Large Energy Development Projects: Lessons Learned from Space and Politics

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LARGE ENERGY DEVELOPMENT PROJECTS: LESSONS LEARNED FROM SPACE AND POLITICS

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ABSTRACT

The challenge to global energy future lies in meeting the needs and aspirations of the ten to twelve billion earthlings that will be on this planet by 2050. At least an eight-fold increase in annual production will be required by the middle of this century. The energy sources that can be considered developed and "in the box" for consideration as sources for major increases in supply over the next half century are fossil fuels, nuclear fission, and, to a lesser degree, various forms of direct and stored solar energy and conversation. None of these near-term sources of energy will provide an eight-fold or more increase in energy supply for various technical, environmental and political reasons.

Only a few potential energy sources that fall "out of the box" appear worthy of additional consideration as possible contributors to energy demand in 2050 and beyond. These particular candidates are deuterium-tritium fusion, space solar energy, and lunar helium-3 fusion. The primary advantage that lunar helium-3 fusion will have over other "out of the box" energy sources in the pre-2050 timeframe is a clear path into the private capital markets. The development and demonstration of new energy sources will require several development paths, each of Apollo-like complexity and each with sub-paths of parallel development for critical functions and components.

I. INTRODUCTION

The economic, technical and political potential of providing adequate energy supplies on Earth must be evaluated in the context of probable global demand for energy and the reasonably competitive alternatives for meeting that demand. The immediate challenge to civilization's global energy future lies in meeting the needs and aspirations of the ten to twelve billion earthlings that will be on this planet by 2050.1 Current per capita use of energy is equivalent to about twelve barrels of oil per year for a global total equivalent to about seventy-two billion barrels of oil equivalent (BBOE) per year,2 or about 410 quads (quad = 10^{15} BTU) per year3. It can be argued, conservatively, that at least an eight-fold increase in annual production will be required by the middle of this century (See Table I). That increase includes a two-fold increase to account for the increase in the world population from 6.3 to ten billion and a four-fold increase to meet the major aspirations of four-fifths of the world's peoples whose standards of living are far below those of developed countries. Even an eight-fold increase would not bring the rest of the world to the current average per capita energy use in the United States of about 62 barrels of oil per year equivalent. As seen in Table I, that goal would take at least an eleven-fold increase, not counting the demands of new technologies and climate change mitigation.

The choice of an "aspiration" or economic growth increase of a factor of four is somewhat arbitrary. It represents, however, a level that not only would relieve much of world poverty and many international tensions but that would provide a measure of indirect control of population growth if not population stabilization at ten to twelve billion. The only historically proven means of a significant reduction in population growth lies in improved standards of living. Human experience shows that only increased energy consumption can provide such increases in living standards on a nation-by-nation basis. Of course, most nations that have both poverty and high fertility rates do not have political and economic systems that encourage increases in standards of living. That problem cannot be solved by new sources of energy supply but must be dealt with by example, education, and persuasion.

TABLE I. Projected Global Growth in Electricity Demand by 2050
(Derived from United States Department of Energy data).

Growth Category	Per Capita
Current Demand	12 BBOE
Population Doubling	12
Added Economic Growth (U.S. today)	62
New Technology Demand	?
Climate Change Mitigation	?
Total for 10 billion persons	860 BBOE
2050 Demand/Current Demand	11

Comparing the per capita energy consumption of countries that have raised living standards (and reduced birth rates) significantly in recent decades suggests an addition of a factor of only two to four to world energy supply by 2050 would have major impact on population growth. For example, the annual per capita consumption of energy (in BBOE) in South Korea and Turkey has increased from 7.6 and 4.0 in 1980 to 31 and 7.9 in 2002, respectively. The annual population increases in these two countries have decreased from 1.5 and 2.2 percent in 1980 to 0.6 and 1.5 percent in 2002, respectively.4

With respect to aspirations, China and India represent special cases in which a desire for economic and political dominance in the world, particularly on the part of China, also drives increasing electrical power consumption. Because of their huge populations and accelerated growth, these two countries will have inordinate influence on the future of total global demand. The contribution of the total, global, standard of living "aspirations" to future growth in per capita electricity demand only can be roughly estimated today. If it is as great, however, in the next fifty years as it has been for South Korea and other countries that have successfully entered the modern industrialized world, then at least a factor of four must be added to projected demand in 2050.

An additional source for growth in electricity demand will come from climate change. With respect to such change, one conclusion is certain from historical, archeological and geological records: climate will change and sometimes very rapidly. Independent of human influence, climate change can appear as gradual warming over several centuries or as rapid cooling over a decade or so or as rapid oscillations over a century or two.5 Whether human activities will exacerbate or modify these natural swings in climate is not known for certain,6 although preliminary global climate models currently forecast continued warming.7 We have no ability as yet to reliably predict which way the inevitable change will occur. What can be reliably predicted is that more electricity and more energy in general will be required to mitigate the adverse consequences of such changes whether from warming or cooling.

