Science Based Nuclear Energy Systems Enabled by Advanced Modeling and Simulation at the Extreme Scale

White Paper on Integration of Nuclear Energy Systems

Charles Forsburg[1] and Steven Goldberg[2]

[1] Massachusetts Institute of Technology

[2] Argonne National Laboratory

Grand Challenge

To model the complex interrelationships of multiple energy outcomes in a carbon constrained world coupled with the technical and institutional barriers that are inherent in the wide-scale deployment of nuclear energy; to develop a detailed and definitive understanding of these interrelationships, including validation and verification capability.

Systems Integration

The use of modeling and simulation to understand complex energy systems analysis—capturing nuclear energy from “cradle to grave.”

Timeframe

The paper is intended to take an immediate- to long-term outlook (20 -50 years).

Questions for this area will include

- What are the important nuclear energy systems relationships that will drive the systems analysis?
- Are the current generation of system analysis tools sufficient to capture the complexity of nuclear energy and if not, what areas of research are needed?
- Will systems analysis require the use of high-performance computing systems?
- Will the analysis provide significantly new information to support policy decisions? How crucial is the capability of high-performance computation?
- Will the database be adequate to support computation power? How reliable will the results be?

Key Issues

- The role nuclear energy will have to address to meet our future energy and water resource requirements
- The design of robust nuclear fuel cycle and reactor systems that meet national and international safety, safeguards, and environmental requirements
- Carbon constrained national and international policy (ies)
- Consumer, commercial, and business behavior as future prices increase for all energy products – the so-called "tolerance" level
- Energy outcomes with and without large new nuclear energy deployments
- The role of nuclear energy to expand the world's energy storage capability significantly
- The design of the future electricity grid

Understanding Nuclear Energy in a Carbon-Constrained World

Future energy systems will be driven by three constraints: economics, the environment, and national security. Because about 85% of the world's energy system is based on fossil fuels, it is the potential future constraints on fossil fuels that create the incentives to consider alternative energy sources and the required timing for deployment of those energy resources.

- Economics. The cost of energy is over 10% of the gross national product. Rapid changes in oil and natural gas prices are highly disruptive to the economy. Because energy is such a large fraction of the national economy and has major impacts on economic competitiveness, there are severe economic constraints on unconstrained increases in energy prices.

- Environment. Increases in atmospheric carbon dioxide concentrations may cause unacceptable global warming and unacceptable changes in the geochemistry of the biosphere. To address this challenge, the goal of the Obama Administration is to decrease greenhouse gas emissions by 80% by 2050.[1] This is to be achieved by conservation, expanded use of non-fossil energy sources, and sequestration of carbon dioxide from fossil-fuel plants. The viability (technical, economic, social) of large-scale sequestration of carbon dioxide is unknown. If carbon dioxide sequestration is undertaken, approximately two billion tons per year of carbon dioxide must be sequestered underground from U.S. coal plants; that is, siting a thousand geological repositories for carbon dioxide with each repository 1000 times larger than a repository for radioactive wastes[2].

- National Security. The national security constraint is that the U.S. and world economies are built on oil and natural gas from politically unstable areas of the world. Oil provides about 35% of the global energy demand and 39% of the U.S. energy demand. Most of that oil is imported and most of the world's oil reserves are in the politically unstable Middle East. It is expected that conventional oil production will peak in this decade while demand continues to climb—driven by the growth of China and India. The next largest energy source today is natural gas that supplies about 30% of the global energy demand. In thirty years, resource depletion is expected to result in two countries controlling most of the world's remaining exportable natural gas: Russia and Iran. While tar sands, shale oil, and coal can be used to produce liquid and gaseous fuels, these options have higher costs and significantly larger carbon dioxide emissions per gallon of gasoline or cubic meter of natural gas.

[1] http://my.barackobama.com/page/content/newenergy.

[2] The U.S. today currently lacks a firm back-end solution to disposition spent nuclear fuel and high-level radioactive waste.

The above constraints will likely result in changes to worldwide energy supply and demand picture – unlikely to be “a soft landing” especially for energy importing countries.

The Role of Fossil Fuels and Replacements for Conventional Fossil Fuels

Fossil fuels provide two functions: they are an energy source and an energy storage media. Energy demand (electricity and heat) vary daily, weekly, and seasonally. In higher latitudes, there is also an approximately three-day cycle associated with weather fronts. Fossil fuels are stored in the form of coal piles, oil in oil tanks, and natural gas in underground storage facilities. The costs of storage are low relative to the costs of the fuel. Furthermore, the fossil technologies to convert fossil fuels to electricity and heat have relatively low capital costs—the primary costs are the fuel costs. As a consequence, we build facilities to produce variable quantities of electricity and heat that operate for only hundreds or thousands of hours per year—yet this is economic because the cost of the final heat or electricity is primarily associated with the fuel.

