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The Technical and Economic Feasibility of a Carbon-Free and Nuclear-Free Energy System in the United States [1]

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The need for the United States to lead on climate and energy issues is now generally recognized, including by President-elect Obama and key members of his incoming administration team. An equal global per person allowance for greenhouse gas (GHG) emissions by 2050 and a goal of 50 to 80 percent reductions below the 2005 level will require U.S. GHG reductions by 85 to 94 percent. Since such reductions in some non-CO_2 GHGs, notably methane and nitrous oxide, are likely to be difficult, a near-total elimination of U.S. CO_2 emissions from fossil fuels (which constitute over 80 percent of U.S. GHG emissions) will be essential. This conclusion is reinforced if global emissions in 1990 are taken as the base from which to calculate the reductions.[2] Finally for the global peak of CO_2 to be reached in less than 10 years, it will be necessary for the United States and the European Union to commit to significant reductions to offset likely short-term increases in the developing countries.

It is technically and economically feasible to transform the U.S. energy sector from an overwhelming dependence on fossil fuels (85 percent) into one that uses renewable energy only. This paper provides details about that conclusion, for the most part about the electricity sector, but also to some extent about other parts of the energy sector. It is largely based on a much more detailed examination of the issue in my book, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy*. This transition to a renewable energy system includes a phase out existing nuclear plants, which constitute about eight percent of primary energy consumption (about 20 percent of the electricity sector).[3] It also briefly takes up the question of whether new nuclear power plants can address the needs of CO_2 emissions reductions in the United States.

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[1] Much of this paper is based on Arjun Makhijani, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* (IEER Press and RDR Books, Takoma Park, MD and Muskegon, MI, 2nd printing, 2008). Hereafter referenced as Makhijani 2008. This book can be downloaded free at http://www.ieer.org/carbonfree/CarbonFreeNuclearFree.pdf.

[2] Calculations by Arjun Makhijani based on the following data and estimates: U.S. GHG emissions in 1990 were about 6.2 billion metric tons CO_2 equivalent; in 2005 they were about 7 billion metric tons. Global GHG emissions in 1990 were about 36 billion metric tons and in 2005 about 45 billion metric tons. Projected U.S. and global populations in 2050 estimates were 420 million and 9.1 billion respectively.

[3] Electricity data are from United States Department of Energy, Energy Information Administration, *Annual Energy Review 2007* (EIA, Washington, DC, June 2008), Tables 1.1 and 8.1. Annual summary data on production and consumption, 1949-2007, can be found at http://www.eia.doe.gov/emeu/aer/txt/stb0101.xls. Electricity data are at http://www.eia.doe.gov/emeu/aer/txt/stb0801.xls.

A. End-Use Perspectives

It has been recognized since the first energy crisis of 1973 that increasing efficiency is not only possible and desirable, but that it is the most sensible approach to achieving energy, economic, and environmental goals. This is especially so given that:

- The efficiency of present energy use is very low in many applications that use a great deal of energy, with space heating and cooling, lighting, and personal transportation being leading examples.
- Efficiency increases can be made rapidly at modest cost.

Efficiency must be the foundation of a transition to an energy system with zero CO_2 emissions, because it is the fastest and most economical way in which to reduce energy use, while maintaining economic growth and the growth of the services, like heating, cooling, lighting, motive power that energy provides. The right combination of policies that will achieve increased efficiency are therefore very critical.

Here are some examples of the inefficiency of the present system. Only about three percent of the energy input into a 100-watt incandescent bulb comes out as visible light.[4] Since compact fluorescent lamps are three to four times as efficient,[5] their efficiency is about 10 percent, which still leaves a lot of room for improvement. Improvement in the form of various types of LED lighting devices is possible; however these devices are not yet commercial. Hybrid lighting, which consists of luminaires that provide a constant level of lighting output that is a mixture of sunshine brought indoors and electric lighting, as well as building design, can further reduce lighting energy requirements while providing fully for lighting requirements. In other words, the ten percent of electricity that is used in lighting can be reduced to a very small fraction of that with advanced lighting systems.

As another example, most building heating energy requirements can be eliminated with suitable building design. These are techniques that are now available, but are not being used. The main problem is the “split incentive.” The building owner or renter who pays the bills does not control the building design; moreover, energy bills are generally a secondary consideration, if they are a consideration at all, in decisions to purchase or rent residential or commercial space.

Figure 1 compares the average residential energy use (on a delivered energy basis – that is, excluding upstream energy losses at the power plant, in natural gas pipeline transportation, etc.). It shows that the average energy use per square foot of residential buildings is about 58,000 Btu per year. But Hanover House in New Hampshire, which was built with passive solar features, such as high thermal mass and one active solar component – a solar thermal water heater with a 1,000 gallon buried tank – uses only about 8,300 Btu per square foot per year (see Figure 1). The total building cost was modest: $111 per square foot. Its features are: careful passive solar building design, a solar water heater with a 1,000 gallon hot water storage tank for most space and water heating, and efficient appliances. Modern building design can actually eliminate almost all space heating requirements in detached and row-house residential buildings.[6]

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[4] T.J. Keefe, *The Nature of Light* (last changed 2/2/2007), at http://www.ccri.edu/physics/keefe/light.htm. Lower wattage bulbs typically have lower efficiency as well. And higher temperature bulbs have higher efficiency.
[5] For efficiencies of various commercially available CFLs, see the website of the Energy Federation Incorporated at http://www.energyfederation.org/consumer/default.php/cPath/25_44_784.
[6] Elizabeth Rosenthal, “No Furnaces, but Heat Aplenty in ‘Passive Houses’,” *New York Times*, 26 December 2008. The houses described are being built in Germany, but there are examples of houses with similar characteristics having been built in the United States for some time. The added cost in Germany is cited as five to seven percent in the article.

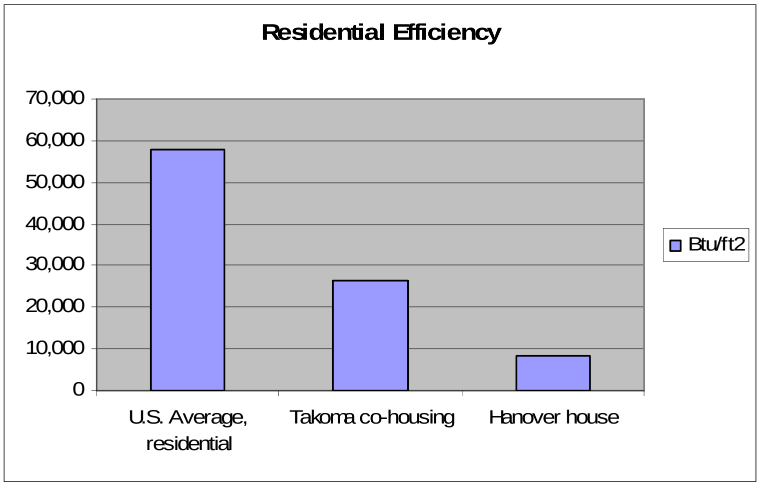

Figure 1: Average residential energy use compared with two efficient buildings: Takoma Co-housing in Washington, D.C., and Hanover House in New Hampshire

Source: Makhijani 2008, p. 79.

