The U.S. Spent Nuclear Fuel Legacy and the Sustainability of Nuclear Power

*By Lorna A. Greening and Erich A. Schneider**

Abstract. *Nuclear generation capacity currently accounts for roughly 20% of annual electricity generation in the United States. Following recent operating successes (>90% plant availability, and lower production costs), license extensions for existing nuclear generation capacity as well as addition of new capacity are being pursued as responses to increases in emissions of greenhouse gases and other pollutants while maintaining reliability and security of supply. However, before increased nuclear generation becomes a viable option in the U.S., the disposal of spent nuclear fuel (existing and future accumulations) needs to be addressed. Options under discussion include long term above ground storage, geologic disposal in engineered repositories or boreholes, and subsequent recycling of recovered unused nuclear fuel. Our work with advanced nuclear fuel cycle technologies suggests several potential strategies that may lead to a sustainable nuclear future and mitigation of the spent nuclear fuel problem.*

Spent Nuclear Fuel: The History and the Future Dilemma

Currently, nuclear power plants provide roughly 20% of electricity generated on an annual basis in the United States.[1] When compared on a full fuel-cycle basis, a kilowatt-hour of electricity generated by nuclear technologies avoids approximately 95% of the greenhouse gas emissions from the use of coal (DeLuchi, 1991). Further, nuclear generation has been demonstrated to be an effective means of compliance with the air quality regulation (South, 1999). However, for every kilogram of nuclear fuel used, roughly 10 grams of plutonium and one gram of actinide elements are produced. Both are considered to be hazardous to health[2] and, if in the wrong hands, national security. But both, if recovered, can be re-cycled as fuel for future use. Although the average U.S. household can be supplied with all of its annual electricity needs with ten grams of uranium, a resulting equivalent amount of spent fuel is also produced. That spent fuel must be either stored under special shielded protective conditions for centuries before it reverts to a relatively harmless state -- federal guidelines call for its essentially complete sequestration for 10,000 years[3] -- or re-processed with the active elements (plutonium and the actinides) recovered (Blowers, 1995).

The economics of nuclear energy in the U.S. are exhibiting the effects of use of a "mature technology" and market forces such as de-regulation. These have combined over the last ten years to decrease operating costs and increase availability factors (Cohn, 1997; Rogner and Langlois, 2001). The economics of nuclear generation in the U.S. have largely improved as a result of increases in operating efficiencies. Much of this improvement can be attributed to an integration of such functions as maintenance, engineering, and operations. Decreases for staff for these functions have averaged approximately 3% per year since 1995 and produced a corresponding decrease in fixed labor costs, a significant cost for nuclear generation facilities.

In addition to operating efficiencies, the economics of nuclear generation have benefited from technological improvements, increases in capacity factors largely due to increased fueling cycle lengths and greater burn-ups, falling fuel costs, and increased thermal efficiency (Kazimi and Todreas, 1999). These technological improvements along with enhanced economics and the improved safety record as a result of the same factors that have reduced forced outages would lead to the assumption that new nuclear capacity will be built and that existing capacity will undergo life-extension through license renewal. Interest has been expressed in license renewal by owners of approximately half of the existing nuclear capacity (Schneider, 2003). This is a particularly attractive proposition at costs ranging from $10 to $50 per kW. However, license applications for renewals and new facilities have not been made at the expressed rate of interest. The lack of construction of new plants can easily be explained by the experience with the previous generation of reactors which were characterized by high capital costs with substantial contingency, and the long lead times. The final units of the previous generation of nuclear power plants, coming online in the late 1980s, had overnight construction costs of $3133 per kW ($1988) and construction times of 12.2 years (National Academy of Sciences, 1992). The "next generation" of reactor technologies available for short-term deployment promise lowered capital costs, shorter construction times, and extended life times (up to 60 years). Limited experience already with this class of reactor has proven this with overnight construction costs of approximately $1522 per kW and construction times of 36.5 months (Taylor, 2001).

When compared on the basis of avoided emissions, increased energy security through reduced dependency on imported fuels, and the relatively low (and declining) costs

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[1] See footnotes at end of text.

of electricity generation from nuclear sources, the issue of spent nuclear fuel does not appear to be a deciding factor for future implementation. However, approximately 40,000 metric tons of spent nuclear fuel (SNF), arising from nearly 30 years of commercial nuclear generation, currently reside at nuclear generation facilities. Estimates indicate that by the end of the lifetimes of the existing 103 licensed, operating reactors, over 80,000 metric tonnes of SNF will require permanent disposal (Macfarlane, 2001). Given the current pace of operating license extensions, this figure could, in fact, exceed 100,000 metric tonnes. The long-term geologic repository at Yucca Mountain, Nevada is slated to begin accepting waste in 2010 with this date subject to change to a later point in time. Congress has, however, legislated the capacity of this repository to be 63,000 tonnes of SNF (Nuclear Waste Policy Act, 1982).