An example of the variable energy demand is shown in Figure. 1. This shows the electricity demand in Illinois for three weeks: in the spring, winter, and summer. The large variations in daily, weekly, and seasonal electricity demand are self evident. Note that the base load demand for energy that is required year round is less than half the electricity demand at times of peak electricity demand. Furthermore, the actual base load in many cases is less than half the total yearly electricity demand.

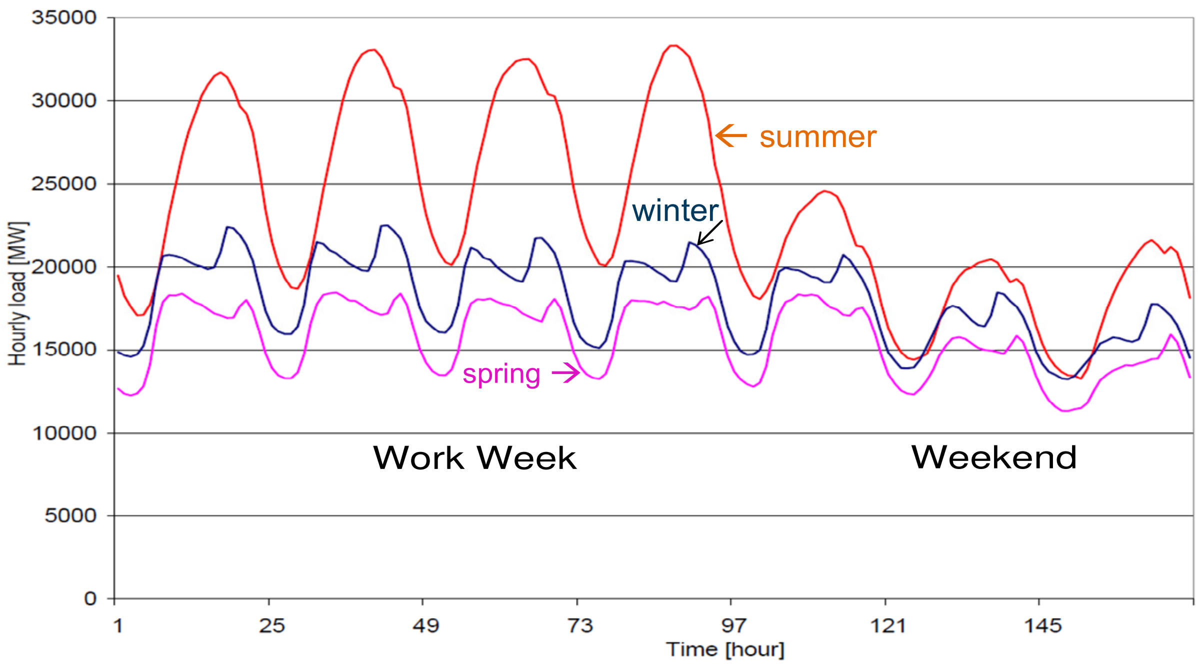

Figure 1. Electrical Demand for Three Weeks in Illinois

There are many replacements for fossil fuels as energy sources; however, today there are very limited replacements for fossil fuels serving as energy storage media. Table 1 shows potential energy sources in a low-carbon world. The only energy systems with the capability to economically vary power output with variable demand are (1) the traditional fossil energy systems and (2) biomass or hydroelectric energy systems. Table 1 describes the current state-of-the art of our energy choices.

Table 1. Characteristics of Future Energy Supply Options

Source	Output Versus Time	Geographical Distribution	Storage Capability
Fossil, no sequestration	Variable	National	Historical way to store energy. Use is limited in the future.
Fossil, with capture and sequestration	Base load	Regional, dependent upon geology	No – only extract the quantity of fossil fuels that meets demand and is sequestered (i.e., "just-in-time fossil production")
Wind, Solar	Intermittent	Regional	No
Nuclear	Base load	National	Very limited[3]
Hydro, Biomass	Variable	Regional	Yes, But limited
Conservation	Variable	Regional options	How does conservation impact storage requirements?

If the goal is an 80% reduction in greenhouse gas emissions by 2050, traditional fossil fuel usage will be effectively limited to the chemical, transport, and consumer product sectors where alternative technologies are extremely expensive. There are today no current technologies or combinations of technologies that can efficiently and economically replace fossil fuels. There are severe limits on each option.