Another problem that can be solved by new sources of energy is the reduction and eventual elimination of the dependence of the world's democracies on unstable sources of energy supply, sources over which there exists limited market control of prices. In this context, however, it is assumed that financing of new capacity will come largely from the private sector. Financing any major increase in capacity through tax revenues would destroy the economic incentives necessary to drive democratic economies. On the other hand, development of new energy technologies, in contrast to their penetration of the energy markets, probably can be accomplished best by cooperative effort between government and private enterprise, historically the case for much technological advancement. Of particular note would be government-private cooperative research and development in ground, sea and air transportation, agriculture, medicine, and communications.

II. "IN THE BOX" ENERGY SOURCES

The energy sources that can be considered developed and "in the box" for consideration as sources for major increases in supply over the next half century are fossil fuels, nuclear fission, and, to a lesser degree, various forms of direct and stored solar energy and conversation. Unfortunately, a combination of political, geological, terrorism, and environmental factors combine to force a conclusion that these currently developed sources of energy cannot provide a major increase in supply by 2050, much less a factor of eight increase.

II.A. Fossil Fuels

Fossil fuels can be broadly defined as crude oil, natural gas, coal, tar sands, and special sources of methane (coal bed gas8, shale gas9, pressurized basin-centered systems10, and sea floor hydrates11). Well developed technology and reserves related to crude oil, natural gas, coal and coal bed methane clearly constitute our current number one "ace in the hole" in meeting near-term future demand.12 Following the 1950s lead of M. King Hubbert,13 however, many observers14 believe that total annual production of these four sources of fossil fuels will peak between 2010 and 2030 at about seventy-five billion barrels of oil equivalent due to natural geological limitations. Crude oil, currently being produced and used at a rate of thirty billion barrels per year, will peak first, natural gas next, and coal much later. Higher prices, new technology, decreased political restrictions on exploration, revised definitions of what is "oil," and substitution of alternatives may push those peaks to later decades and higher peaks, as they have in the past, but some natural limit on economical fossil fuel availability clearly exists. On the other hand, indefinitely increasing fossil fuel supply by several factors in the face of steady, routine increases in demand seems impractical.

Coal represents a somewhat special case within the fossil fuels category of energy sources as immense reserves of varying quality exist throughout the world. In the United States, however, access to those reserves continues to be hampered by litigation of various kinds.15 Globally, coal use is under fire because it contains more carbon relative to hydrogen than other fossil fuels, and thus releases more carbon dioxide per unit of energy. "Clean coal," coal to oil, and coal to gas technologies continue to be of interest in the United States and, along with various carbon sequestration techniques, have the potential to improve coal's environmental reputation as well as prolong its use as a long-term energy source.

Even though water vapor constitutes the principle greenhouse gas in the Earth's atmosphere, carbon dioxide and its possible effects on global climate has become a national and international political issue in recent years. The interaction of the extremely complex natural carbon cycle with increased carbon dioxide produced by human activities remains poorly defined, however, general reluctance exists to add anymore of this gas to the atmosphere than absolutely necessary. A similar greenhouse potential exists with releases of methane that is not captured during the extraction of fossil fuels in general or is released by natural and agricultural processes. Burning coal also creates ash and gaseous oxides of nitrogen and sulfur with accompanying capture and disposal problems. The amounts of these waste products depend on where the coal comes from. Further, some coal ash has high concentrations of radioactive elements that can be of concern in some situations and nitrogen and sulfur oxides contribute both to pollution and acidic rain. For the foreseeable future, in spite of the above issues, coal will continue to be tapped as a primary source of fuel for generating electrical power because of its broad availability and mature technology base and supply infrastructure.

Supplies of fossil fuels will always be very sensitive to price and the predictability of that price, not to mention the difficulties of finding and producing these materials from increasingly more complex, generally deeper, and more hostile geological environments. Additional and more costly resources may be identified and tapped by private companies at higher prices if these prices can be assumed to be stable at least until development costs are paid off. These frontier fossil fuel resources include deep-sea crude oil production; very thick, deep or less clean coal beds; tar sands; deep pressurized brines, and sea-floor methane.