Much of the hesitancy to either re-license and the lack of new construction of nuclear generation can be explained by past and current U.S. policies toward the disposal of spent nuclear fuel. Under the Nuclear Waste Policy Act (NWPA) of 1982, the U.S. Federal government was to take title to all spent fuel, and begin to move it to a geologic repository by January 31, 1998 (Montange, 1987). Under the Amendments to the NWPA in 1987, Yucca Mountain, located partially within the boundaries of the Nevada Test Site, was designated as the location of the permanent geologic repository for U.S. high-level waste (Macfarlane, 2001). For the accumulation of SNF to be limited to the legislated capacity of Yucca Mountain, the approximately 100 giga-watts of current nuclear generation capacity would need to be replaced with other sources of electricity generation capacity. To further compound the problem, this replacement process must occur in the time-frame of 2005 to 2020 as licensed ceilings for on-site SNF storage are met. Therefore, not only is the waste problem still unresolved, but also the issues of potential short-falls of electricity or steep increases in the price of electricity to the consumer or both must be faced.

Although the legislative groundwork had been laid, early in the decade it became quite apparent that the U.S. DOE would be unable to meet the 1998 deadline for opening Yucca Mountain (Macfarlane, 2001). Currently, the repository is not estimated to open until 2010 or later. DOE's own total system life cycle cost estimates, conducted every five years, have shown that the anticipated cost of building and operating Yucca Mountain has almost doubled, in constant dollars, since 1980 (Schneider, 2003). Further, although applications have been made for the construction of interim-storage facilities, none have been approved. Finally, many existing nuclear facility operators have and are experiencing problems on receiving licensing approval for at the reactor on-site dry-cask storage. Without the appropriate avenues for the disposal of waste, the future of current nuclear generation facilities and the construction of new generation facilities is highly uncertain. As a result, even with the improving economics of nuclear power, few private firms are willing to undertake the politically induced risks associated with ownership of a nuclear facility (Rosenbaum, 1999). Utilities have claimed that the unplanned additions of storage capacity associated with this delay have cost $56 billion (Nuclear Energy Institute, 1998) – roughly $1400/kg or 2.8 mills/kWh for the affected SNF.

In other countries, such as Japan, the United Kingdom, and France, where firm commitments have been made to waste disposal strategies, construction of new nuclear generation is occurring. While the U.S. produces approximately 20.5% of its electricity with nuclear generation, France produces 76%, Japan 32%, and the UK 28% (International Energy Agency, 2001). All of these countries to one extent or another have struggled with the issue of SNF disposal (Blowers, 1995; Kondo, 1998; Delmas and Heiman, 2001; Pickett, 2002). And, these three countries have adopted SNF disposal strategies that include reprocessing and the fabrication of mixed-oxide fuels. Considering that only 5% of the energy content of nuclear fuel is released when it is burned in a light water reactor, not only are these countries reducing the decay heat and radiotoxicity of the waste for permanent geologic disposal, but also are recovering a valuable energy source (Banks, 2000). The limited economic analyses that are available of the reprocessing in these countries do indicate that reprocessing is economic particularly if compared with interim- or permanent storage options for SNF (Jones and Pearson, 1981; International Energy Agency, 2001). However, in the U.S., policy decisions in response to proliferation concerns currently remove reprocessing as an option (Beck, 1999).

With the growing concerns over the volumes of legacy SNF, and the very strong potential of exceeding the statutory limits of Yucca Mountain with the associated political and social risks of building a second such repository, a closed nuclear fuel cycle is necessary for sustaining nuclear generation in the U.S. (Rosenbaum, 1999). A closed nuclear fuel cycle would of necessity require reprocessing. During reprocessing one metric tonne of SNF can be reduced to 930 kg of relatively harmless uranium,[4] 10 kg of plutonium, and 60 kg of high level waste (Schneider, 2003). This strategy would result in a 10-fold increase in the 'effective' capacity of Yucca Mountain. Although, plutonium is separated from the fuel– this is considered to pose a proliferation risk–new advances in nuclear fuel cycle technologies (e.g., transmutation[5]) avoid complete separation of plutonium (Schneider, Bathke et al., 2003). Combined with new nuclear generation technologies such as high-temperature gas cooled or fast spectrum reactors, the nuclear fuel cycle becomes completely closed and sustainable (Lake, Bennett et al., 2002).

In this analysis, several different strategies are evaluated for resolving the conundrum of spent nuclear fuel, expiration of nuclear capacity licenses, and meeting the growing demand for electricity in the U.S. We have implemented expanded detail for the nuclear fuel cycle, including short-term storage, long-term disposal options, reprocessing of spent fuel, and technologies associated with "next-generation" reactors in a widely used energy system model. Use of an energy system model allows the comparison of various strategies to resolve the "nuclear" conundrum, including a phase-out of nuclear generation, permanent disposal of nuclear fuel in a geologic repository, and replacement with other types of electricity generation such as natural gas-fired combined cycle, "clean coal," or renewables. Alternatively, potential strategies include the reprocessing of SNF to reduce the volume of materials requiring permanent disposal and to recover fuel components for future use.