While new residential and commercial buildings can be designed to have far lower energy input requirements, existing buildings present a greater challenge. However, one-third to a half of the external energy inputs into existing buildings can be eliminated using backfits and existing technology such as better insulation and windows, sealing duct leaks, geothermal heat pumps, solar water heaters, and efficient lighting and appliances. A backfitting experiment on low cost housing in Florida found many measures with short payback times – 3.6 years on average. The payback time for doing it right in the first place was only 0.7 years. Among the more expensive measures was a solar water heater backfit, which had a payback time of 10.2 years at an electricity price of 8 cents per kilowatt-hour (kWh). When a $50 per metric ton of CO_2 is added in, the payback time would be about seven-and-a-half years, assuming the present mix of electricity generation. One of the most interesting features of this trial was that the solar water heater reduced the utility electricity load during the day and early evening. These payback times do not include any benefit to the system due to reduced peak load. Figure 2 shows the measurements averaged over a three-year time period.[7]

[7] For details on the backfit trial see Makhijani 2008, pp. 81-82. The reference paper is Danny Parker, John Sherwin, David B. Floyd, *Measured Energy Savings From Retrofits Installed in Low-Income Housing in a Hot and Humid Climate*, FSEC-PF-339-98 (Florida Solar Energy Center , University of Central Florida, Orlando, 1998) at http://www.fsec.ucf.edu/en/publications/html/FSEC-PF-339-98/index.htm.

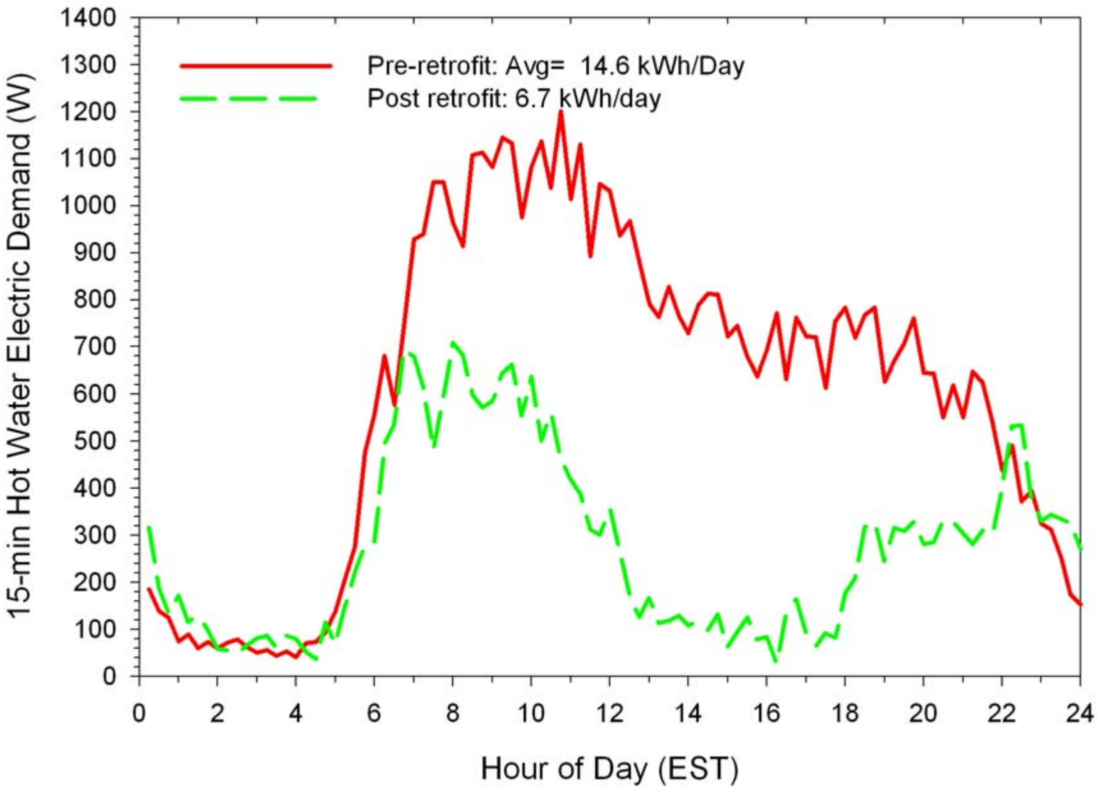

Figure 2: Load Profile of an Electric Water Heating System Without and With a Solar Water Heating Supplement

Courtesy of Florida Solar Energy Center. Source: Parker, Sherwin, and Floyd 1998

The potential for improvements in new and existing commercial sector buildings is dominated more by lighting and air-conditioning. There is also much greater potential for using combined heat and power systems in the commercial sector (as well as in large residential apartment buildings and new residential developments), which use waste heat from an electric generating system to provide heating and air-conditioning, the latter using absorption air-conditioners.

Overall, with moderate investment in efficiency and combined heat and power systems, energy use in the residential and commercial sectors can be reduced by 20 percent compared to 2005 even as per person area expands and per person use of appliances is the same as under "business as usual assumptions." An investment in efficiency (including geothermal heat pumps), combined heat and power, and solar hot water heaters of $15 to $20 per square foot overall is estimated. These figures are part of the Reference Scenario developed in Makhijani 2008. Table 1 shows the comparison of costs for energy services in GDP terms in the year 2050. The renewable energy system costs are comparable to the business-as-usual costs, even under the assumption of much more expensive energy supply under the renewable scenario. The main difference is the efficiency investments.

It should be noted that the "business-as-usual" scenario is a construct to estimate the energy services that would be required in the future; it is not a realistic projection of continued present-day energy supply patterns and prices. The delivered prices of fossil fuels and nuclear energy, which can expect to be the mainstays of a business–as-usual approach, are likely to be considerably higher than those assumed in Table 1. Indeed, their continued use and expansion will likely entail much higher costs than shown in Table 1. In other words, we may expect that a redirection towards a much more efficient buildings sector will save a great deal of money relative to a persistence of present building norms.

Table 1: Comparison of CFNF and Business-as-Usual Residential and Commercial Costs, GDP Basis

Table 8-4: Annual Residential (R) and Commercial (C) Energy and Investment Costs in 2050, in Billions of Constant 2005 Dollars

Item	IEER Reference Scenario	Business-as-Usual Scenario
R + C Electricity	$326	$442
R + C Fuel	$150	$247
Sub-total energy cost	$476	$689
Added annual investment for efficiency (Notes 2 and 3)	$205	$0
Total GDP-basis amount (rounded)	***$681***	***$689***
GDP in 2050 (Note 4)	$40,000	$40,000
GDP fraction: residential and commercial energy services	***1.70%***	***1.72%***

Notes:
1. Business-as-usual (BAU) fuel and electricity prices: about $12 per million Btu and 9.6 cents per kWh. Reference Scenario prices: $20 per million Btu and 14.1 cents per kWh respectively. BAU electricity price is from January 2006.
2. Added efficiency investments: existing residences: $20,000 per residence each time, assumed to occur in one of every three sales of existing buildings between 2010 and 2050; new = $10 per square foot (about $20,000 per house, approximate LEED-certified house added cost); plus cost of replacing appliances every 15 years with then-prevailing advanced appliances. Investments for solar thermal heating, combined heat and power, and geothermal heat pumps added to these figures for the proportion of residential area using them. LEED stands for Leadership in Energy and Environmental Design; it is a building certification program.
3. Commercial efficiency investments: $10 per square foot; this is more than examples of platinum level LEED investment. Investments for solar thermal heating, combined heat and power, and geothermal heat pumps have been added to these figures.
4. GDP = consumption expenditures + investment + government spending (on goods and services) + exports – imports.

Source: Makhijani 2008, Table 8-4 (p. 162)

Much greater reduction of energy use that assumed in the Reference Scenario in Makhijani 2008 is possible without reduction of the energy services (like heating, cooling, and lighting) with more vigorous pursuit of building standards, which could include zero-net energy residential buildings and parallel requirements for commercial buildings. These have not been included in the above estimates for the CFNF Reference Scenario, for which efficiency achievements have been rather conservatively estimated. That said, it will require suitable financial, policy, legal, and regulatory mechanisms to overcome the problem of the split incentive and of an energy sector oriented towards supply.