The problem for investors and governments in predicting short- or long-term price stability of fossil fuels, particularly for crude oil, lies in the obvious political and security instability of the Middle East and in the terrorist, political and economic motivations of various Middle Eastern regimes. It is not even clear that the reported reserves (proven resources) from these countries and from some major oil companies are correct. They may be significantly inflated16. Also, several international companies have recently revised their published reserve estimates downward. Price is under the control of the same regimes with questionable reserves, dominated by Saudi Arabia. Artificial oil production limitations has been (oil embargo of the 1970s) and could be used again in attempts to intimidate the world's democracies. Clearly, if democratic governments can be established in Afghanistan and Iraq and integrated into the world democratic community, the long-term stability of the region and of oil markets may one of many positive results.

A major, relatively new factor in the future of fossil fuel markets and supply arises from the economic growth of China and India and to a lesser extent by other developing economies.17 China's entry, for example, as a buyer in world crude oil and coal markets, in spite of large reserves of both fuels, already appears to be causing prices of these commodities to rise. If China continues to successfully raises its standards of living, and other developing countries do likewise, fossil fuel demand and prices will increase further, at some point finally opening the door for new energy technologies.

Pressures on supply and price also exist for natural gas. The desirability of relatively low carbon natural gas, specifically methane, as a relatively low polluting fuel for electric power plants has rapidly increased. An increase in use of about three percent per year is a rate greater than the identification of new reserves. In addition, if the United States and other countries succeed in developing hydrogen as a portable fuel for automobiles, etc., an accelerated demand for natural gas will arise. Using natural gas, or any fossil fuel, to produce hydrogen, in this regard constitutes a form of energy storage and its conversion to useful energy, such as use in fuel cells or internal combustion engines, is inherently more inefficient than direct burning. The net result of a near-term increase in the use of hydrogen is an increase in the use of fossil fuels, absent a means of direct, economical production from solar energy, waste heat, or off-peak use of electricity produced by fission or fusion.

Fossil fuels also are under increasing regulatory pressures due to concerns about the health effects of hydrocarbon and sulfur dioxide pollution and the potential effects on climate from carbon dioxide and methane emissions. The proposed Kyoto climate treaty18, in fact, is an attempt to roll back use of fossil fuels in developed countries, particularly the United States. Nations advocating the Kyoto proposals probably have their motivations more in gaining trade and other economic advantages over the United States than in preventing significant climate change. None-the-less, regulation or restriction of the use of fossil fuels increase the costs of energy derived from them, or from more expensive alternative sources, and thus increase the prices consumers must pay for fuel or electricity and most manufactured and agricultural goods.

Clearly, there exist many natural and political pressures leading to a decrease in the rate of growth in the supply of fossil fuels and an increase in their price to users. It would not be prudent, therefore, to depend on this source of energy for meeting increasing demand for more than a few more decades.

II.B. Nuclear Fission

Nuclear fission currently produces about 4.6 billion barrels of oil energy equivalent in electrical power annually, worldwide. It constitutes our second "ace in the hole" relative to meeting major demand growth for energy. In the United States, nuclear power produces about twenty percent of all electricity and, in recent years, has grown in its share of the power market due to improved on-line performance and regulatory extensions of plant life. France currently produces about eighty percent of its electrical power through nuclear plants, and has been increasing this percentage steadily Worldwide, seventeen percent of electrical power comes from nuclear plants.

The technology of nuclear fission for commercial and defense energy supply has always been the safest relative to other major power sources. Over time, real operational risks have gone down significantly. Perceived risks, however, continue to be high due to negatively biased education and reporting on the level of actual hazards that exist from fission plants. In fairness, the designs of nuclear plants built and exported by the former Soviet Union were seriously flawed as the 1986 Chernobyl accident in Ukraine so sadly demonstrated. Plants in use in the United States, Japan, France, and most other countries have an outstanding safety record.

Nuclear fission power, possibly including thorium-based reactors19, would seem to be a logical candidate for accelerated growth to meet rising domestic and world demand for energy. Support for this logic comes from renewed interest in new plants in the United States, plans in Asia for many new power reactors, and France's intention to begin to replace their many old reactors with new ones.20 Relative to greenhouse emissions, only during the construction phase of nuclear plants, when large volumes of energy intensive materials must be produced, are any greenhouse gases produced as a net effect of using nuclear power. Increasingly, this conclusion appears to be creeping into the thinking of energy policy makers in diverse parts of the political spectrum.21