The remainder of this paper is organized as follows. In Section 2, an energy system model used in the development of the analysis, and the underlying structure and data for the U.S. energy system are discussed. Results of the analysis are presented in Section 3. Finally, in Section 4 the policy implications are discussed, and some conclusions are drawn. Our work indicates that a strategy utilizing a "closed nuclear fuel cycle" starting in the time frame of 2015 to 2030 will lead to a reduction in volumes of spent nuclear fuel in various stages of storage. This will allow the continued implementation and use of an electricity generation source that is relatively low in other types of emissions, dispatchable, resource conserving, and economic. However, strategies involving reprocessing would be necessary to reduce the volumes of spent nuclear fuel. These results are sensitive to the economic costs associated with technological development, market conditions, and the political process. Since these factors are changeable, we are continuing to evaluate the sensitivity of results to each of these parameters and the range over which our conclusions are robust.

Method of Analysis and Description of LA-US MARKAL

Within the framework of a widely-used energy system model (MARKAL), a detailed depiction for the nuclear fuel cycle, including short-term storage, long-term disposal options, reprocessing of spent fuel, and technologies associated with next–generation reactors has been implemented. Embedding such a detailed depiction in an energy system model allows the evaluation of the life-cycle (through spent nuclear fuel disposal) costs of nuclear generated electricity in comparison with other sources including fossil–and renewable–centrally dispatched generation sources and distributed generation. Further, use of a general energy system model allows the inclusion of the effects of end-use energy efficiency gains, the demand response to electricity price increases, and fuel substitution for all energy types on future levels of electricity demand, and the required generation mix to meet that demand.

Method of Analysis

MARKAL (MARKet ALlocation model) is a technology-oriented energy system model, which utilizes a dynamic linear programming framework and where all energy supplies and demands for energy services are depicted (Goldstein, Greening et al., 1999). Technologies within the modeling framework are described by initial investment and operating and maintenance (fixed and variable) costs, capacity utilization for demand technologies and availability for process and conversion (i.e., electrical generation technologies), and the efficiency (or heat rate in the case of electricity generation) of fuel use. As is typical of energy system models, energy flows are conserved, all demands are satisfied, previous investments in technologies are preserved, peak-load electricity requirements are honored, and capacity limits are observed along with similar traits of an energy system. Technologies are selected for inclusion in the solution based on comparison of life-cycle costs of alternative investments. Using linear programming, MARKAL minimizes energy system (capital, operating, and fuel) costs over the entire planning horizon.[6] In addition, MARKAL provides an accounting mechanism for emissions by either the application of emissions coefficients on fuel consumption and/or on the per unit output of a conversion, processing, or demand technology. Emissions constraints or "caps" may be defined on a per period basis (e.g., limits on SO_2 under the U.S. Clean Air Act) or cumulatively. Alternatively, emissions taxes or estimates of environmental damages and benefits may be depicted in this modeling framework. Further, emissions can be depicted on an economy-wide basis or on a more disaggregate basis (e.g., mercury emissions from fossil fuels used in the electrical sector).

The MARKAL family of models consists of a number of variants (Goldstein, Greening et al., 1999). For the work presented here, MARKAL_Elastic Demand (MED) (see Loulou and Lavigne, 1996, for additional details), a linear programming formulation with demand response to price changes, was used. As a result of addition of a price response to the standard linear programming formulation, a key factor, energy price demand response, in the consideration of any energy policy can be incorporated into the analysis. Without a demand response, costs of the implementation of a policy resulting in increases in energy prices could be overestimated, i.e., any reduction in energy consumption or emissions must be made totally through investment in new equipment. Further, this MARKAL variant does allow for the asymmetry of price response. As often demonstrated, energy demand exhibits a lag in response to downward movement of prices (Gately, 1993). This asymmetric demand response is the result of rates of capital turnover and technological innovation, and as a result energy demand may not return to previous levels.