Vehicular transportation efficiency is also poor. Overall, only about 15 percent of the energy in the gasoline goes to move the car and its passengers, and most of that is for moving the car. If the energy used to move the passengers is used as the criterion, the typical efficiency of personal internal combustion engine cars is on the order of only one percent. High vehicle weight relative to passengers, loss of energy as waste heat in the process of converting the chemical energy in gasoline to the mechanical energy at the crankshaft, and loss of energy at stop lights due to braking are all factors leading to low efficiency.

All-electric vehicles using today's materials and advanced batteries charged using solar PV or wind-generated electricity can get the equivalent of about 120 miles per gallon.[8] A factor of two improvement should be possible in this performance with more advanced car construction materials and more advanced batteries and/or ultracapacitors, using technologies that are on the horizon. An added investment of $24,000 in an all-electric car would be justified for a vehicle such as a taxi that is driven 50,000 miles per year; the corresponding figure for a typical family car, driven 15,000 miles per year, is $7,000. Both assume a five year payback time.[9]

With advanced efficiency, electrifying the personal transportation sector would require ~10 to 15 percent of present-day electricity use. More than this can be saved using available efficiency measures that are economical. The evolution of electricity use in the Reference Scenario in Makhijani 2008 is shown in Figure 3.

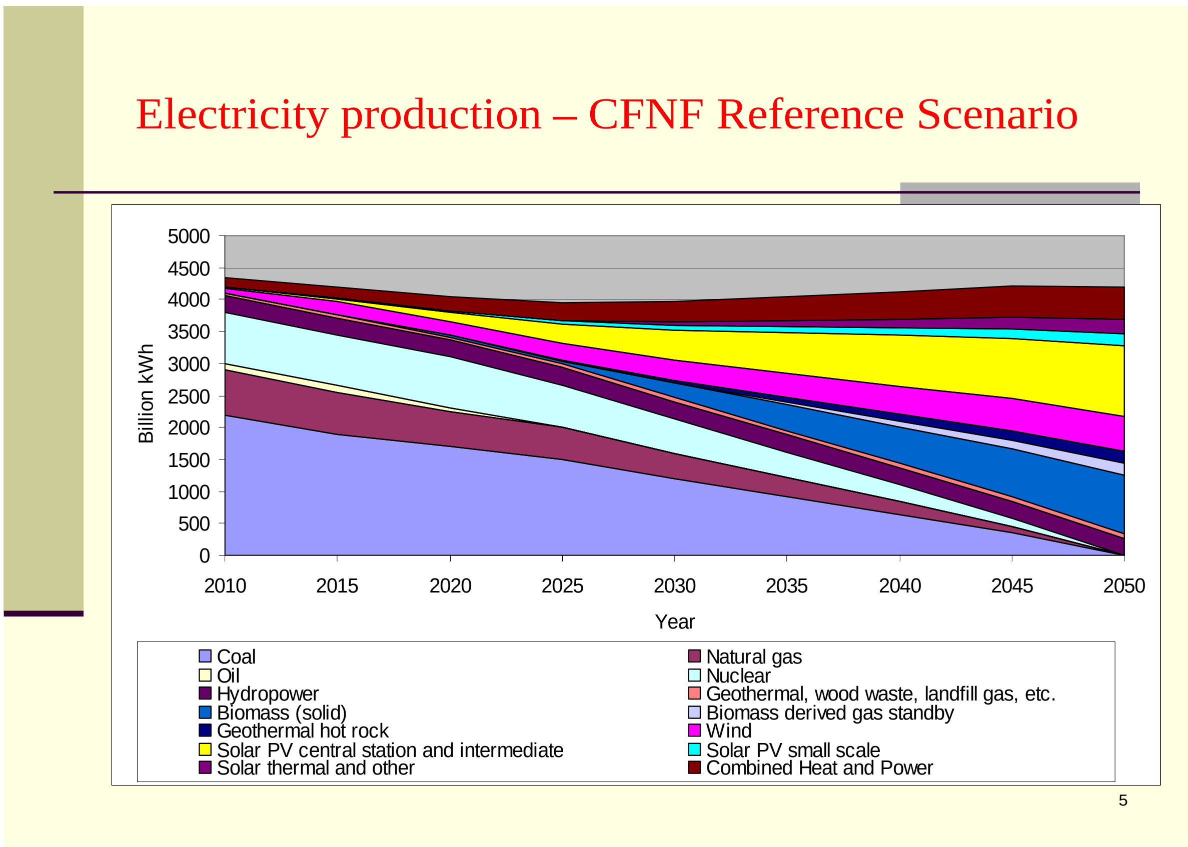

Figure 3: Electricity Use in the Reference Scenario in Carbon-Free and Nuclear-Free: Roadmap for U.S. Energy Policy

Source: Makhijani 2008

[8] Assumes presently available performance: an electric car that uses 250 watt-hours per mile of electricity and 85 percent battery charging efficiency.

[9] Electricity cost at 10 cents/kWh; gasoline at $3/gallon. Vehicle efficiencies: gasoline – 25 miles per gallon; all electric car 4 miles per kWh. The payback time for a typical urban taxi would be much shorter since mileage if often considerably less than 25 mpg. Reduced electric vehicle maintenance (shorter payback time) and battery replacement (longer payback time) are not taken into account.

B. Wind and Solar Energy Availability

The United States is a renewable energy paradise. Land-based wind energy resources for large-scale development in the top 20 wind potential states (excluding unavailable area such as national parks, and urban areas) amount to more than two-and-a-half times the total U.S. electricity generation in 2005. This is considerably more than all the oil production of all OPEC countries put together, were it used to generate electricity with similar efficiency to the use of coal today. Six states – North Dakota, Texas, Kansas, South Dakota, Montana, and Nebraska *each* have more wind energy potential than all 104 U.S. nuclear power plants put together.

In addition, the United States has considerable offshore potential off its sea coasts, as well as in the Great Lakes region. The offshore potential is especially important since it is near the areas of high population density and high total population. If the legal and political objections can be overcome, as they have been in much of Europe, properly sited offshore wind generation can be increased without waiting for the construction of a large-scale transmission infrastructure. Denmark has extensive experience with offshore wind (since 1991) and has recently completed a comprehensive environmental assessment. Its conclusions are as follows:

> The comprehensive environmental monitoring programmes of Horns Rev Offshore Wind Farm and Nysted Offshore Wind Farm confirm that, under the right conditions, even big wind farms pose low risks to birds, mammals and fish, even though there will be changes in the living conditions of some species by an increase in habitat heterogeneity.
>
> The monitoring also shows that appropriate siting of offshore wind farms is an essential precondition for ensuring limited impact on nature and the environment, and that careful spatial planning is necessary to avoid damaging cumulative impacts.[10]

Offshore wind generation near present-day industrial areas on the coasts and the Great Lakes region can also be used to accelerate the replacement of fossil fuels in industry since it can be used for distributed electrolytic hydrogen production. This hydrogen can be used in place of natural gas derived hydrogen in industry, for instance.

Solar energy is even more plentiful than wind. Only about 10,000 square miles of land in the southwest could supply the entire electricity generation of the United States in 2005.[11] Constructing solar PV over parking lots, over urban highways and other similar areas (such as unused land near airports) as well as on commercial rooftops can supply much or most U.S. electricity requirements (given efficiency improvements).