- <u>Fossil fuels with carbon dioxide sequestration.</u> Heat and electricity can be produced from fossil fuels with carbon dioxide sequestration; however, carbon capture and sequestration will be expensive, the technologies are likely to be viable only as base load technologies because of high capital costs and the technological difficulties in rapidly changing power levels, the technology is not applicable to small fossil users, and there are strong geographical limitations on sequestration sites.
- <u>Renewables.</u> Wind and solar are low-carbon energy sources that are intermittent. They have high capital costs and low operating costs; thus, the economics strongly favor operating such facilities at their full capacity. Experience in Great Britain and Texas shows that in the case of wind, the wind can suddenly decrease over very large areas. Solar has a night-day power cycle. Consequently, both solar and wind require backup energy sources.
- <u>Nuclear energy.</u> Nuclear power systems can operate under intermediate loads; but, they are a capital intensive technology with significant cost penalties for part-load operations.
- <u>Hydroelectric and biomass.</u> These energy sources have excellent characteristics as energy sources and methods to store energy; but, worldwide resources are limited and available in significant quantities in only a few locations.
- <u>Conservation and energy efficiency.</u> These actions can reduce total energy demand and in some applications, such as building insulation, can significantly reduce the seasonal swings in energy demand and, in turn, the energy storage requirements. Historically, energy efficiency studies have emphasized energy savings, not the implications on energy storage.

While energy storage is a fundamental problem, the storage challenges are different for storing energy on a daily, weekly, or seasonal basis. While there are many technologies that have been deployed for daily storage (pumped hydro storage, compressed air, batteries, etc.), there is a severe shortage of non-fossil options to address weekly and seasonal variations in energy demand.

[3] Nuclear power levels can be varied but the economics are unfavorable. Nuclear plants refuel once a year where the refueling time can be adjusted to times of low seasonal electricity demand.

In this context, the nuclear option is more restricted than generally recognized. The variable demand in time for electricity and the characteristics of nuclear energy generally limit the use of nuclear energy to providing approximately 50% of the electricity requirements.[4,5].

There are exceptions. In France, 80% of the electricity is produced by nuclear energy. This is possible because of a combination of three strategies: (1) there is strong time-of-day pricing to reduce daily variations in power demand and increase the fraction of electricity that is base load electricity, (2) excess electricity at times of low electric demand is sold to neighboring countries, and (3) some of the nuclear plants are operated at partial load during times of low electricity demand. The option of selling excess electricity at times of low electric demand to neighboring countries is only viable if the neighboring countries (Switzerland) have massive hydro dams and effectively store electricity in the form of elevated water or have fossil plants (Spain, Germany, Italy) that are cycled up and down with low-cost nuclear replacing fossil fuels at times of low electricity demand. This last option is only viable if a country has neighbors who burn large quantities of fossil fuels to produce electricity.

Restrictions on carbon dioxide emissions require rethinking the entire energy system—something that has not been done. Until the system is rethought, we do not know nor can we credibly estimate the possible range of nuclear energy futures.

Nuclear Futures

The energy systems in a low-carbon world must be radically different to replace the energy and energy storage functions provided by burning fossil fuels with greenhouse gaseous releases to the atmosphere. Such a world has different constraints and thus the key question is: What is the role of nuclear energy? The role of nuclear energy determines what types of reactors are required and their purpose (electricity, heat, etc.), the demand for fissile fuels and thus the timing of decisions on future nuclear fuel cycles, and the choice of fuel cycles via the reactor choice that partly determines fuel types. The reactor choices have major impacts on fuel cycle choices. Three different roles can be defined.

<u>Base load electricity – traditional</u>. Nuclear energy can become the primary base load electricity source for the world. This is the traditional role of nuclear energy.

<u>Base load electricity – nontraditional</u>. Nuclear energy could become a significant electricity source for plug-in hybrid vehicles and/or all electric vehicles that service a more robust electricity distribution grid. The pricing of electricity for PHEVs and all-electrics could result in the bulk of recharging occurring during off-peak periods – smoothing out the demand curve sufficiently to produce a higher base load capacity[6].

<u>Peak electricity</u>. Nuclear energy can become the primary source of peak electricity, the primary backup energy supply for energy supply for wind and solar, and finally a backup energy source to desalinate water. Nuclear peak electricity systems and their respective technologies are in various stages of development. One example will be described herein—the Hydrogen Intermediate and Peak Electricity

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[4]This is further restricted by State laws and public policies primarily in the Southeast and Texas that affect about 20 percent of the national load.