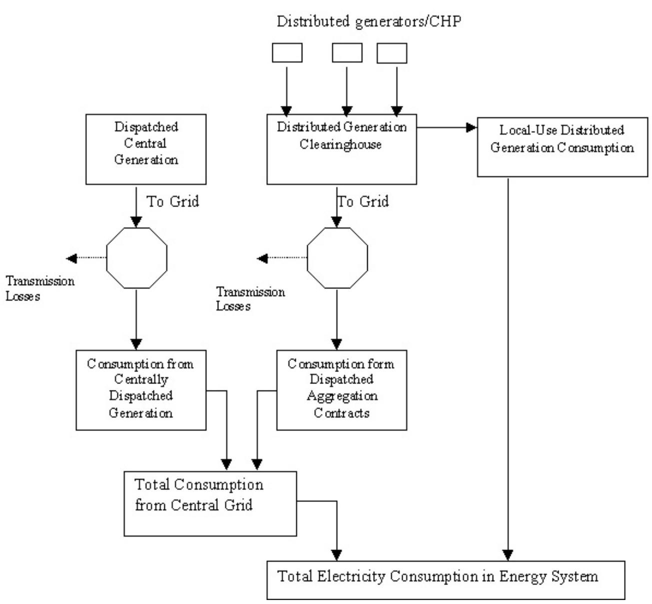
However, this variant of MARKAL does not capture the macro-economic feedbacks depicted in MARKAL-MACRO, another widely implemented variant of the MARKAL family. But, comparison of the two variants indicates that a GDP response (or feedback) accounts for less than 5% of demand response (Loulou and Lavigne, 1996). To capture the expanded detail of the nuclear fuel cycle, and other details of the U.S. energy system, a trade-off must be made between expanded detail, and the tractibility of solution of the non-linear component of MARKAL-MACRO.

Description of LA-US MARKAL[7]

The data used in this analysis depicts the energy system of the U.S. and is from a number of publicly available sources (Greening, 2003). This version of US MARKAL depicts over 3000 energy using technologies in the industrial, commercial, residential, and transportation sectors, 90 centrally dispatched and over 300 distributed electricity generation technologies, both conventional (e.g., coal, petroleum, nuclear) and non-conventional (e.g., geothermal, biomass, solar) fuels, and approximately 100 categories of energy service demands. Table 1 provides a comparison of the technology characterization underlying US MARKAL with that underlying NEMS (National Energy Modeling System) which is used by the U.S. Energy Information Administration to produce the Annual Energy Outlook (see NEMS documentation for complete details, EIA, 2000). As demonstrated by this comparison, the two modeling frameworks are similar in detail. The base year for this analysis was 1995 (i.e., all costs are in $1995) while energy service demands and other parameters are consistent with AEO 2002 (EIA, 2001).). Although similar in detail, NEMS does have a number of forecasting capabilities resulting from its modular structure that MARKAL does not have.[8] Therefore, MARKAL should not be viewed as a forecasting model, but rather as a tool to evaluate different potential views of the future. Further, MARKAL, because it is a linear optimization framework depicting the entire energy-system, can be more difficult to develop, calibrate and achieve "sensible" results.

Electricity generation in this version of US MARKAL is depicted as centrally dispatched and distributed generation (Figure 1). For centrally dispatched generation, over 90 generation technologies are characterized. The generation types characterized include fossil (i.e., oil, natural gas, and coal) steam, combined cycle, and conventional and advanced turbines. As part of this technology choice set, nine 'clean coal' technologies including integrated coal gasification combined cycle, atmospheric and pressurized fluidized bed, and advanced turbines are depicted. Renewable technologies including solar (power tower, central thermal, thermal dish Stirling, and photovoltaic concentrator), wind (three classes), biomass (combined cycle and direct fired), hydroelectric, geothermal (binary cycle and flashed steam) and municipal solid waste (mass burn, modular, RDF, and methane) are also included.

Figure 1
Distributed Electricity Generation (DG) versus Central Electricity Generation (CG)
LA-US MARKAL



A detailed summarization of the data for electricity generation technologies depicted in US MARKAL is quite lengthy and available from the author on request.

For nuclear generation, this framework incorporates one of the most complete models of the nuclear fuel cycle, nuclear generation, and nuclear spent fuel currently in existence, and exceeds the detail found in earlier efforts (e.g., Joskow and Baughman, 1976). The nuclear fuel cycle represented in this version of US MARKAL includes uranium enrichment by diffusion and centrifuge techniques, fuel fabrication processes for oxide and metal fuels, and aqueous and pyrometallurgical SNF reprocessing. These facilities support a variety of current, evolutionary and next generation reactor types: advanced light water reactors, high temperature gas cooled reactors, fast-spectrum ("breeder") reactors, and several systems (accelerator-driven systems) dedicated to efficient burning of actinide materials. These facilities are modeled upon those being considered in three Department of Energy programs: Nuclear Power 2010 (U.S. DOE, 2001), the Advanced Fuel Cycle Initiative (U.S. DOE, 2003), and the Generation-IV Program (U.S. DOE, 2002b). Unique to this framework is the inclusion of advanced reprocessing and the implementation of several types of storage including cooling, interim dry storage, and permanent storage with the characterizations (i.e., costs) based on decay heat and radiotoxicity. As part of this depiction, we are able to track heavy metal tonnage throughout the system, and can estimate amounts of different materials (such as transuranics) in stockpiles, reprocessing, reactors, cooling and interim dry storage, and permanent geologic depositories. This approach allows the evaluation of limitations on different types of storage, technological innovations in fabrication and reprocessing, strategies involving the use of the Nuclear Trust Fund for subsidizing different disposal strategies, and the impacts of market conditions including the availability and price of competing energy sources.