Decades ineptness on the part of the United States Government and Congress, have caused the failure to provide either for recycling or disposal of the spent, highly radioactive fuel rods after their replacement in plant reactors. These spent fuel rods in fact represent a vast future resource of energy if they were recycled and their unused fissionable material extracted for use in new fuel rods. Referring to this material as "waste" strains normal logic. Because President Jimmy Carter stopped development of a civil sector recycling capability in the United States, a capability that exists in France and Japan, this resource now is considered just that, "waste**.**" Nevertheless, temporary storage of 77,000 tons of high-level radioactive waste, mostly spent fuel rods now in more than one hundred water-filled ponds and dry storage sites near nuclear power plants, is nearing the physical and regulatory capacity of these locations. The Government's preferred permanent, underground burial site in the Yucca Mountain facility in Nevada22, continues to be unavailable due to political disagreements and legal challenges.23 Safe, geological stabilization of nuclear materials has been demonstrated by nature in the case of natural fission reactors.24 At this time, however, there appears little chance that a waste storage facility for spent fuel rods will be available by the target date of 2010 or that there will be any reconsideration of their reprocessing to greatly reduce the amount that must be buried**.**

Additional issues confound the long-term prospects for nuclear power plants. They represent attractive targets for terrorists. In other parts of the world, they offer means of producing weapons grade materials that can be used in weapons of mass destruction. On the other hand, reactors in nations that support terrorism invite pre-emptive attack by the world's democracies.

Proposals for a high temperature, high conversion efficiency Generation IV (Gen IV) reactor, part of the Department of Energy's 25 year plan, make up one of the hopes to resolve many of the real and imagined problems with fission power.25 Considerations of Gen IV include an initiative for an Advanced Fuel Cycle that would reduce reactor waste by ninety percent. This could permit the United States to add nuclear power without needing a second waste repository. The plan, joined in by ten or more other nations, would be to make the reactors highly proliferation resistant and to destroy (transmute) weapons-grade plutonium and other nuclear materials.26 As ambitious and politically attractive as the Gen IV plan appears, only small probability that it will be able to satisfy significant new demand before 2050. Thus, as with fossil fuels, we cannot count on nuclear fission power to play a major role in a global, eight-fold increase in energy supply over foreseeable decades.

II.C. Terrestrial Solar Power

Strong advocacy exists and significant tax resources have been expended on behalf of the development and subsidization of terrestrial solar power in all its various forms, particularly wind power. None of these forms of solar energy conversion, i.e., "renewable energy", have reached the level of "in the box" technology and markets that exists for fossil fuels and nuclear fission. Many believe, however, that some solar technologies are close enough to full commercialization to be considered as near-term possibilities.27 These advocates neglect the issues of energy storage and efficient long distance transmission,28 which must be addressed before solar can be considered a major global contributor to meeting future demand.

Direct conversion of solar energy to electricity through photocells has found applications in space and other remote locations where other sources of electrical power are either not cost competitive or have political drawbacks as in the case of several types of modular nuclear technologies. Some commercial and residential solar photoelectric arrays feed power into base load grids where subsidies are provided, energy storage is not an issue, and benefits in public opinion are realized by utilities. Steady progress in photocell conversion efficiency has been made over the last four decades. Some very high efficiency photocells, however, use toxic materials that will limit their exposure to fire and the environment. In spite of all this progress, significant doubt exists about the potential of direct solar to contribute to pre-2050 global energy supply.29

Without the benefit of taxpayer subsidies and efficient energy storage systems, collection of solar energy as heat, that is, "solar thermal conversion," to use as hear or to provide electricity also has found no broad commercial niche. As in the case of photovoltaic systems, thermal conversion has many detailed technological issues remain to be solved related to exposure to natural environmental conditions (extreme heat and cold, dust, moisture, etc.) before broad-scale commercial applications will be cost effective. Further, if direct and thermal solar conversion systems ever reach the technological and net-cost level to warrant broad scale application, the dispersed and intermittent nature of solar radiation will make land use issues increasingly important.

Stored solar energy in wood, peat, animal oils, and dung has been used for heat and light since the discovery of fire. Similarly, elevated sources of water provided mechanical energy through water mills for thousands of years. Since late in the Twentieth Century, other stored solar energy resources have been studied, including waves and thermal gradients in the sea. Lunar tidal energy systems have been investigated as well. The only significant stored energy contributor continues to be hydroelectric systems, but such systems still only account for about seven percent of world energy supply.

Technological use of stored solar energy has been subsidized by governments since the first large-scale development of sailing ships, windmills and hydropower systems beginning in pre-history. Most recent emphasis in stored energy by the private sector has been on advanced wind turbine farms. Net, cradle to grave, cost analyses30, without subsidies and fully burdened with the cost of money, have indicated that large-scale wind systems may be cost effective in some specific cases when their generated power feeds directly into existing power grids and does not exceed about ten percent of a systems power. In this sense, they are a form of peaking power for those regions where wind speeds and consistent availability are appropriate. Wind energy generation also is popular with portions of the public and state regulators. In the absence of an efficient energy storage system, however, economical wind energy penetration above ten to fifteen percent cannot occur. The intermittent nature of wind (low capacity factor) results in increasing costs of providing backup energy sources. With a geologically based, effective compressed air energy storage system available, and appropriate expansion of transmission capacity, wind energy may be cost effective up to about thirty percent of an energy system that is suitably located, geographically. Increasing concern, on the other hand, is being expressed over the visual appearance of huge "wind farms" as well as over the deaths of increasing numbers of wild birds that are hit by the turbine blades. Further, subsidies may be losing favor - it appears that the government of Denmark, the world's largest producer of wind turbines, has withdrawn its subsides for domestic use of this technology.