[5] Nuclear energy is a capital intensive, low-operating-cost technology. Economic conditions barely, at best, support new nuclear energy deployments to meet base load electricity production. That, in turn, "severely" limits the fraction of electricity that can be economically produced by nuclear power plants.

[6]See, "How Plug-in Hybrids will Save the Grid" (The use of vehicles that run on electricity could be a boon to the ailing electrical grid). http://www.technologyreview.com/energy/17930/.

System (Appendix C) to provide an understanding how energy storage may drive the choice of energy production systems. This system consists of four components:

- *Steam production*. Light-water reactors produce steam under base load conditions. The power plant may operate as a conventional nuclear plant where all the steam is used to produce electricity. Alternatively, electricity and some of the steam may be diverted to hydrogen production.

- *Hydrogen production*. Steam and electricity are used to produce hydrogen and oxygen using high-temperature electrolysis (HTE) at times of low electricity demand. A nuclear reactor producing steam and electricity can produce hydrogen for almost the same efficiency as it produces electricity. It is significantly more efficient than using traditional electrolysis to produce hydrogen and oxygen. The technology is being developed but is not commercial.

- *Hydrogen and oxygen storage*. Underground storage facilities are used for the low-cost storage of hydrogen and oxygen on a daily, weekly, and seasonal basis. This uses the same technologies used for seasonal storage of natural gas.

- *Peak electricity production.* Variable electricity to the grid is achieved by two methods: (1) switching steam from the nuclear reactor from producing just electricity for the grid to producing electricity and steam for hydrogen production and (2) using the hydrogen and oxygen for electricity production to meet peak load demand by operating the high-temperature electrolysis unit in reverse as a high-temperature solid-oxide fuel cell. The economic challenge is that the capital cost for the peak electricity production systems must be very low to be economic because these systems operate for a limited number of hours per year. The reversible use of the electrolyzer as a fuel cell maximizes equipment usage to minimize total capital costs.

Each of the proposed nuclear peak electricity systems has technological characteristics that couple it to nuclear reactors. In this specific example, there are several such characteristics.

- The HTE production of hydrogen and oxygen with heat and electricity has a significantly higher efficiency than the production of hydrogen and oxygen from electricity as would be required if the energy source is electricity from wind or solar. This couples the technology to nuclear reactors that can produce heat and electricity rather than traditional electricity-generating renewables.

- There are large economies of scale associated with bulk hydrogen and oxygen storage in underground facilities using the technologies developed for natural gas storage. Economies of scale drive seasonal storage to centralized storage systems and drive the system structure.

- The bulk storage of hydrogen and oxygen creates low-capital-cost peak power systems such as fuel cells and oxy-hydrogen steam systems (Appendix C)

In a broader context, this and other examples raise the question: Is nuclear energy the enabling technology for the large-scale use of renewables? In a non-fossil world, energy storage options may ultimately drive energy production choices.

<u>Fuels production</u>. The conversion of feed stocks into liquid fuels is energy intensive. Today about 7% of the nation's energy is used by refineries—by coincidence this equals the thermal energy output of the nation's nuclear reactors. In the future, liquid fuels may be made from biomass to avoid net greenhouse gas emissions; however, the conversion of feed stocks such as biomass to liquid fuels is extremely energy

intensive. If one considers conventional renewable biomass available for liquids fuel production, its energy value is about equivalent to burning 10 million barrels of oil per day. If it is converted into ethanol, the energy value is equivalent to about 5 million barrels per day. If external sources of energy are used and all the carbon in the biomass is converted into diesel fuel, it is equivalent to about 12 million barrels of diesel fuel per day. In effect, the liquid fuel potential of biomass depends upon whether biomass is a feedstock for liquid fuels production or both the feedstock and energy source for a bio-refinery.[7]

Today oil provides 39% of the nation's energy demand. There are low-carbon liquid fuels options but they require massive quantities of low-carbon energy inputs. Depending upon the technology, the inputs are in the form of low-temperature heat, high-temperature heat, and/or hydrogen. There is also a technical constraint. Bio refineries are chemical plants that do not operate well with variable energy inputs and thus may not couple well with variable energy sources. Understanding these options is central to understanding future energy demands and may be central to understanding the requirements for future nuclear power plants.[8]

Hydrogen production. The role of hydrogen in a low-carbon world is a critical issue for nuclear energy because the intrinsic characteristics of hydrogen may match the characteristics of nuclear energy—a centralized large-scale technology. However, there are different roles for hydrogen with two distinct hydrogen futures. The public vision of the hydrogen future is where hydrogen replaces fossil fuels primarily as an energy source for everything from home heating to fueling vehicles. The second vision of the hydrogen future is where the chemical characteristics of hydrogen result in its wider use in specific markets. Hydrogen today is the basis for fertilizer production and the upgrading of low-quality fossil fuels to liquid fuels. It is used to a limited extent for the conversion of iron ore and other minerals to metals. In a low carbon world, it is the alternative chemical-reducing agent that replaces fossil fuels for the conversion of metal ores to metals and for the production of cement. It may also be used for peak power production (oxy-hydrogen peaking units) and fuels production. In such systems, hydrogen is confined to industrial users. Understanding the role of hydrogen is central in two other contexts in a low-carbon world.