Distributed generation (DG) and combined heat and power (CHP) are depicted with an end-use sectoral-specific (e.g., commercial or each industrial sector) electricity and steam or heat grid. The sector-specific electricity grids are also connected to the main electricity grid through a broker or "aggregation" function, and as a result the option exists for inter-sectoral trades of electricity from distributed sources. Where appropriate, it is assumed that technologies can produce either heat or power (based on the technical constraint of a minimum production of electricity), and that the heat to power ratio is flexible changing in response to the demand for each. In any event, DG and CHP are treated as the "marginal" producer to central generation sources. This configuration defines a limited, but expandable, market niche for DG and CHP. DG and CHP generation types include turbines (fossil-

Table 1. Comparison Between NEMS and US MARKAL

End-Use Sector	NEMS	US MARKAL
Residential Demand	14 end-use services	13 end-use services
	3 housing types	2 housing types
	34 end-use technologies	150 end-use technologies and building conservation measures
	No distributed generation	36 distributed generation technologies (fuel cells and photovoltaics)
Commercial Demand	10 end-use services	9 end-use services
	11 building types	1 building type
	10 distributed generation technologies	36 distributed generation technologies (fuel cells, reciprocating engines, microturbines, photovoltaics, conventional coal, oil, natural gas, biomass, MSW)
	64 end-use technologies	325 end-use technologies and building conservation measures
Industrial Demand	15 industrial sectors including 7 energy intensive industries	10 industrial sectors including 8 energy intensive industries
	End-use demands defined as annual sectoral output in real dollars	Demands for each sector based on end-use service demand (e.g., lighting or HVAC) or physical unit demand (i.e., tons of product) or annual output in real dollars
	Use of production possibility frontier for each sector	Over 2400 technologies in a process train formulation using materials flows
	cogeneration	Up to 34 CHP/distributed generation per sector
Transportation Demand	6 automobile sizes	3 automobile sizes (sub-compact, small to medium, and full size).
	6 light truck sizes	3 light truck sizes (SUV, minivans, pickups and large vans)
	59 fuel saving technologies for light-duty vehicles	Fuel saving devices are combined with vehicle types (68 LDVs including up to 8 time dependent improvements in fuel efficiency for conventional combustion, fuel cells, SIDI, hybrids); each vehicle type has its own emissions characterization 8 emissions dependent upon type of combustion and fuel (e.g., reformulated gasoline)
	15 fuels for light-duty vehicles	7 fuels types (gasoline, diesel, hydrogen, electric, flex alcohol, biofuels, and CNG)
	20 vintages for light-duty vehicles	Aggregate existing stock (with average characteristics for each vehicle type)
	8 types of aircraft	4 types of aircraft
	12 types of freight trucks	30 types of trucks (Classes 3-6, 7-8), 10 types of buses, 3 types of rail, and 4 ship types
Electricity Generation	29 capacity types (10 renewable) Regional disaggregation with vintaging of existing coal technologies Generic DG/CHP	90 generation technologies (see text) Existing generation represented on a national aggregate basis Sector specific DG/CHP
Conventional Resources	Coal by region, rank, and sulfur content Petroleum discovery sub-module simulating exploration and finding of oil, natural gas, and natural gas liquids	Coal by region, rank, and sulfur content Oil, natural gas, and natural gas liquids by region, proven versus potential resource (USGS) for conventional and unconventional reservoirs
Alternative fuels	Biomass supply curves MSW and cap. CH_4 cost per BTU Wind Solar	Biomass supply curves MSW and cap. CH_4 supply curves Wind supply curves on basis of costs to reach main grid and congestion, and wind class Solar supply curves on basis of grid connection costs and congestion Biofuels including ethanol and biodiesel
Hydrogen	Cost per BTU	Centrally produced hydrogen from natural gas, coal, electrolysis of water, biomass, petroleum coke, and advanced nuclear. Decentralized production from natural gas, electricity, methanol, and gasoline.
Nuclear Fuel Cycle	Cost per BTU, 2 nuclear generation technologies, no disposal of spent nuclear fuel	Full nuclear fuel cycle represented with advanced nuclear technologies (see discussion in text)
Emissions	For electricity generation: mercury, SO_2, NOx On an economy-wide and by end-use sectors: CO_2	On an economy-wide, and an end-use sector or energy resource produced basis: mercury, particulates, CH_4, CO, CO_2, N_2O, NOx, SO_2, VOCs

fueled and biomass for example in the paper and pulp industrial sector), microturbines, fuel cells, reciprocating engines, and photovoltaic sources.