Unlike wind, direct and thermal solar conversion systems are far from being cost effective in the absence of subsidies31 and storage. The dollar and net energy costs of manufacture, the lack of efficient storage systems, their intermittent nature and need for backup, and inherently low conversion efficiencies seriously undermine the economics of such systems. Stand-alone systems of these three types are not close to cost effective, as no large-scale, economical storage system has yet been demonstrated. Stored energy in the form of ethanol made from grain also is not cost effective without the subsidies currently provided by various governments.

Exceptions to the general lack of cost effectiveness for solar systems exist in special geographic situations where access to other power systems is impractical or cost prohibitive. With a concentrated and well-conceived research and technology development program, such as that briefly attempted by NASA in the mid-1970s,32 various forms of solar energy could make significant contributions to meeting some regional energy demand growth. In the foreseeable future, however, terrestrial solar energy cannot be a major means of meeting the 2050 and subsequent demand for major new energy sources.

II.D. Conservation

Great progress has been made in energy conservation and conversion efficiency since the oil embargo of the 1970s. In spite of the growth in interest in conservation of energy, progress, has not kept pace with the growth of consumer demand for more products that consume energy. Thus, even though automobiles get better average mileage and the price of gasoline in constant dollars is less in 2004 than in 1974, most families have several cars rather than just one or two. A new, constant drain of electricity comes from home and business electronics. Many other examples of hidden electricity consumption can be cited.

To a significant degree, however, a conservation ethic has replaced a consumption ethic since and the holy grail of "sustainability"33 continues to receive worldwide attention. Too often, proposals for sustainability in energy would require either a massive decrease in living standards or equally massive increases in prices or taxes paid by consumers or a significant loss in freedom of choice. For now, without "unsustainable" expenditures on new energy, transportation, agricultural and other infrastructures, advocates of sustainable technologies must work to make them competitive in price, convenience, and desirability to technologies already in the marketplace.

More in conservation and conversion efficiency surely can be done and a research and technology development partnership between industry and government would be cost effective up to a point. Some of the technology areas that probably could benefit from such energy conservation, research, and technology partnerships are as follows:

- Industrial process heating34
- Commercial heating and cooling35
- Building and homes36
- Motor Vehicles37
- Fuel cells38
- Electric motors and pumps39
- Thermo-acoustic technology40
- High power density storage41
- Lighting42

As desirable as technological improvements related to energy conversion can be, conservation and conversion efficiency alone will contribute relatively little to meeting escalating future demand until they can compete independently in the competitive marketplace, that is, consumers actually want to buy them. Some commentators also submit that conservation increases the difficulty of a transition to new energy sources by reducing the pressure on the reserves of fossil fuels43 although this seems to be an overly pessimistic suggestion and certainly not one with which most Americans would agree.

II.E. The "Portfolio" Approach

Many advocates exist for a "portfolio" approach to meeting foreseeable demands for new energy using a mix of forced conservation and "in the box" sources.44 These approaches pick and choose various portions of the energy sources discussed above until their hypothetical numbers for availability match their predicted demand curve. Rarely do proponents include a significant "aspiration" demand increase in their projections of demand. Usually, these portfolios consist of combinations of conservation, efficiency gains, wind and other solar sources, and various "carbon free" sources to be adopted by the world as a whole. Some portfolios include nuclear fission as a carbon free source to be considered.

The primary difficulty with these approaches, in addition to low estimates of future demand, lies in dealing with the complexity of national and particularly international management of the development and oversight of the various mixes outside the controls and constraints normally provided by a relatively free marketplace for energy. Adam Smith's "invisible hand"45 remains the most efficient manager and arbiter of any definable segment of the civilization's market for goods and services. Energy is no exception.

III. "OUT OF THE BOX" ENERGY SOURCES

Only a few potential energy sources that fall "out of the box" appear worthy of additional consideration as possible contributors to energy demand in 2050 and beyond. These particular candidates are deuterium-tritium fusion, space solar energy, and lunar helium-3 fusion. Each is under current development or detailed consideration by the private sector or governments or both. Because the broad-scale introduction of hydrogen as a means of energy storage and transport requires sources of electricity or heat or a combination of these in excess of normal demand, it will be considered below as well. Each of these future energy sources should be viewed in the context that energy sources currently in broad-scale use (discussed above) will be competitors during their initial development and implementation phases.