- Storage. Today hydrogen is the only non-fossil transportable energy storage system capable of storing energy to meet seasonal changes in energy demand.
- Super Base Load. For the electrical grid, there is an alternative strategy to address daily, weekly, and seasonal variations in electricity demand. That alternative is to build sufficient base load that when combined with available hydroelectricity and daily energy storage systems, the electricity demand can be met. In such a system, there is a massive weekly and seasonal excess of base load generating capacity that can be used for hydrogen production. Hydrogen can be seasonally stored to meet the various needs. This option is currently being considered in France where it is proposed that the hydrogen be primarily used in converting low-grade fossil fuels, wastes, and biomass to liquid fuels.

Nuclear Constraints

Nuclear energy has its own constraints. To ensure a sustainable future for nuclear energy, several requirements can and must be met. These include safety and efficiency, proliferation resistance, sound nuclear materials management, and minimal environmental impacts (nuclear waste products). The desirable environmental benefits of economic viability, resource optimization and waste minimization

[7] C. W. Forsberg, "Meeting U.S. Liquid Transport Fuel Needs with a Nuclear Hydrogen Biomass System," *International Journal of Hydrogen Energy* (2008), doi.10.1016/j.ijhyden.2008.07.110.
[8] AEHI is planning to produce electricity and biofuels from the waste heat near Mountain Home, Idaho to sell power locally and to the west coast (www.alternativeenergyholdings.com).

need to be considered under a variety of policy tools, including constrained carbon policies, expanded R&D support for next generation reactor systems/fuel cycles, and enhanced risk-informed, performance based regulatory policies. The economics of new nuclear energy deployments dominate the go- no-go decision both in the U.S. and worldwide; still other societal factors are important as well, particularly nonproliferation policies and waste disposal.

Today's worldwide financial crisis has greatly complicated the prospects for financing capital-intensive projects of all kinds, including nuclear power plants. Moreover, the global industrial infrastructure required to support essential elements of nuclear power construction is at present inadequate to meet the needs of a broad nuclear power resurgence. For example, there is at present just one global supplier of the ultra-large forgings needed to make major nuclear components such as reactor pressure vessels, and the waiting list for delivery of these components has been lengthening. The electric grid infrastructure in many parts of the world is currently unable to support the deployment of large nuclear power plants. Serious shortages of human capital will be exacerbated by the approaching retirement of many highly educated and trained nuclear specialists whose careers began during the first wave of nuclear growth in the 1960s and 1970s. There is a pressing need to attract high-quality students into the nuclear engineering discipline in order to support the growing needs for new power plant design, construction, and safe, efficient and reliable operation. Similarly, the stringent quality demands associated with the construction of nuclear plants and their supporting infrastructure call for a highly-trained trades workforce, which today is seriously depleted and must be rebuilt worldwide.[9]

Systems Modeling for Nuclear Energy

In order to address these complex, interrelated technical, economic, and societal issues and provide the input needed by decision makers to make decisions on our energy future, dynamic end-to-end systems analyses are required. These objective analyses are required now for several reasons including:

- Key role of nuclear energy as a clean, sustainable, and secure energy source for the future;
- Responsibility of our generation to allow for sustainable nuclear energy and solve the waste problem for future generations;
- Significant progress in advanced fuel cycle and advanced reactor R&D in U.S. and worldwide.

The intent of the systems tools is to obtain consistent answers to complex, interconnected problems with different degrees of approximations and uncertainties. Global system analysis for nuclear energy and the nuclear fuel cycle would assess various options and configurations. The systems analyses would consider the following: a) range of nuclear futures; b) economics; c) proliferation; d) nuclear materials management; e) greenhouse gas emissions; f) environmental impacts from waste management; g) sociopolitical factors; and h) regulatory interfaces.