Results

For this analysis, we analyzed three cases: (1) a reference case assuming current nuclear capacity factors with no added capacity and that spent nuclear fuel is not a problem; (2) a case where gradual ‘extinction’ of nuclear generating capacity occurs, no re-licensing or reprocessing are assumed, and no additional repositories are built beyond those necessary to dispose of spent nuclear fuel generated with the current stock; and (3) a case with reprocessing or a closed nuclear fuel cycle is implemented. The assumptions of the first case parallel the Annual Energy Outlook (AEO) 2002 reference case between 1995 and 2020 in terms of fuel prices, other costs and investment. Those assumptions have been projected for the remainder of the forecast horizon. The AEO also assumes that SNF disposal is not an issue. The second case represents the extreme end-point where existing nuclear generation is replaced by other generation sources, and all existing SNF is disposed of in a permanent geologic repository (e.g., Yucca Mountain). The third case represents an optimistic view of nuclear generation. In this case the spent nuclear fuel issue is at least temporarily ameliorated through the use of reprocessing to reduce the volumes sent to a permanent geologic depository. Further, separated components are recycled into mixed-oxide fuels and advanced nuclear fuels.

Comparison of these cases indicates the value of reprocessing and the ‘closed nuclear fuel cycle’ in terms of maintaining the sustainability of the nuclear option for electricity generation. Nuclear generation in the reference case grows at a rate of approximately 2.5% per year with 125 giga-watts of advanced light water reactor capacity installed by 2070 while existing licensed nuclear capacity has expired. Figure 2 illustrates the mix of electricity generated over the forecast horizon for the reference case. In addition to nuclear generation, renewable generation increases to slightly over 12% of total generation, while the shares of coal and natural gas become nearly equivalent. However, facilities for repository disposal approaching the equivalent of five to six Yucca Mountains will be required.

Without reprocessing and specifically in the case where nuclear generation is phased out of the generation mix, as illustrated in Figure 3, renewable technologies are the primary substitutes for the replacement of nuclear generation capacity. Renewables increase to nearly 24% of the total electricity generated, and the shares of coal and natural gas increase by slightly over the reference. However, even with the termination of nuclear generation in the U.S., facilities for repository disposal on the order of between 1.5 and two Yucca Mountains will be required. The on-going costs for disposal of this waste burden must be included in the overall costs of supplying the U.S. with electricity.

With a nuclear strategy, however, that includes reprocessing and transmutation, a fission technology where the undesirable elements of SNF are consumed, an entirely different picture unfolds. With the implementation of these technologies, once again nuclear generation grows to approximately 100 giga-watts by 2070 or very similar to the reference case. However, these technologies are not widely available until approximately 2030. The overall generation mix appears once again to be similar to the reference case with the exception of renewables. During the period of time that the share of nuclear generation is declining while new technologies are commercialized, renewables are the preferential technology. As a result, emissions do not increase substantially over the reference case. However, geologic disposal requirements exceed the capacity of Yucca Mountain only slightly in the near term (2015 to 2030). This extra capacity is provided by interim dry-storage, which is a temporary holding facility. As fast-spectrum transmutation facilities come on line and

Figure 2
Reference Case
Centrally Generated Electricity by Fuel

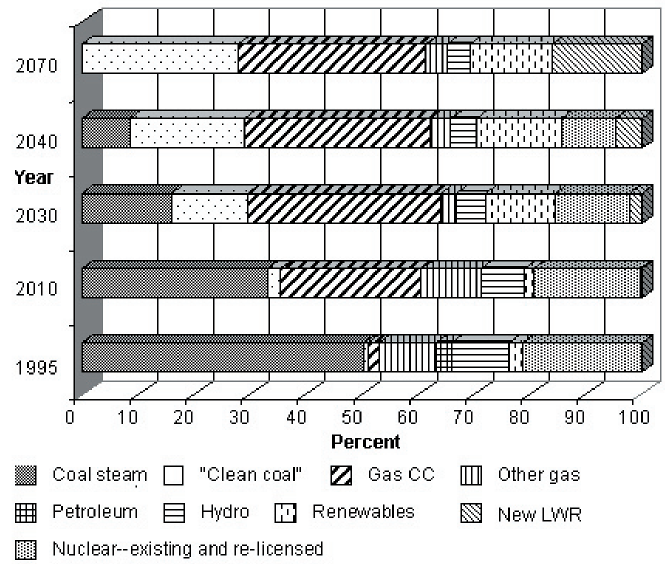
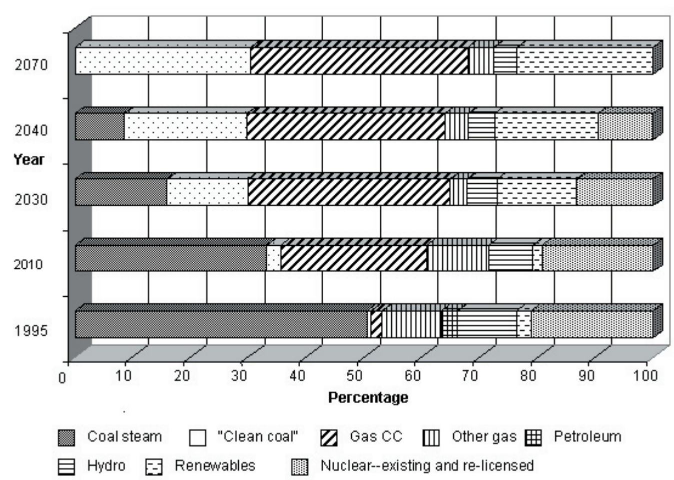