III.A. Management of New Energy Systems Development

In the context of the management of large scale, complex technical programs, bringing these unproven sources of large-scale energy supply to a point where they can be evaluated relative to each other and "in the box" energy options will require that certain conditions be met. It helps to compare the challenge of providing global and sustainable sources of energy to meet an eight-fold increase in demand to the challenge faced by the Apollo space program. For example, to have a sufficient base of technology to proceed with development, the existing base would need significant enhancement along multiple paths with clear and important decadal milestones. In fact, the development and demonstration of new energy sources will require several development paths, each of Apollo-like complexity and each with sub-paths of parallel development for critical functions and components. Figure 1 summarizes the Keys to Success for Apollo in relation to those for future energy.

KEYS TO PROGRAM SUCCESS

1969 APOLLO
Sufficient Base of Technology: WWII/Cold War/ Eisenhower Decisions

Reservoir of Young Engineers and Skilled Workers: 1957 "SPUTNIK" Generation

Pervasive Environment of National Unease: Campaign of 1960

Catalytic Event that Brings Focus: Gargarin's Flight

Trusted and Persuasive President: John F. Kennedy

Competent and Disciplined Management: Post-Apollo 204 Fire

FUTURE ENERGY
Sufficient Base of Technology: Enhancement of Existing Base along Multiple Paths

Reservoir of Young Engineers and Skilled Workers:
Fund University-Based Research
Improve Elementary and Secondary Schools

Pervasive Environment of National Unease: Current Climate of Unease Should Suffice

Catalytic Event that Brings Focus: 9/11/01

Trusted and Persuasive President: Time will Tell

Competent and Disciplined Management: ???????????

Figure 1. Comparison of the keys to the success of the Apollo Program and those required for successful energy source development.

The existing reservoir of young engineers and skilled workers would need to be augmented through restructuring of the nation's elementary and secondary system of education in math and science. Broad private and federal funding of university-based science and engineering research projects needs to be generated so that the necessary pool of engineering and scientific talent exists when it is needed which is now.

The current climate of national unease brought on by the potentially catalytic events of September 11, 2001 and the War on Terrorism should suffice to build and maintain political and financial support for government and private initiatives related to energy supply. An Administration committed to leadership in this arena and the formation of competent and disciplined management teams for each energy path, of course, also will be critical to ultimate success in these endeavors.

III.B. Hydrogen

Hydrogen often constitutes a useful means of storing and transporting energy where mass or power density exist as more important considerations than cost. Recent technical and political hype surrounding the potential of a "hydrogen economy,"46 and the fact that other energy sources are required to produce it, makes some mention of hydrogen appropriate at the beginning of a treatment of "out of the box" energy systems.

At the present time, any hydrogen used in petroleum refining, space missions, and a few other limited applications must be produced from or through the expenditure of natural gas by "steam methane reforming." Sustainable, that is, non-fossil fuel based, large volume hydrogen production will require scientific advances in photo-biological, photoelectrical, and other approaches to splitting water; large expenditures in research and technology development of production and conversion technologies; costly development of the infrastructure to carry hydrogen to consumers and store it prior to use; and a gradual, but still disruptive introduction of hydrogen fueled systems in the market place.47 Heavy handed and costly regulatory forcing of hydrogen use may be advocated if not implemented. If coerced or voluntary consumer demand for hydrogen increases steadily in the next few decades, the use of excess and off-peak base load electrical power capacity will be the most economical and environmentally friendly means of production.

A great deal more investigation, business analysis, and actual engineering must take place before we can reasonably assess the role of hydrogen in meeting pre- or post- 2050 demand for energy. Nothing changes the fact that hydrogen is a form of energy storage and that energy is consumed in its production and energy is lost in its conversion to useful purposes. Photo-biological and photo-electrical production, possibly assisted by the use of waste heat from other energy systems, would appear to be the long-term hope for a cost effective hydrogen economy, at least for transportation systems48.

III.C. Deuterium-Tritium Fusion

On-going national and international research related to the possible commercialization of deuterium-tritium fusion power plants has concentrated mostly on magnetic confinement concepts, although hypothetical potential exists in the defense related research in inertial confinement of these two heavy isotopes of hydrogen. The principle focus of the international program in magnetic confinement fusion is the International Thermonuclear Test Reactor (ITER) project,49 now projected to cost $5 billion rather than the $10 billion estimate based on the original design50. Designed to reach fusion ignition (burning plasma) in a fusion reaction of deuterium and tritium, ITER has stalled over an international stalemate on where it will be located. ITER will be predominately an experimental physics project and lies a long way from the prototype plant necessary to demonstrate commercial viability.