1. Nonproliferation analysis is a complex modeling challenge, by itself; just to simulate outcomes that are significantly more proliferation-resistant than today's systems permit.[10] Highly

[9] The difficulties recently encountered by the French firm AREVA in building a nuclear plant in Finland, the first in a new generation of large pressurized water reactors, are a reminder of how important the availability of highly-trained trades, including civil construction, is to keeping this type of project on budget.
[10] The National Laboratories have been developing extensive modeling capability in the nuclear security and nonproliferation areas; here are two illustrative examples:

- National security – under development at PNNL and ANL are extensive behavioral modeling and simulation tools to characterize or predict various aspects of human individual and social actions and interactions; in the areas of energy, environmental, transportation, or computing infrastructures, modeling of group behaviors may give clues to possible impacts on critical infrastructures of concern to the national security.

integrative, interactive modeling, encompassing the full range of parameters, would increase the already complex "nonproliferation" analysis by several orders of magnitude.

Such global systems modeling are important for market actors and policy makers. For example, systems analysis codes are used to evaluate economic, energy demand, energy resource, and energy technology characterization for energy sector planning. These tools can investigate the necessary conditions for nuclear energy market penetration when competing with fossil and renewable-based energy alternatives and inform energy policy related to economic competiveness, energy security, and environmental responsibility.

Other systems analysis codes are required to integrate nuclear process models for the analysis of proposed nuclear energy systems on (a fuel batch, reactor) micro (self-sustained), grid-specific, country, regional, or worldwide level. These tools are needed to assess the effect of different nuclear energy system deployment paths (including hydrogen generation, clean water, PHEV utilization, and electric storage) on such factors as carbon footprint assessments, fuel resource efficiency, fuel/waste management, nonproliferation risks, and economics. Such approaches need to be incorporated into an integrated assessment tool for nuclear energy and the nuclear fuel cycle, with the capability to conduct comprehensive sensitivity analyses and uncertainty evaluation based on deterministic or probabilistic methodologies. This capability achieves several goals, including identifying trends and issues, and quantifying uncertainties.

From a broad perspective, this results in three layers of issues to be addressed.

1. What Applications of Nuclear Energy are Important in a Low-Carbon World

Nuclear reactors are built to meet energy needs. To understand nuclear futures, we must have some understanding of the possible roles of nuclear energy in a low-carbon world. Such an understanding does not currently exist. The first need is for systems modeling to begin to understand what roles nuclear energy might fill based on the fundamental characteristics of nuclear energy (base load, large-scale technology) and competing energy systems. The goal is to understand what is required: base load electricity, intermediate load electricity, peak electricity, large-scale industrial heat demand (as a function of temperature), nuclear-biomass options, and external constraints (such as water or size of reactor). Key characteristics of such an analysis include:

- *Energy storage*. In a carbon-constrained world, what replaces the storage functions of fossil fuels? The peak energy storage requirements depend upon the differences between energy production and demand but different energy production systems have different outputs as a function of time and, thus, different storage requirements. Historically with a fossil-fuel dominated system, decisions on energy options were driven by the cost of energy from different sources. That may not be true in a low-carbon system. Will energy storage requirements drive system economics and thus the choice of energy systems?

- *Regional analysis*. A regional energy analysis is required because of (1) the different roles of renewables such as hydroelectricity by region, (2) the viability of carbon sequestration which is strongly dependent on the local geology (the region), and (3) the energy demand is dependent

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- Materials management – modeling is going on to keep tabs on nuclear materials worldwide and verify that users are honest with regard to their nuclear fuel and waste inventories ; a team of LANL and LLNL experts are developing sophisticated models to evaluate the proliferation risk associated with advanced nuclear fuel cycle materials. The resulting data and analyses are a critical part of an objective multi-component risk assessment for an advanced nuclear energy technology or fuel cycle system.

upon the region. A shift away from fossil fuels implies larger regional differences in the choice of energy production technologies and the requirements imposed on those technologies.

- *Liquid fuels production*. Fuels production is energy intensive. What are the requirements for the reactor (temperature, size, etc.) if lower-cost heat (rather than hydrogen) is used for fuels production? Current technologies require continuous sources of process heat. Does support of the liquid fuel system (40% of total energy demand) drive energy choices?

- *Water resources*. Water resources are a critical nuclear power issue for two separate reasons: (1) need for cooling water for power production and (2) siting. Existing nuclear plants and people both need water and thus tend to be collocated. If the connection with water was broken, nuclear plants could be more easily sited away from population centers. Should the development of nuclear systems that do not require water be a fundamental goal for nuclear energy? (Example: Two hundred miles east of the west coast are the western deserts—perfect sites for nuclear plants with low populations and relatively short electrical transmission distances—except no water).