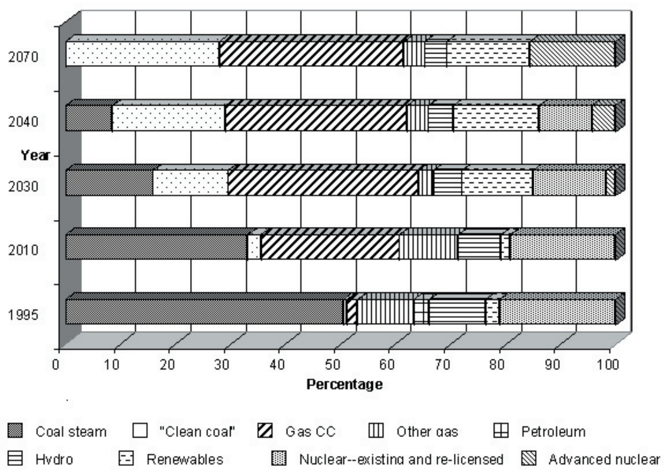
Figure 3
Phase-out of Nuclear Generation
Centrally Generated Electricity by Fuel



increase in share of the generation mix, the total volumes of 'legacy' and freshly generated nuclear requiring permanent geologic disposal fall well below the statutory limits of Yucca Mountain. Further, required volumes of temporary interim-dry storage contract and eventually disappear.

These results should be viewed as preliminary, and representative of first-order estimates of the impacts of advanced nuclear technologies. As such, these results are subject to both economic and technological uncertainty. The economic conditions including potential subsidies from the Nuclear Waste Trust Fund for development of flexible disposal strategies, changes in the regulatory climate and institutional setting, and the sensitivity of our results to declines in technology costs are all subjects of research by the authors. These initial results, however, do suggest that our energy future may very well include a nuclear component which can continue to support the U.S. style of life at relatively low levels of emissions and contribute to the development of a "hydrogen economy."

Figure 4
Advanced Nuclear Case
Centrally Generated Electricity by Fuel



Conclusions

The nuclear "conundrum" poses an interesting problem to policy makers, and the energy industry. If on one hand, nuclear generation is phased out in this country, other sources of electricity generation must be developed, and many of those sources emit greater levels of several critical air pollutants and greenhouse gases. Some of those sources are dependent upon decreasing domestic resources of non-renewable resources such as oil and natural gas. Other replacement sources such as certain types of renewable generation (e.g., wind) sources do not currently have attributes such as dispatchability and the high availability factors that characterize other more conventional sources of electricity. Many of the alternative conventional and unconventional electricity generation sources currently have higher costs than the nuclear generation that they would replace.

Efficiency improvements for various end-use technologies do hold potential for reducing the amount of energy we consume. However, eventually, diminishing returns from that source result from thermodynamics, economics, and utility or acceptability (e.g., comfort and convenience). And, we can avoid some energy consumption through price increases. However, energy demand in the short-run is inelastic, and in the long-run highly dependent upon the choices available for energy-using capital. As recent events have so aptly demonstrated, "going without" or energy at high prices will probably not gain widespread political acceptance.

If on the other hand, nuclear electricity generation is part of our energy future, then we will need to find a way to deal with the resulting spent nuclear fuel. Our work does, as does the work of many others, indicate that there are options available to the expanded development of permanent, geologic depositories. However, before we can reach the goal of a "closed nuclear fuel cycle" interim strategies involving reprocessing will be necessary. As a result, much thought will need to be given to the political, social, and security ramifications of strategies that include reprocessing as an interim and long-term solution.

We have only touched on some of the economic aspects of the "nuclear conundrum." Our results are highly dependent upon the sensitivity of the economics to technological innovation, the relative prices of competing electricity generation sources, and changes in the political and regulatory arenas. Nuclear energy has both positive and negative aspects as does any source of energy. Trade-offs among those aspects must be considered by all participants in the policy arena, and weighed in terms of the over all implications for long-term economic and social wellbeing. Our concentration in this analysis has been very limited, focusing on only nuclear electricity generation. A more complete analysis in which factors directly affecting other types of generation might lead to an entirely different set of conclusions. As a result, the future of nuclear generation remains an open, unresolved question.

Footnotes

[1] The Energy Information Administration reports that the 103 nuclear power plants in this country generated over 768.8 billion kWh of electricity in 2001, and operated at an 89% capacity factor (EIA, 2002).