C. Dealing with Intermittency

Intermittency does not become a significant issue until they assume a share of the electricity system much greater than the present one percent. Wind energy deployed with due attention to geographic diversity can supply ~15 percent of electricity generation with only a modest increase in reserve requirements. Reserve requirements can be reduced if wind and solar are coordinated. Due to the huge overbuilding of natural gas fired power plants in the last two decades, done in anticipation of continued cheap gas supplies, a significant

[10] Dong Energy, Vatenfall, Danish Energy Authority, Danish Forest and Nature Agency, *Danish Offshore Wind: Key Environmental Issues* (November 2006) at http://windpower.utah.edu/pdfs/danish_study.pdf. The quote is from the first page of the Executive Summary.
[11] At 15 percent PV module efficiency or solar thermal equivalent; non-tracking solar PV arrays at 10 degree tilt.

surplus of natural gas capacity is available as standby capacity.[12] Reserves can be complemented in many areas by using hydropower in a manner that is coordinated with wind energy availability. Finally, by taking advantage of the diversity in solar and wind energy and building a smart grid, a solid foundation for a distributed grid can be laid in the next 15 to 20 years.

A smart grid approach is important. At present, we have what we may call the "dumb grid": there is no communication between consuming and producing devices other than the flip of a switch by the consumer, who is completely in the dark about the state of the system. This means that electricity generation must occur whenever it is demanded and whatever the stress that the flip of the switch may put on the system. This results in higher costs, lower efficiency, and lower reliability.

Smart meters and control points at the consumer's end that receive information about the state of the system and mediating storage devices can reduce costs, increase the value of renewable energy sources, notably of wind-generated electricity, and make the system more reliable for a given amount of money. For instance, a laptop and software can connect a bank of central air-conditioners and ice-making machines to wind electricity production. Ice is made when the wind is blowing, which is very often at night, when electricity is least needed. The coldness stored in the ice can then be used during the peak of a hot summer day for providing air-conditioning. The marginal value of wind-generated electricity at night might be one or two cents per kilowatt-hour. Some wind energy is "spilled" – that is, there is no demand even though the wind is blowing. Since almost all the daytime electricity use for air-conditioning would now be supplied whenever the wind is blowing, the value of wind-generated electricity would correspond to that experienced by the utility at peak load times – often in the range of 10 to 20 cents per kWh.

A Colorado-based company, Ice Energy,[13] makes machines that can be combined with central air-conditioners in the manner described to provide controllable resources to the electricity system.[14] This kind of system is even useful when combined with solar PV generation. Figure 4, provided by Ice Energy, shows the electricity consumption of a net zero energy home (ZEH)[15] on a typical peak summer day (light blue line) compared to a conventional home (yellow line). It also shows a computer model of the net ZEH home electricity use on the same day as it would be if it were combined with an ice-energy system.

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[12] The capacity factor of U.S. natural-gas fired power plants, excluding industrial captive plants, was only 18.6 percent. The total capacity is well over 300,000 megawatts of capacity.

[13] See the website of the company at www.ice-energy.com. See also the July 16, 2007, *New York Times* article by Matthew L. Wald entitled "Storing Sunshine" at http://www.nytimes.com/2007/07/16/business/16storage.html

[14] Trane and Carrier make central air-conditioning systems compatible with Ice Energy Machines.

[15] The net zero energy (i.e., home renewable electricity production equals utility electricity used) is calculated over a whole year (assuming typical weather conditions). The home is still a net electricity importer on peak summer days when the solar energy production is much lower than consumption.

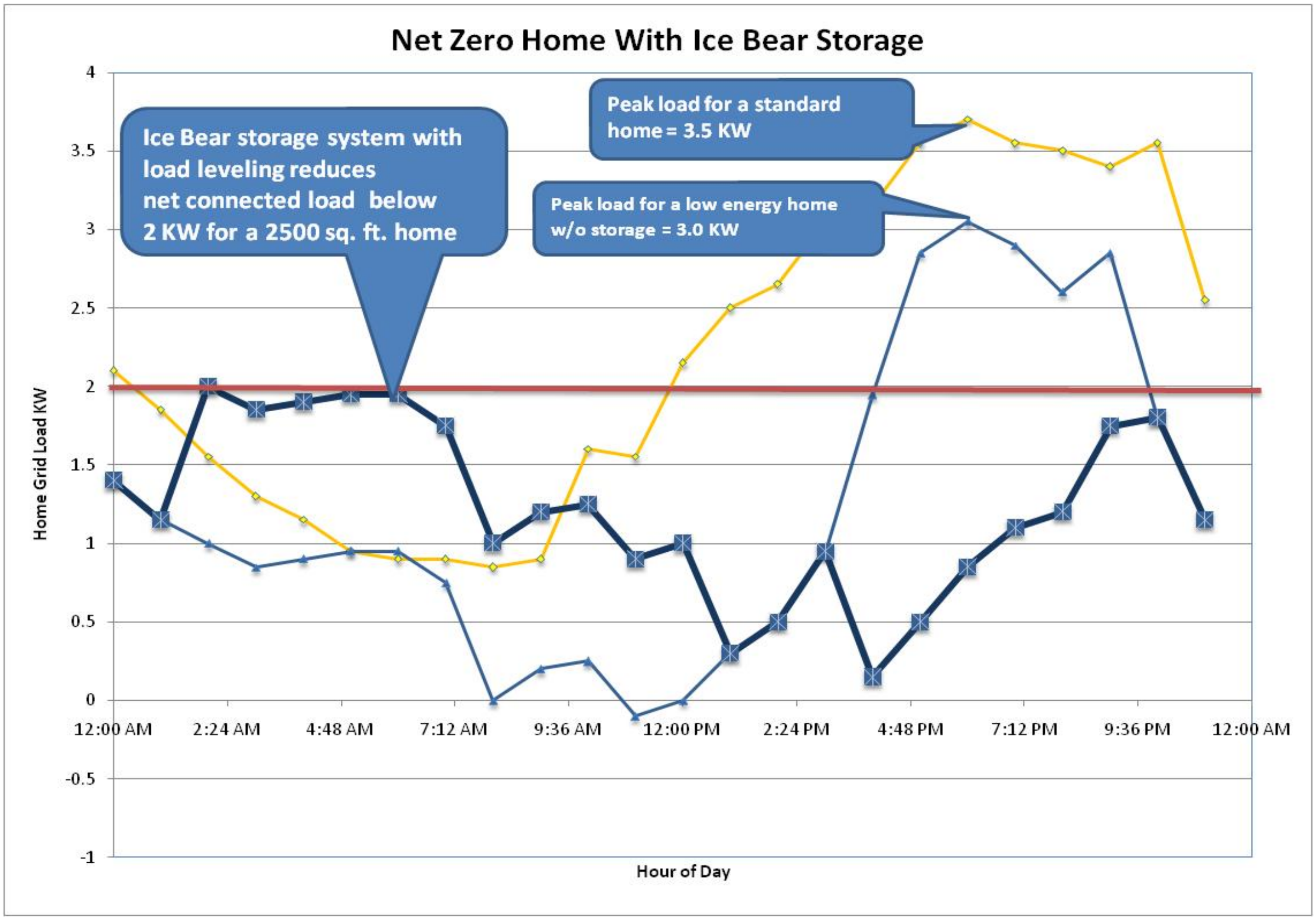

Figure 4: Conventional and Zero Net Energy Homes in the Sacramento Municipal Utility District area, with computer simulation of an Ice Energy machine ("Ice-Bear")

Source: Graph courtesy of Ice Energy, www.ice-energy.com, with permission

While efficiency and solar PV reduce the peak load by about half a kilowatt at the time of system coincident peak (6 p.m.), there is a much greater reduction when this is combined with coldness storage.[16] The overall peak reduction relative to a conventional home is now increased, with ice storage, by almost five times, from about half a kilowatt to over 2.5 kilowatts. Estimated peak load reduction relative to the net Zero Energy Home is over 2 kilowatts at the time of system peak (6 p.m.). Ice Energy is working with utilities to implement this system and with the National Renewable Energy Laboratory to make measurements and to refine it.