Understanding of these effects will require the development of scenarios that fill needs and preliminary estimates of economics. These should include different assumptions about technological advances. This type of modeling in very crude form was done for nuclear energy in the 1960s to understand the roles of nuclear energy but has not been done since. Unlike earlier efforts, such scenarios must consider the central challenge of storage and the large regional differences.

2. For alternative futures, what must reactors deliver to meet energy needs?

Based on analysis, what requirements are imposed on nuclear systems (electricity requirements, heat and at what temperatures, possible reactor size limits for some applications, water demand restrictions including incentives for dry cooling, need for hydrogen production). There are domestic requirements but also national security requirements (such as nonproliferation) that will strongly impact choices. Historically, the nonproliferation impacts have not been considered in the choice of reactors.

3. What fuel cycles to match requirements for reactors?

The primary drivers of fuel cycles are: (1) the size of the enterprise, (2) the fuel types that are partly dictated by reactor choices, (3) public acceptance, and (4) nonproliferation. Social acceptance is based on multiple factors from economics to waste management to nonproliferation. The size of the enterprise determines whether there may be constraints on uranium resources and thus the need for advanced fuel cycles. External factors such as the demand for high-temperature heat, inherent safety, or proliferation resistance may drive the choice of reactor and thus the choice of fuels. Further complications are the proposals for new nuclear systems from once-through breeder reactors to fission-fusion machines.

Historically, fuel cycle studies have been comparisons between once-through and classical breeder reactors. There are now more options, the ground rules and assumptions have changed, and the complexity has dramatically increased. Historically, fuel cycle studies have not been integrated with outside constraints—indeed they have yet to be fully integrated with waste management. We do not understand this more complex set of options today.

Status of Modeling

Modeling the deployment of nuclear energy today is based on meeting conventional base load requirements using conventional databases. An example of this type of modeling is WASP[11] and

[11] Wien Automatic System Planning Package, an electricity planning model.

EMCAS[12] (See Appendix A for illustrative data sets used by the two models). These models are used to judge the economic competitiveness of nuclear energy. While such models are a good starting point, they do not profess to address the complicated issues that are sufficiently interactive and dynamic to address the energy future scenarios described above. An illustrative set of parameters that would be considered in an advanced modeling simulation are identified in Appendix B.

Does this all really matter?

The last major energy transition was at the beginning of the industrial age where fossil fuels replaced biomass and wind as the primary energy sources. That changed the world. The transition to a low-carbon world could be equally radical—but we do not know.

Is nuclear energy just another energy option or is it in a low-carbon world the enabling technology for renewables by providing peak electricity to match variable renewable electrical outputs and the bio-refinery energy source for biomass to be a serious source of liquid fuels? If nuclear energy becomes a requirement, the nature of nuclear energy radically changes.

The historical example of nuclear energy as a game changer is France. After the 1956 Suez crisis, the French-Algerian conflict that led to the fall of the 4th Republic and start of the 5th Republic, and the 1973 oil embargo—the French concluded they had to get off oil. That led to the nuclear power program that today produces 80% of the electricity in France. The French did not choose nuclear energy because they liked or wanted it. It was chosen because the alternatives were unacceptable. When it was recognized as the path forward, the political and economic changes were made to create a cost-effective, safe system.

Today we are entering a new future and blind to the implications. Modeling is the one tool to try to understand that future. We do not know what the results will be. They may be inconclusive or they may drive energy policy and the directions of nuclear energy for the next century.

[12] Electricity Market Complex Adaptive System, an electricity market behavior model.

APPENDIX A

Conventional Model Parameters

Table 1. WASP System Parameters

Parameter
Study period
Planning period
Number of periods in each year
Number of hydrological conditions
Load forecast
Reserve margin range
Unit dispatch
Spinning reserve requirement
Present value date
Discount rate for cost discounting
Salvage value of capital investments
CO_2 allowance costs
Energy-not-served cost

Table 2. Basic Grid Assumptions

Parameter
Base Year
Actual analysis year
Peak hours
Summer months
Number of zones
Pricing mechanism
Transmission losses
Transmission grid configuration and characteristics
Chronological loads for analysis year

Appendix B

Sample Parameters

A. Interface with Fuel Cycle
1. Increase use of thorium – U-233 fuel cycle (timetable, waste amount, cost)
2. Actinide burning technologies (timetable, waste amount, cost)
3. Unconventional mining of uranium – seawater (timetable, amount, cost)
4. Advanced technologies (LIFE, Gen-IV) (timetable, cost)

B. Interface of Renewables and Nuclear Energy
1. Advanced storage technologies (hydrogen storage) (timetable, cost)
2. Smart grid technologies (supply and demand side management) (timetable, cost)
3. Advanced end-use systems and devices (more efficient appliances (timetable, cost)