Although the emphasis on ITER has resulted in a major contraction of alternative as well as related fusion research funded by governments, several important efforts are still being pursued. One of these is the FIRE initiative that would focus on the physics and technologies related to a specific power plant design (AIRES-RS/AT).51 Another includes the long-term power potential of inertial confinement fusion research, directed primarily toward the non-testing stewardship of the United States' nuclear weapons stockpile.52

The major hurdle deuterium-tritium fusion must overcome before a commercial prototype can be built is in the development and engineering of materials that can withstand the intense flux of neutrons produced by this reaction. Those neutrons carry the fusion energy into the walls of the reactor where their kinetic energy is released as heat. Circulating fluid in the walls would pick up this heat and use it to drive turbines that in turn drive electrical generators. Unfortunately, no materials are known that can withstand the damage produced by the neutrons for more than a few years. Current estimates are that any plant of this kind must be shut down at roughly twenty-five percent of the time so that the damaged wall materials can be replaced.53 This approximately seventy-five percent maximum on-line performance (capacity factor) compares unfavorably with the more than ninety percent capacity factor for nuclear fission plants. Clearly, materials engineering constitutes a major area that requires emphasis in the expansion of the technological base for deuterium-tritium fusion.

The problems caused by neutrons do not end with the removal of the damaged wall material. Nuclear reactions in this material have caused it to become high-level radioactive waste. Unlike the spent fuel rods of fission plants, this waste is not amenable to reprocessing so burial becomes the only option for disposal. Indeed, a deuterium-tritium fusion plant would produce more waste per kilowatt of power by than would one of today's nuclear fission plants.

Other problems face the commercialization of deuterium-tritium fusion. The tritium fuel is radioactive must be produced from lithium in fission reactors, a process costly in both dollars and energy. Construction and operating costs for large magnetic confinement fusion plants, and certainly for large inertial confinement plants also will be high, but no reliable estimates of those costs yet exist. Until the feasibility and commercial viability of these plants has been demonstrated by government efforts, no path to private capital markets exists. Finally, of course, the radioactive fuel and waste associated with deuterium-tritium fusion power plants will draw legal and political challenges from the anti-nuclear activists.

All of the above indicates that deuterium-tritium fusion has a tough row to hoe to become a player in the pre-2050 supply picture and not enough time to do so.54

III.D. Space Solar Energy

Since the 1970s, a significant amount of federal, international and privately funded study and analysis has been dedicated to concepts involving the placement of large arrays of photocells in space for the collection of solar energy.**55** On its face, the concept has much appeal. Solar electric energy would be converted to microwaves and beamed to very large collection antenna on the Earth and from there fed into the power grid. Two variations on this theme have been explored: satellite solar power systems and lunar surface solar power systems. Implementation of either would require very large space construction projects. The satellite system would be built from components launched from Earth, possibly augmented by lunar materials, and the lunar surface system's solar collector would be manufactured from lunar soil. Successful assembly, construction and maintenance of the International Space Station (ISS), particularly its large photocell arrays56, should be noted in this context.

Advances in the efficiency and decreases in the cost per watt of photovoltaic solar cells obviously will be critical to the economic feasibility of space solar power. Gradual advances in this regard continue, however, cradle to grave analyses of the use of photocell arrays to generated electricity on Earth, much less in space, show that there is still a long way to go.57 The potential exists for major breakthroughs in cell manufacturing costs and in conversion efficiency by pursuing flexible, ultra-thin, molecular organic solids. These materials also may have the potential for self-assembly. 58

The two approaches to space solar power have been studied extensively, however, both are dependent financially on taxpayer support of the research, development and initial operational activation of the first prototype system59. Until a large-scale prototype demonstration has taken place, and an "apples to apples" comparison to competitive energy sources has been performed, investors are unlikely to provide the necessary capital to create a truly commercial enterprise. Further, even with governmental support of a prototype, a major reduction in launch costs either to earth-orbit or to the Moon will be required before a return on investment is possible for private investors. At the present time, then, there is not an obvious path into the capital markets without tens of billions in expenditures by the government.

III.E. Lunar Helium-3 Fusion

Lunar helium-3 fusion power represents a relatively new entrant into the Twenty-first Century energy sweepstakes.60 Recently, it has become possible to define the financial and technical envelope into which a commercial lunar helium-3 fusion power option must fit if it is to be a source of pre-2050 energy supply. Comparable envelopes need to be developed for other Twenty-first Century energy options.

Technically, like other potential, but undeveloped energy sources, a prototype demonstration of a helium-3 fueled power plant will be required along with a financial and risk comparison against its competitors. In addition, a clear means of significantly reducing lunar launch costs also will need to be defined as will a detailed approach to extracting lunar helium-3 from the lunar surface materials.