There can be other refinements. An experiment in Holland has shown that wind energy can be coupled to existing cold storage warehouses for food. The temperature of the warehouse is lowered slightly below normal food storage temperatures when the wind is blowing and then the refrigeration system is cut off during the peak electricity demand period. With smart meters in all buildings, every freezer can become a renewable energy storage device.

A smart grid that incorporates distributed generation (small-, medium-, and large-scale units) and nested levels of grids (micro-, intermediate-, and large-scale) will also be more secure. It will be far less likely to have

[16] The peak of the air-conditioning in the home occurs earlier, but system peak occurs at 6 pm due to the combination of air-conditioning, lighting, television, cooling, etc., demand when people return home from work.

large-scale breakdowns, such as the one that occurred in the Eastern United States in August 2003. That blackout occurred due to a problem at a single interchange point in the Eastern Interconnect near Cleveland. For the same reason, a smart, distributed grid will be far less vulnerable to terrorist attack, both in terms of lower attractiveness as a target and far lower damage in case of attack.

Some form of storage of renewable that will enable electricity supply when it is needed will be required at high levels of renewable electricity generation. The types of storage include pumped hydro (using existing reservoirs), compressed air storage, and storage of heat at central station solar thermal power plants in oil, molten salt, water, or other media. Arizona Public Service has ordered a solar thermal power plant with enough heat storage for generating electricity for six hours. This will enable electricity generation for 90 percent of the time on summer days.

A smart grid will allow optimization of heat and coldness storage with solar and wind energy. It will also change the meaning of baseload, intermediate load, and peak load as we know it today. For instance, in Figure 4 above, the highest summertime load put on the system by an efficient house equipped with a rooftop solar PV and an ice-energy system occurs between 2 a.m. and 6 a.m. And were one of the control points actuated by the availability of wind energy on the grid, a load curve that partly follows the availability of solar and wind combined could be created. This would leave large-scale concentrating solar thermal power plants with heat storage and large-scale solar PV plants to supply day time commercial, industrial, and other residential loads. Further, there is a wind energy concept that is being developed that will enable disptachable electricity generation from wind. The turbine drives an air compressor not an electric generator. Then the compressed air is stored (either for a few hours storage in tanks or a few days in a geologic reservoir) and is used to generate electricity as needed. See www.generalcompression.com. The website is not very informative, but the concept is most interesting.

It is not difficult to see that the concept of baseload, intermediate load, and peak load will change substantially in a renewable smart grid that has efficiency, storage, large-scale renewables, and some renewable generation built into the consumer's end of the system. In that kind of grid, the energy is gathered when renewable resources are available and the energy services, like cooling and refrigeration and lighting are provided when needed.

We assume that some conventional generation capacity, fueled by renewable will likely be required to support a grid in which solar and wind play dominant roles (in the absence of transformative technology breakthroughs like very cheap electricity storage). Biomass can be a significant source of renewable energy for electricity with the major caveat that agricultural land or land suitable for agriculture not be used for fuel. In any case, most food plants have very low solar energy capture efficiency – typically much less than one percent; therefore they cannot be a mainstay of energy supply due to unacceptably high land requirements. Even sugarcane, which captures sunlight with about one percent efficiency, is not a suitable basis for large-scale energy use, at least in the United States. Moreover, it requires energy intensive inputs as well as agricultural land. It is best to use high efficiency plants that do not require agriculture land or quality water resources to produce biomass. Productivity of several aquatic weeds, such as microalgae, water hyacinths, and duckweed, ranges between 100 metric tons to 250 metric tons per hectare per year (compared to ~10 metric tons per hectare for corn and about twice that for the entire corn plant). Aquatic plants, notably, microalgae, are very prolific sources of biomass, including for electricity generation. Moreover, they can be grown in wastewater and in brackish water. While microalgae can be converted into liquid fuels for use in internal combustion engines, solid biomass can be used for electricity generation and co-generation using integrated gasification combined cycle (IGCC) power plants that were initially developed for coal. A medium-scale Swedish IGCC plant – six megawatts of electricity and nine megawatts-thermal of heat – was demonstrated to have successful technical performance with low emissions on a variety of fuels – mainly wood, but including straw and municipal waste – between 1993 and 1999.[17] A large-scale demonstration plant using this technology with various aquatic plants, preferably grown as part of wastewater treatment, should be an urgent priority. Such biomass generation can provide some of the baseload capacity that will likely be needed even in a smart grid renewable system (unless storage becomes very cheap); it can also be used in combination with carbon sequestration methods to remove CO_2 from the atmosphere. This may be needed to achieve climate protection goals in the coming decades. Geothermal energy is another obvious candidate. Biogas derived from high efficiency biomass can provide the fuel to replace natural gas for standby capacity. Finally, combined heat and power plants can and should be a part of renewable energy system optimization as they increase efficiency and provide standby capacity. They fueled by liquid or gaseous fuels derived from biomass or possibly with hydrogen derived from wind or solar energy.

D. Nuclear Energy

Many people have come to believe that nuclear energy is necessary to protect climate and achieve a phaseout of energy-related CO_2 emissions rapidly and reliably. James Lovelock, for instance, has stated that the world should be like France, which gets 75 to 80 percent of its electricity from nuclear energy.[18] Others want to leave nuclear energy "on the table" because they fear that renewable energy sources are not reliable enough or that the effects of intermittency cannot be overcome. These beliefs and fears arise from an understandable tendency to lean towards the known way of doing things, since the costs of more frequent electricity system disruptions are far greater than can be measured in the value of the lost electricity alone. However, our assessment of the technical and economic feasibility of a fully renewable electricity system and that path to get there should be not be driven by apprehensions or utility conservatism, but on a careful assessment of the present rapidly evolving state of energy technology. We are not lacking in low- or zero-CO_2 energy sources; it is money and time that are limited – the latter dictated, of course, by the urgency of the climate crisis. In an age of laptops and the Internet, it is critical not to be intellectually stuck in the age of punch cards and mainframe computers. They were brilliant in their time but we could hardly have the tremendous power at our fingertips that we have today without courageous technological leaps and corresponding policies and investments. They have become such a central part of the global economy and society that we have today a U.S. President-elect who is utterly attached to the information power that his Blackberry literally puts in his hands at all times.

Nuclear energy cannot be a significant help in overcoming the most pressing short-term CO_2 issue in the United States: urgent reduction of CO_2 emissions from coal-fired electricity generation by obviating the need for new coal-fired power plants and by reducing the need for existing ones in the next ten years. While there are applications and expressions of interest for as many as 34 new nuclear reactors in the United States, the earliest time at which a reactor may come on line if there are no delays is the year 2016. Industry estimates put the number of reactors that can be built at 4 to 8 in the next ten years. Assuming six reactors and a total installed capacity of about 8,000 megawatts becoming available between 2016 and 2019, the total expected *cumulative* generation from new nuclear power plants in the next decade would be on the order of 130 billion kWh. This amount cannot be increased significantly for a variety of reasons, including limited industrial capacity, lack of sufficient trained manpower, and the need to scrutinize new designs that are either not certified or certified designs that are being modified.

[17] Krister Stahl, Lars Waldheim, Michael Morris, Ulf Johnsson, and Lenhart Gardmark, *Biomass IGCC at Värnamo Sweden – Past and Future*, GCEP Energy Workshop, Stanford University, Palo Alto, CA, April 27, 2004, at http://gcep.stanford.edu/pdfs/energy_workshops_04_04/biomass_stahl.pdf.
[18] Arjun Makhijani, "Nuclear isn't necessary," *Nature Reports Climate Change* v.2 (October 2008), pp. 132-134 at http://www.nature.com/climate/2008/0810/pdf/climate.2008.103.pdf. Posted online October 2, 2008. "Commentary."

