner than most believe possible. If not, ES will forever remain a matter of dishonest hype, and there will be grave damage in other areas.

4. The Big Picture and Conclusions

This paper has proposed a strategy for the United States and other energy-consuming nations to achieve true energy security and sustainability at the soonest possible time. But what about the needs of the oil producers, who stimulated this analysis in the first place, in 2003 (section 1)?

In 2003, Oscar Soria Nicastro posed the following question: “what can the oil-producing regions of the world do to maintain rapid economic growth, even as the reserves of oil slowly decline?” The obvious strategy is to *conserve* the oil, and maintain revenue based on higher prices rather than high volume, as long as possible. If Mexico required GEM flexibility in all of its own cars and trucks, it could avoid paying money to import refined gasoline from the United States. (Of course, there are people in Mexico well-funded to try to prevent such a possibility.) It could make more money by developing its own biofuels capability. It could avoid getting in the way of food production by focusing on novel sources of biomass and novel bioliquids, as discussed in section 2. Like California, it could benefit tremendously from building low-cost solar farms as discussed in section 3.2. It could produce more electricity both for its own use and for export to the US.

Oil reserves will last much longer in the Middle East, but they will not last forever. Michael Scheuer, the CIA’s former lead analyst for Al Queida, has reported that Al Queida is motivated by three main grievances (Scheuer 2006). One of them is “overproduction of oil at garage sale prices.” Western analysts, calculating present value in dollars with high interest rates, argue that it is better just to pump out all the oil at a rapid rate. However, the fundamental ethics of Islam say that high interest rates are immoral, and even Western ethical philosophy suggests that lower interest rates should be used (Werbos 1990) in order to properly reflect our concern for future generations. This suggests the possibility of a new “grand bargain” in which crude oil prices do remain high – ever higher – but we all support strong measures to allow the world economy to continue to grow *despite* such price rises. It is realistic for the Middle East to charge as much for oil *as the Western economies can reasonably sustain*; thus it is actually in their interest to encourage Western efforts to make their economies able to sustain higher oil prices without real damage to world economic growth.

President Lyndon Johnson once said: “If you bake a bigger pie, you can set it up so that everyone has a bigger piece.” (Some would call this the principle of “Pareto optimality in game theory.”) Because energy security and sustainability are essential to *global* economic growth, it should indeed be possible to arrive at some kind of grand bargain.

Where does Exxon stand in all of this? Exxon has major sunk costs which need to be written off, in trying to capture the “rent” from oil in the ground outside the US. All over the world, nation-states have demanded ever more effectively that *they* will capture the rent. Exxon’s real assets now lie in its distribution system, its chemical processing technology, and in its reserves of capital which can be used to create a more diversified investment portfolio in the energy sector. As an example, many have suggested that Exxon might be in a unique position to capture key enabling technologies for energy from space, which governments around the world have not been competent or aggressive enough to capture. But is Exxon competent and aggressive enough itself to reposition itself in this way? One may hope. Any player, anywhere in the world, who rises to these challenges deserves the full support of the rest of the world.

References

Bekey, George 2000, *Joint NSF/NASA Workshop on Autonomous Construction and Manufacturing for Space Electrical Power Systems, Final Report*. University of Southern California. Reposted at www.werbos.com/SSP2000/SSP.htm

Census 2004. Clara Reschovsky, *Journey to Work 2000, A Census 2000 Brief*. Census report C2KBR-33, March 2004. Posted at www.census.gov/prod/2004pubs/c2kbr-33.pdf

Chase, Ramon (2006) Designing a responsive space launch vehicle, *Aerospace America*, May 2006. Also see R. Chase, *A Least Cost Design strategy for a Near Term Earth-to-Orbit Transportation System Based on Legacy technology*. AIAA: AIAA-2004-3731, Revision #81b.

EPRI/NRDC 2007. *Environmental Assessment of Plug-In Hybrid Electric Vehicles*. EPRI report 1015325. EPRI: Palo Alto, CA, July 2007. Posted at www.epri-reports.org.

Horvath 1987. R.E. Horvath, S.J. Bodilly, R.W. Hess, E.W. Merrow and K. E, Phillips (Rand Corporation), *Analysis of Selected Energy Technology Cost Estimates*, WD-1098-2-ORNL (planned as R-2571-ORNL), Marcch 1982.

IEEEUSA 2007. *Position Statement: Plug-In Electric Hybrid Vehicles*, June 2007. Posted at www.ieeeusa.org/policy/positions/PHEV0607.pdf

Kempton 2005a. W. Kempton and J. Tomic, Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large-Scale Renewable Energy, *J. of Power Sources*. Vol. 144, no. 1, p.280-294.

Kempton 2005b. W. Kempton and J. Tomic, Power Fundaments: Calculating Capacity and Net Revenue, *J. of Power Sources*, Vol. 144, No. 1, p.268-279.