The primary advantage that lunar helium-3 fusion will have over other "out of the box" energy sources in the pre-2050 timeframe is a clear path into the private capital markets. This path is a consequence of the potential of several near-term applications for fusion technology in existing markets, prior to reaching breakeven power levels.61 These applications can provide early returns on investment as well as lead technically toward competitive electrical power production.

Apollo samples collected in 1969 by Neil Armstrong on the first lunar landing have shown that helium-3 concentrations in lunar soils are probably between twenty and thirty parts per billion in undisturbed, titanium-rich soils. Twenty parts per billion may not seem like much, however, the value of helium-3 relative to the probable energy equivalent value of coal in 2010-2020 ($2.50 per million BTU) will be almost $40,000 per ounce!

At $40,000 per ounce, 100 kg of helium-3 would be worth about $140 million. 100 kg constitutes more than enough fuel to power a 1000 megawatt electric plant for a year when fused with deuterium. The production of a hundred kilograms of helium-3 per year would require annual processing of about two square kilometers of the lunar surface to a depth of three meters.

In addition to lunar mining and processing, two other major technical challenges must be met if the private sector, or the government, or a partnership between both is to be successful in a lunar resource endeavor. First, before any other related investments can go beyond conceptual design, helium-3 fusion technology must be developed and adapted to the production of competitively priced electricity. A "second generation" approach to controlled fusion power involves combining deuterium (D) and helium-3 (^3He). This reaction produces a high-energy proton and an alpha particle. Some D-D fusion side reactions result in a low level of neutron production, minimized by optimizing the amount of excess helium-3 introduced into the reactor. These neutrons will result a need to dispose of a small amount of radioactive waste at the end of a thirty to forty year plant life.

The most important potential advantage of the D-^3He fusion reaction for power production as well as other applications lies in its compatibility with the use of electrostatic fields to control fuel ions and the fusion protons. Protons, as positively charged particles, can be converted directly into electricity, through use of solid-state conversion materials as well as possibly other techniques. Potential conversion efficiencies of seventy percent may be possible as there is no need to convert proton energy to heat.

A "third generation" approach to fusion power fuses helium-3 with itself and would eliminate any neutron producing reactions and thus also eliminate all radioactive waste at the end of plant life. Nuclear power without nuclear waste therefore becomes the ultimate promise of lunar helium-3 fusion. The theoretically predicted fusion of helium-3 and helium-3 has not been demonstrated in the laboratory as yet, however, that demonstration appears to be only a matter of time and the ability to optimize the performance of existing electrostatic confinement research reactors.

D-^3He fusion power promises much lower capital and operating costs than its Twenty-first Century competitors due to less technical complexity, higher conversion efficiency, smaller size, no radioactive fuel, no air and water pollution, and only low level radioactive waste disposal requirements. Recent estimates by analysts at the Wisconsin Fusion Technology Institute suggest that about $6 billion in investment capital will be required to develop and construct a demonstration plant for commercial helium-3 fusion power.

A major development challenge for lunar helium-3 fusion is to have a much greater payload capability and much lower cost for Earth to the Moon launches than that planned by NASA. The Apollo Saturn V rocket remains the benchmark for a reliable, heavy lift Moon rocket. This huge booster could reliably launch forty-eight tonne payloads to the Moon at a cost of about $57,000 per kilogram (2004 dollars). A new, modernized "Saturn" rocket would need to be capable of launching fifty to one hundred tonne payloads to the Moon at a cost of $3000 per kilogram or less. A number of considerations related to vast technological advances in the over forty years since the Saturn V was designed and manufactured indicate that the necessary factor of nineteen reduction in payload costs can be accomplished with investment capital of about $5 billion. Critically, we know what we need to do this time, unlike in 1960 when President Eisenhower began the Saturn project.

The economic envelope within which helium-3 fusion must fit is tight. Major parts of that envelope related to other Twenty-first Century energy sources are: total development cost <$15 billion, competitive energy costs equal to or greater than $2.50 per million BTU, and payload costs to the Moon equal to or less than $3000 per kilogram. It may be worth noting that a capital investment of less than $15 billion would be about the same as was required for the 1970s TransAlaska Pipeline and the 1980s EuroTunnel (Chunnel).

IV. CONCLUSION

Satisfying an eight-fold increase in global energy demand by 2050 will require the development of new sources of clean, efficient electrical power. Of the few possibilities, lunar helim-3 fusion power appears most conceptually attractive and has many implications beyond being a source of new energy supply. Its development, or that of other alternatives, will require competent and disciplined management of large, complex programs, comparable to the Apollo lunar landing program, as well as the availability of private investment capital.

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