By contrast, 7,500 megawatts of wind capacity, the equivalent of about two large new nuclear reactors of about 1,300 MW each,[19] were added in 2007. Annual additions to capacity could be double that amount within a few years. Concentrating solar thermal power and solar PV are much smaller industries than wind today, but they are growing rapidly and their costs are coming down. Generating ten times as much electricity cumulatively from new wind and solar installations during the next ten years is well within the achievable range. Efficiency and smart grid elements can greatly increase the reduction of emissions. Investing hopes and money and governmental resources, including 100 percent loan guarantees, which the nuclear industry wants, and advance ratepayer money, is an unwarranted diversion of resources for little gain. Moreover, with the costs of solar PV and CPS coming down and wind-generated electricity already being cheaper than new nuclear plants, there is a significant probability that merchant nuclear plants will not be able to compete. In that case, the likelihood of default would be correspondingly high.

Over the next decade an emphasis on nuclear would result in hundreds of millions of metric tons of additional CO_2 emissions compared to going ahead with efficiency and renewables. The additional emissions due to the deficit of low CO_2 sources in the nuclear case would continue for many years after the first decade, since the low CO_2 generation gap would persist for some time.

The common assumption that nuclear energy is needed to address CO_2 issues arises partly from a theoretical notion about the role of baseload power in future electricity systems. This notion is misplaced; it does not take into account available technology in efficiency and storage. Neither does it consider the advances in electronics and information technology that allow smart grids to be implemented. Moreover advocates of a large role for nuclear energy have not put forth a comparative CO_2 reduction schedule that would demonstrate the compatibility of that approach with the urgent imperatives CO_2 emissions reduction for climate protection.

The uncertain economic climate only adds to the problems arising from the long time it takes to build a nuclear power plant. In this context it is important to remember that the first energy crisis that started in October 1973 also led to an intensified interest in nuclear power. But none of the reactors ordered after that date were completed. More than 100 were cancelled, resulting in tens of billions of dollars of losses for ratepayers, stockholders, utility bondholders, and banks. Facing the reality of the nuclear industry makes it clear that nuclear energy would be too little, too late, too risky, and too costly to successfully address a significant fraction of the CO_2 problem.

The problem of long lead time is also applies to “clean coal” technology. It is important to develop carbon sequestration technologies both for the redundancy it would provide to create a low to zero CO_2 system and as an approach that could very useful in removing already-emitted CO_2 from the atmosphere. But relying on “clean coal” to address a significant portion of CO_2 emissions reduction in the next two decades is far too risky. The safest course is to intensify work on and investment in an efficient, renewable smart grid.

The prospects for new designs of reactors, such as the fast neutron reactors, to play a role in addressing urgent climate change issues are even worse. One hundred billion dollars (1996 dollars) have been spent world wide trying to commercialize such reactors and their associated plutonium separation, fuel fabrication, and fuel use technologies. This effort has been an economic failure. Even the underlying fast neutron reactor technology is not developed enough to be firmly commercialized. For instance, the most recent demonstration reactors, such as the Monju reactor in Japan and the Superphénix in France (by far the largest such reactor ever built), have had severe problems. Monju had a secondary loop sodium fire in 1995; it was commissioned in 1994. It has not yet reopened as of

[19] One megawatt of wind is typically the equivalent of about 35 percent of a megawatt of nuclear in terms of total annual electricity generation per unit of installed capacity.

the end of January 2009. Superphénix was closed after 14 years of operation at an average capacity factor of about seven percent.[20]

It should be noted that proposals to pursue the Integral Fast Reactor have not publicly addressed these problems. Why has there not been a clear learning curve to the commercialization of either sodium-cooled fast neutron reactors or the various reprocessing technologies that have been proposed? The PUREX technology in use in France can be called commercial only in the sense that governments are paying for reprocessing services. But it is not commercial, in the sense that it remains far more expensive than using fresh uranium fuel. So far, France only reuses about one percent of the spent fuel as fuel.

The specifics are as follows. About one percent of the spent fuel is plutonium, but not all of it is used as fuel – some is stored as surplus – there are over 80 metric tons of plutonium stored at La Hague, enough to make about 10,000 bombs. The majority if French, but there is also a significant amount owned by others, including the Japanese, who have contracted with la Hague for reprocessing services. The about 85 percent of the uranium (which is 95 percent of the spent fuel) is simply stored and has not been reused. About 15 percent has been sent to Russia for re-enrichment, and most of this then becomes depleted uranium stored in Russia. The 15 to 20 percent of this uranium that becomes fuel has been loaded into reactors (the rest is depleted uranium that is left over from the re-enrichment process). But then only about five percent of the fuel actually generates electricity (since most of it is U-238, which is not a fuel and just two percent of this is converted to plutonium in the course of reactor operation).[21] Hence, so far France has used less than one-fifth of one percent of recovered uranium to as material that has been fissioned in reactors and actually generated electricity. Overall, it would be fair to say that about one percent or just over one percent of the reprocessed spent fuel has been used as fuel in France. In the context, based on current reality, the term "recycling" for French spent fuel management is 99 percent false – or if one puts it more positively, about one percent true. Further, MOX fuel creates a proliferation risk since it can be chemically separated into a weapons-usable (plutonium) and non-weapons-usable component (depleted uranium) without much sophistication or danger of immediately lethal radiation exposure. It also results in higher costs to the French consumer and the discharge of about a hundred million gallons of radioactively contaminated liquids into the English Channel.[22] Further, French high-level waste (four percent of spent fuel by weight and most of the radioactivity) is piling up on storage at the French reprocessing plant. A geologic repository is needed, and the French have a program to create one, but it has run into problems, including difficulties of public acceptance quite similar to those in the United States. Ninety five percent of spent fuel consists of contaminated uranium; almost all of it is piling up – some in Russia (where it was sent) and most of it in France. Only a very small portion of French fuel is "recycled" in the strict sense of being used as new fuel that actually produces energy.

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[20] For an analysis of the development of the plutonium fuel cycle, including breeder reactors (the most common design of which is the fast neutron sodium-cooled reactor) see Arjun Makhijani, *Plutonium End Game: Managing Global Stocks of Separated Weapons-Usable Commercial and Surplus Nuclear Weapons Plutonium* (Institute for Energy and Environmental Research, Takoma Park, Maryland, January 2001), at http://www.ieer.org/reports/pu/peg.pdf. Hereafter Makhijani 2001.
[21] All values are rounded.
[22] For details see Makhijani 2001 and Annie Makhijani, Linda Gunter, Arjun Makhijani, *COGEMA: Above the Law? Concerns about the French Parent Company of a U.S. Corporation Set to Process Plutonium in South Carolina* (Institute for Energy and Environmental Research, Takoma Park, Maryland, May 7, 2002). The latter is on the web at http://www.ieer.org/reports/cogema/report.html.

C. Electricity System Investments

Any electricity system will require huge investments over the next several decades. A fossil fuel- and nuclear-oriented system will require investments in new power plants but also in uranium and coal mines, natural gas fields, possibly in reprocessing plants for nuclear spent fuel, fuel preparation and processing plants, uranium enrichment plants, and the like. A system with fossil fuels in it will require large-scale carbon-sequestration investments, which may be one of the largest costs of such a system. In addition, since building nuclear power plants takes seven to ten years from start to finish, few such plants can be built in the next decade or so. Carbon sequestration is not yet commercial. Hence a business-as-usual approach is very likely to incur huge CO_2-related costs if energy policy is seriously oriented towards reducing greenhouse gas emissions. However, putting a specific price tag on the added costs is very difficult in the context of the very limited capacity of nuclear to address the CO_2 issue (see below) and the uncertainty of the timing and cost of carbon sequestration.