Kordesch 1996. Karl Kordesch and Guneter Simader, *Fuel Cells and Their Applications*, Wiley.

Merrow 1981: Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants http://www.rand.org/pubs/reports/R2569/

NAIST 2005.*International Workshop on Power Electronics New Wave: Abstracts*. Report AIST05-K00002, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.

Roberta Nichols, The Methanol Story: A Sustainable Fuel for the Future, *Journal of Scientific & Industrial Research*, Vol. 62, January-February 2003, p. 97-105. Posted with permission at www.werbos.com/energy.htm.

NREL 2006. P. Denholm and W. Short, *An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles*. NREL Technical Report NREL/TP-620-40293, revised October 2006.

NSF 2002, Joint Investigation of Enabling Technologies for Space Solar Power (JIETSSP), www.nsf.gov/pubs/2002/nsf02098/nsf02098.pdf

PNNL 2007. Michael Kintner-Meyer, Kevin Schneider and Robert Pratt, *Impacts Assessment of Plug-In Hybrid Vehicles On Electric Utilities and Regional U.S. Power Grids. PNNL-SA 53700 and PNNL-SA-53523.* Posted at www.pnl.gov/energy/eed/etd/publications.stm

Prokhorov 2007. Toyota Prius HEV Neurocontrol. In *Proc. of the International Joint Conference on Neural Networks (IJCNN07)*. IEEE.

Qiao (2007) Wei Qiao, Ganesh Venayagamoorthy and Ronald HarleyDHP-Based Wide-Area Coordinating Control of a Power System with a Large Wind Farm and Multiple FACTS Devices, In *Proc. of the International Joint Conference on Neural Networks (IJCNN07)*. IEEE.

Raiffa, Howard 1968, *Decision Analysis*, Addison-Wesley, 1968.

Sarangapani (2007) Peter Shih, Brian Kaul, Sarangapani Jagannthan and James Drallmeier, Near Optimal Output-Feedback Control of Nonlinear Discrete-time Sys-tems in Nonstrict Feedback Form with Application to Engines. In *Proc. of the International Joint Conference on Neural Networks (IJCNN07)*. IEEE.

Scheuer, Michael 2007. *Through Our Enemies' Eyes: Osama Bin Laden, Radical Islam, and America*, Revised Edition. Potomac Books, 2006.

Sobey and Johansson (2006) The Status of Double Acting Swash Plate Drive Stirling Engines (DA/SH). Posted with permission at www.werbos.com/energy.htm.

Spectrum (2005). W.D. Jones, Take this car and PLUG IT, *IEEE SPECTRUM*, July 2005.

Urquidi-Macdonald 2005. Mirna Urquidi-Macdonald, Ayusman Sen, Patrick Grimes et al., *Design and Test of a Carbon-Tolerant Alkaline Fuel Cell* (2005). Posted at http://ArXiv.org.abs/physics/0504130

Venayagamoorthy 2003 Venayagamoorthy GK, Harley RG, Wunsch DC, Implementation of Adaptive Critic Based Neurocontrollers for Turbogenerators in a Multimachine Power System", *IEEE Transactions on Neural Networks*, vol. 14, no. 5, September 2003, pp.1047 - 1064.

Ward, Logan (2008), Super Soaker Inventor Aims to Cut Solar Costs in Half, *Popular Mechanics*, January 8. Posted at http://www.popularmechanics.com/science/earth/4243793.html. Additional information is posted at www.werbos.com/energy.htm.

Werbos 1990 P.Werbos, Rational approaches to identifying policy objectives *Energy: The International Journal*, 15 (3/4), 1990, p.171-185

Werbos, P. 2003 Reassessing The Global Energy Future: How Can We Achieve Sustainability? In *State of the Future 2004*, Millennium Project (www.stateofthefuture.org), CD ROM. See also www.werbos.com/energy.htm.

Werbos P. 2004 ADP: Goals, Opportunities and Principles. In Jennie Si, Andrew G. Barto, Warren Buckler Powell and Don Wunsch (Editors), *Handbook of Learning and Approximate Dynamic Programming* (IEEE Press Series on Computational Intelligence), Wiley-IEEE Press, 2004

Werbos 2007 P. Werbos, Using ADP to Understand and Replicate Brain Intelligence: the Next Level Design. In R. Kozma, ed., *Neurodynamics of Higher-Level Cognition and Consciousness*, Springer 2007. (see arXiv.org, q-bio.NC/0612045.)

Werbos, P. 2008 Towards a Rational Strategy for the Human Settlement of Space, *Futures*, forthcoming (special issue on space policy edited by William Bainbridge)

World Bank 2006 World Bank Global Environment Facility, *Assessment of the World Bank/GEF Strategy for the Market Development of Concentrating Solar Thermal Power*.