C. Interface of Nuclear Energy with its End Users

1. Advanced desalination technologies (timetable, cost)
2. Advanced PHEV (timetable, cost)
3. Advanced industrial processes for cogeneration (fuels, petrochemicals, etc.) (timetable, cost)

D. Regional/Multinational Compacts Interfaces

1. Transmission hubs (timetable, cost)
2. Collaborative nuclear fuel supply and disposition arrangements (advanced contracting, economics)

E. Climate Modeling and Policy Interfaces

1. Cap-and-trade impacts
2. Adaptation measures
3. Sudden climate impact

F. Feedback loops and sensitivities among A-E

Appendix C

Nuclear Peak Electric System

Nuclear energy can become the primary source of peak electricity and the primary backup energy supply for wind and solar. There are at least two major classes of nuclear peak electricity systems—each with multiple variants. All of these technologies are in the developmental stage. One example will be described herein—the Hydrogen Intermediate and Peak Electricity System (Fig. C.1). It consists of four components.[13]

- *Steam production*. Light-water reactors produce steam under base load conditions. The power plant may operate as a conventional nuclear plant where all the steam is used to produce electricity. Alternatively, electricity and some of the steam may be diverted to hydrogen production.

- *Hydrogen production*. Steam and electricity are used to produce hydrogen and oxygen using high-temperature electrolysis (HTE) at times of low electricity demand. A nuclear reactor producing steam and electricity can produce hydrogen for almost the same efficiency as it produces electricity. It is significantly more efficient than using traditional electrolysis to produce hydrogen and oxygen. The technology is being developed but is not commercial.

- *Hydrogen and oxygen storage*. Underground storage facilities are used for the low-cost storage of hydrogen and oxygen on a daily, weekly, and seasonal basis. This uses the same technologies used for seasonal storage of natural gas.

- *Peak electricity production.* Variable electricity to the grid is achieved by two methods: (1) switching steam from the nuclear reactor from producing just electricity for the grid to producing electricity and steam for hydrogen production, and (2) using the hydrogen and oxygen for electricity production to meet peak load demand. The economic challenge is that the capital cost for the peak electricity production systems must be very low to be economic. These systems operate for a limited number of hours per year. If the capital costs are high, the costs of peak electricity are high.

Peak electricity from hydrogen and oxygen can be produced by either operation of the HTE system in reverse as a fuel cell or use of an oxygen-hydrogen steam turbine. Because the HTE and fuel cell is the same piece of equipment and is used to either produce hydrogen from electricity or electricity from hydrogen, the capital costs for this equipment are spread out over both hydrogen production and peak electricity production. This lowers the costs of such a peak power system.

Alternatively, hydrogen can be converted to electricity using gas turbines (today's option) or oxygen-hydrogen steam turbines (the longer-term option). In this system hydrogen, oxygen, and water are combined to produce 1500°C steam that is fed to an aero-derived steam turbine. This combustor replaces the boiler. The high temperatures result in steam plant efficiency of ~70%. The capital costs are far below any other fuel-to-electricity technology—but the system can only burn hydrogen oxygen mixtures. The low costs of the oxy-hydrogen steam turbine makes it a candidate to provide the massive backup that would be required if a significant fraction of the electricity comes from wind and solar.

[13] C. Forsberg and M. Kazimi, "Nuclear Hydrogen Using High-Temperature Electrolysis and Light-Water Reactors for Peak Electricity Production," *4th Nuclear Energy Agency Information Exchange Meeting on Nuclear Production of Hydrogen,* Oak Brook, Illinois, April 10-16, 2009

The choice of hydrogen production technology may have major implications for a low-carbon-world energy architecture. The HTE production of hydrogen and oxygen with heat and electricity has a significantly higher efficiency than the production of hydrogen and oxygen from electricity (as would be required if the energy source is electricity from wind or solar). There are large economies associated with bulk hydrogen storage. Oxy-hydrogen turbines are intrinsically central-electric power systems. If this suite of technologies is successful, nuclear energy in a low-carbon energy system may have a major advantage relative to electric renewables in the production of peak electricity and may, in fact, be the enabling technology for large-scale electric renewables that require backup electricity production.

The central question herein is what replaces fossil fuels for peak electricity production? The issues are considerably more complex than this simple example because there are alternative competing nuclear and non-nuclear peak power production technologies—but it points to the need to understand how low-carbon systems fit together because storage considerations may ultimately drive energy supply choices.

Figure C.1. One Example of a Nuclear Peak Electricity System