A renewable electricity system will also require large-scale investments – in the manufacture of solar cells and solar thermal and wind power plant components, in biomass and geothermal power plants, and infrastructure and the like. It will also require some additional investments in energy storage and smart grid elements, and possibly also larger investments in transmission lines due to the dispersed nature of solar and wind resources. By the same token, transmission costs can be reduced if a large fraction of the solar PV capacity is built on commercial parking lots and rooftops, etc., as discussed above.

Creating a fully renewable electricity system is far less risky both in terms of climate protection and finances than trying to approach climate change by coal with CCS (carbon capture and sequestration) and nuclear. This is especially so in the context of an economic crisis. Wind projects can be completed in two to three years. Solar PV projects can be completed in less than a year. They are also far more modular than nuclear power plants. Investments can therefore closely tailored to the evolving demand situation, costs associated with a price on CO_2 emissions, and regulatory and legal requirements, such as those created by Renewable Portfolio Standards. Storage and smart grid development can be similarly tailored.

A study of the electricity system of the municipal utility owned by the City of San Antonio, Texas, CPS Energy, showed that it would save between $1.4 billion and $3.1 billion to invest in a combination of efficiency, combined heat and power, ice energy storage, and a solar thermal power plant than purchasing new nuclear capacity to do the same job. These savings did not include the early CO_2 reductions that would be achieved by the efficiency-renewables approach.[23]

If the transition occurs over about four decades, the total investment costs in the U.S. electricity system would be about $5.2 trillion, in 2007 dollars. Annual operating costs after the transformation of the electricity system are also shown. The details of the per unit capital costs as well as the maintenance and fuel costs for the various system elements are also shown. It should be noted that the amount of storage deemed necessary is rather low (one-fourth of average daily system generation) because of the following factors:

- It is assumed that wind and solar investments will be optimized along with the corresponding heat and coldness storage elements.
- About one-third the wind capacity will be offshore, which typically has a higher capacity factor than land-based wind energy.
- Standby capacity of over 20 percent of wind capacity is provided.
- Baseload generation will provide 20 percent of the overall electricity use.

[23] Arjun Makhijani, *Energy Efficiency Potential: San Antonio's Bright Energy Future*, Institute for Energy and Environmental Research, Takoma Park, Maryland, October 9, 2008, at http://www.ieer.org/reports/SanAntonioEnergyEfficiencyPotential.pdf.

- A smart grid incorporating all the above, smart meters, and storage elements such as vehicle-to-grid technology, stationary batteries, compressed air storage, etc.

The cost elements are estimated as follows, in 2007 dollars. Some cost reduction in solar technology, which is widely expected, is assumed (though not to the extent that can be found in the literature):[24]

- **Solar CSP with storage**: 250 GW, $750 billion (@$3,000 per kW)
- **Solar PV**: 250 GW, $500 billion (@$2 per peak watt, installed – expected in a few years from now)
- **Wind**: 400 GW, $1,000 billion (mix of 2/3 land-based @$2,000 per kW and 1/3 offshore at $3,500 per kW)
- **Combined Heat and Power**: 100 GW, $100 billion.
- **Baseload (biomass IGCC, geothermal, etc., no CCS):** 120 GW, $600 billion.
- **Biogas standby generation**: 90 GW, $140 billion (@$1,500 per kW).
- **Replacement of wind and solar PV** (1/3 of total in 40 years): $500 billion.
- **Storage, smart grid elements**: $300 billion + replacements over 40 years, $200 billion = $500 billion total. Average capital cost of storage elements ~$100/kWh.
- **Transmission system**: $1,100 billion.
- **Total (rounded):** $5,200 billion, constant dollars spent over time.
- **Present value @ 6% discount rate, assuming uniform expenditures over 40 years (carbon-free, nuclear-free in 2050)**: ~$2,000 billion.
- **Estimated annual operating and maintenance expenses in 2050**: ~$120 billion.

Existing nuclear power plants would be phased out as their licenses expire (unless there are safety reasons to close some of them earlier). Note that the total generation in 2050 is not much different than present-day U.S. generation. This is because efficiency and smart grids will play a much larger role in providing energy services than they do today. A near complete electrification of personal vehicles and a partial electrification of other land transportation can be accomplished in this context without significant increase in total generation. Note that the assumed role of efficiency in Makhijani 2008 is considerably less than can be accomplished with existing building design techniques and technology.

D. Steps in the Creation of a Fully Renewable Electricity System

Getting to a fully renewable electricity system that is reliable and secure from the present fossil fuel and nuclear dominated system requires different things at different stages. In other words, the requirements are quite different when solar and wind contribute a few percent of total generation than when they contribute 20 or 30 percent or more of generation. Further short term requirements for making large quick reductions in CO_2 emissions will put a premium on efficiency investments. Further, existing natural gas plants are available in the short term to firm up wind and solar as they grow, but they will need to be replaced by renewable capacity. Similarly, existing nuclear power plants are essential to maintaining system reliability in the short-term; but they can be phased out and replaced by renewables as their licenses expire. The following gives an idea of the roles of the various technologies at different stages of the conversion to a renewable electricity sector. This is in the nature of an illustration rather than a prescription.

- Phase 1, short-term (to 2015): Deploy increasing amounts of wind-generated electricity and associated transmission infrastructure, combined heat and power (CHP), local solar PV (parking lot, rooftop, excess airport areas, e.g. Dallas Ft. Worth), Concentrating Solar Power with heat storage and some large-scale PV + associated transmission. Smart grid elements would begin to be put into place.

[24] The proportions of the generation elements for which costs are estimated here are different than in the Reference Scenario in Makhijani 2008. This is an updated version that is estimated to have lower overall costs.

Existing natural gas generation and (as much as possible) hydro would be redeployed (in terms of their functions) and used largely as backup and reserve capacity as renewable capacity grows. Begin large-scale revamping of existing building efficiency and put in place standards for new buildings. Implement demonstration projects (such as biomass IGCC)

- Phase 2, medium-term (2015-2030): Continue renewable, efficiency, CHP, etc. investments, as in Phse I; phaseout existing of coal, begin nuclear phaseout, put extensive storage and smart grid elements in place, biomass IGCC (possibly with CCS, pyrolysis/biochar storage to remove atmospheric CO_2). Use aquatic plants (microalgae, water hyacinths, duckweed, etc.), prairie grasses. Aim to remove CO_2 from atmosphere as part of energy system design. Complete efficiency and renewable energy upgrades of existing buildings, with all new buildings being built to zero net-energy standards some time in this period. Continue demonstration projects (such as vehicle-to-grid, hot rock geothermal energy, etc.) and begin large-scale implementation.
- Phase 3, long-term (2030-2050): complete phaseout of coal and nuclear; replace natural gas with biogas in central station and CHP. Hydrogen fuel CHP would be preferable if hydrogen production from solar and wind energy is developed. This could possibly be implemented in Phase 2, with a vigorous research, development, and demonstration (RD&D) program.

While the nominal time frame assumed for the transformation is by the year 2050, the present state of the technology and the direction of its development is such that, with sound climate protection and energy policies that put efficiency (especially standards for new and existing buildings) and smart grids at the foundation of future development along with suitable carbon pricing policies, a considerably faster transformation can be accomplished.[25] In this context, one may note that the Department of Energy estimated that a wind energy capacity of over 300 million kW (300 gigawatts) could be installed by the year 2030.[26] This is only about a quarter less than the capacity assumed for 2050 above. We may also note that, whatever one's views on nuclear energy, the French conversion from eight percent nuclear-generated electricity to 75 to 80 percent nuclear was accomplished less than 30 years after the decision was made to greatly reduce the role of oil from France's electricity sector made after the oil price shock of 1973. Given the current urgent need to protect the planet, a similar effort to create an efficient renewable electricity system in the United States is surely possible.