[2] Health hazards result from the ionizing radiation that is emitted from both substances. Short-term effects of exposure to ionizing radiation include radiation sickness with symptoms akin to an acute case of the flu. Long-term effects of chronic exposure include cancer, reproductive failure, birth defects, genetic defects, and death (Blowers, Lowry et al., 1991).

[3] The dose to the maximally reasonably exposed individual at the site boundary of a repository is not to exceed 15 millirem (mrem) per year for 10,000 years following waste emplacement. An average individual in the United States receives a dose of 360 mrem/year from background radiation (U.S. DOE, 2002a).

[4] The resulting uranium with an enrichment of less than 0.72% is considered to be Class C waste and requires less restrictive disposal measures (Montange, 1987).

[5] Transmutation closes the nuclear fuel cycle by recycling actinides (of which plutonium is but one of several heavy elements created when uranium is irradiated) until they are fissioned. In so doing, energy is extracted from these elements that otherwise would have gone unutilized. This is also the only way—short of natural

decay over millions of years—to permanently dispose of these materials.

[6] Linear programming has a set of embedded economic assumptions that have implications for the modeling of energy markets (Dantzig, 1963). Those assumptions include: (1) all cost functions are homogeneous and linear; (2) perfect competition is assumed with a large number of participants in the market and all are ‘price takers’; (3) all economic agents operate at the minimum of their total cost curve; (4) ease of exit and entry is assumed; (5) all markets are in equilibrium; and (6) perfect foresight exists. These assumptions are particularly idealized for energy markets which are very rarely in equilibrium, very often can be characterized by economies of scale, and rarely have a market structure that includes a large number of participants.

[7] LA-US MARKAL is one of four US MARKAL models currently in existence or under development. Each model has a different level of detail, a different forecasting horizon, and is designed to evaluate a different set of problems. If the reader has a particular interest in determining which model is the “best,” direct contact with the developers is recommended. Of course, the reader should be forewarned that each set of developers would claim “superiority.”

[8] The modules in NEMS forecast the mix of technologies and resources available based on non-energy related characteristics. For example, in the transport module, NEMS can produce the mix between vehicle sizes based on characteristics such as number of passengers carried, interior compartment size, acceleration, and similar passenger amenities. The parameters for this sub-module are from the econometric analysis of survey data. To produce a similar result in MARKAL requires the conversion by the analyst of output from a discrete choice model into a system of linear proportionality constraints. These constraints are not endogenously responsive to price, and must be updated by the user to changed economic or demographic conditions.

Bibliography

A detailed bibliography is available from the authors on request.

IAEE Student Activities – Paving the Way to Becoming Acquainted With the Energy Economic Community

One of the major benefits of conferences and work shops is that they offer in a relaxed and friendly manner the opportunity to get in contact with colleagues (or students) of your profession from around the world. IAEE activities, like the annual International Conference, offer this possibility in an excellent and very pleasant way, as I had the chance to experience at the Prague International Conference. The conference proceedings (as well as the other IAEE publications) are valuable resource for papers on energy related matters. In short, the IAEE activities not only provide an excellent starting point for students to become acquainted with the international energy economic community but also offer resources to further build up this initial stepping stone. Thus, encouraging students to attend IAEE conferences by offering reduced conference fees or even scholarships as well as special students program activities is one important way the IAEE could address new students, who might not have attended any conference before.

Surely a lot of students do not have the opportunity to attend an IAEE International Conference due to, amongst other reasons, limited financial resources. Local (or national) activities on the other hand, are much easier to attend and less of a cost burden. As the IAEE started appointing student council members three years ago to help supporting student matters on an international level, affiliates are also encouraged to do this (or something similar) within their organization. This, along with other means to enhance student involvement on the affiliate level, would also improve IAEE’s chance to reach out to new students: Due to their better knowledge of national universities, affiliate student council members could directly address relevant faculties or departments concerning IAEE activities.

To offer students the chance for international networking on energy related matters (beside international conferences), the student section on iaee.org was started by the preceding Student Council members. After some reorganization and improvements its main features are now the IAEE Student Directory and the IAEE Student Newsgroup. Students interested in energy economics from around the world, who don’t necessarily have to be members of the IAEE, are encouraged to send in their student information to be displayed on the Student Directory page and are then subscribed to the IAEE Student Newsgroup. The student information contains country of studies, university, study subject, current research project, energy interests etc. Students are also encouraged to send in an abstract of their current research project, which is then made available on the Student Directory page and could be the starting point for discussions within the newsgroup. The newsgroup is open to postings on current energy related matters, student research projects, or IAEE student activity proposals. Subscribers also receive the IAEE Student Newsletter, which contains listings of special events and programs for students, and IAEE members in general, as well as abstracts of student research projects.

Future initiatives for the student section of iaee.org will address additional student’s needs, for example the mediation of internship opportunities; a service which especially will need the support of the IAEE’s membership. I would like to take this opportunity to ask for the continuing excellent support from the membership for the IAEE student activities to help students to become acquainted with the energy economic community.

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