E. The Rest of the Energy System

The use of gaseous and liquid fuels for various purposes such as space and water heating in existing buildings, process heat and feedstocks in industry, and in transportation, notably air transportation is very high. The requirements will remain large even with efficiency improvements under typical economic growth assumptions, unless further efficiency measures are taken and technology changes are made to substitute hydrocarbons with other fuels, notably hydrogen derived from renewable sources, or electricity.

While aquatic plants, such as microalgae, water hyacinths, and duckweed, can greatly reduce land area requirements, the land area required would still be very large. Even if most of the needed biomass comes from aquatic plants, a modest amount required from prairie grasses or other similar plants quickly adds to the land area needed. Table 3 shows the Reference Scenario land area requirements in *Carbon-Free and Nuclear-Free*.

[25] See Table 6-1 in Makhijani 2008, p. 122.
[26] United States Department of Energy, Office of Energy Efficiency and Renewable Energy, et al., *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Energy Supply*, DOE/GO-102008-2567 (DOE, Washington, DC, , July 2008), p. 7, at http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf.

Table 3: Land Area Requirements for the IEER Reference Scenario (rounded)

Energy source	Land area, square miles	Side of a square	Comments
Wind	490	22	Mainly infrastructure, including roads
Centralized Solar PV	1,800	42	See note 2
Solar thermal (central station)	1,150	34	See note 3
Biofuels (solid and liquid)	184,000	429	About five-sixths of the area is harvested area for biomass; rest is microalgae and aquatic plants
Total	**187,440**	**443**	**About 5.3 percent of U.S. land area**

Notes: 1. Wind capacity factor = 30% and land footprint per megawatt = 0.6 hectares.
2. Solar PV efficiency = 15%; generation rate = 120 kWh/m²/yr.
3. Solar thermal: generation rate = 75 kWh/m²/yr.

Source: Makhijani 2008, Table 5-1 (p. 111)

It is noteworthy that the land-area requirements for renewable electricity in terms of the footprint of the facilities is very modest. It is the biofuels piece that creates significant issues. The Reference Scenario in CFNF has the merit of enabling a very straightforward comparison with a business-as-usual approach since it depends only on technologies that are either already commercial or developed enough that their commercialization can be anticipated in a decade or less, given sound policies. But with a strong research, development, and demonstration program a much more desirable approach to a renewable energy system can be created. The elements of such a system would be:

- More efficiency: 15,000 Btu/square foot residential, 30,000 Btu/square foot commercial accomplished by using more efficient building envelopes, more efficient and hybrid lighting, advanced geothermal heat pumps, etc.).
- Nearly complete electrification of land transportation.
- Distributed direct solar hydrogen production and/or electrolytic hydrogen production from offshore and onshore wind-generated electricity.
- TGV type trains to greatly reduce aircraft use for distances less than 1,000 miles
- Hydrogen-fueled aircraft. (Note: such aircraft would still have greenhouse gas emissions in the form of water vapor and NOx emissions. The amount of the effect is altitude-dependent, low at less than 30,000 feet. Emissions of water vapor + NOx from kerosene-like biofuels used in will be higher than hydrogen fuel.)[27]
- Combined heat and power with hydrogen fuel cells
- Hydrogen as basic feedstock material in industry (to a far larger extent than its use in industry today).

[27] For bar graphs showing relative greenhouse gas emissions of hydrogen vs. kerosene aircraft fuel at various altitudes see Makhijani 2008, p. 88.

G. Policies

A dozen policies, vigorously implemented, would do the job of creating a fully renewable energy system in the United States:

1. Put a hard cap on carbon dioxide emissions for large users (more than 100 billion Btu fossil fuels per year) or upstream cap for all carbon. All allowances should be sold in one national market, with no offsets and credits. Resale would be allowed in U.S. only. There would be no international allowance trading or offsets. If no clean allowance scheme, free of offsets and credits and international trading is possible, then a carbon tax is preferable. A 100 percent allowance sale was part of the Obama campaign commitments on climate protection. The hard cap would decline each year going to zero by a date certain.
2. Eliminate subsidies for fossil fuels, nuclear energy (no loan guarantees for new reactors), and biofuels from food crops.
3. Put a price on CO2 emissions rising to around $50 per metric ton of CO_2 in a decade and regulations (e.g., efficiency standards), and state Renewable Portfolio Standards for electricity. Most of the money would be returned to middle and low income people.
4. U.S. government energy investments (including assistance to state and local governments) of about $50 billion per year would probably be adequate to leverage a larger private effort in the context of a meaningful CO_2 price and regulations (notably efficiency standards for appliances, buildings, and vehicles). Another $50 billion or so would probably be needed as the U.S. contribution to developing country transition. A larger sum would be warranted for a few years in the context of the large expenditures being planned to address the current economic crisis.
5. Build demonstration plants; examples of needed plants include biomass IGCC, green crude, biomass pyrolysis and biochar storage, hybrid power plants, and demostratoins of local smart grids and vehicle-to-grid technology.
6. Leverage federal, state, local expenditures – e.g., carbon neutral buildings, electric or plug-in hybrids as the standard government vehicles, advanced efficient equipment
7. Ban new coal-fired power plants without CCS
8. Stringent state and local building standards and federal incentives for them – all new buildings net zero CO_2 by 2025?
9. Set stringent vehicle efficiency standards and make electric vehicles or plug-in hybrids standard government vehicle by 2015. The annual purchases by the federal, state, and local governments have been on the order of 300,000 vehicles per year. This would be enough to leverage the market and make efficient electric vehicles and plug-in hybrids widely available at reasonable cost in the context of competitive bidding.
10. Put in place federal contracting procedures to reward bidders who have low CO_2 emissions per unit of output in their industries.
11. Engage in a vigorous and consistent research, development, and demonstration (RD&D) program – especially direct production of hydrogen from solar energy, electrolytic hydrogen production, hydrogen aircraft (RD&D center in Wichita, Kansas?), stationery fuel cells for various applications including combined heat and power, advanced efficiency lighting (hybrid lighting, advanced LEDs), advanced air-conditioning systems with very high coefficients of performance, alternatives to steel and cement for construction, and strong light materials for vehicles. Encouraging RD&D to reduce feedstock requirements and increase efficiency in key industrial processes would yield considerable benefits.

12. Create a standing committee on Energy and Climate as part of the EPA Science Advisory Board

The energy system that would result from these policies would create many more jobs in the United States. For one thing, the $250 billion spent in 2007 on imported oil would be spent on domestic energy sources and efficiency. Overall, CFNF estimates that the proportion of GDP spent on energy services would be about the same as in a business-as-usual scenario (which assumes no turbulence and no costs of climate change, and which is therefore unlikely to be realized). The cost will be no higher than the rosiest of business-as-usual assumptions: a smooth ride ahead with fossil fuels and carbon sequestration, nuclear power, a modest role for renewable; cumulative carbon emissions would be much higher, and there would be no significant price on carbon emissions. Under any realistic set of climate protection policies, real world fossil fuel political-security dynamics, and real world proliferation threats, the actual cost of a business-as-usual approach will likely be much higher than that assumed in *Carbon-Free and Nuclear-Free*.

It will take vision and political courage to enact the tough policies that will be needed to create an economy free of fossil fuels and nuclear power. But an announcement of such an economy as the U.S. goal along with those policies can put the United States in a positive global leadership role on possibly the most critical issue to face humanity. That would surely help reverse the precipitous recent decline in the regard in which it is held in the world. More than that, the United States can help lead the world to a fully renewable energy system that reduces the threat of nuclear proliferation.