ASSESSMENT OF SMALL AND MODULAR REACTOR NUCLEAR FUEL COST

A Senior Scholars Thesis

by

CHRISTOPHER PAUL PANNIER

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major: Nuclear Engineering

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Approved by:

Research Advisor:	Radek Skoda
Associate Director, Honors and Undergraduate Research:	Duncan MacKenzie

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ABSTRACT

Assessment of Small and Modular Reactor Nuclear Fuel Cost. (May 2012)

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The nuclear energy industry is experiencing a renaissance of new reactor design and construction in Asia, North America, and Europe. The new Generation III designs are some of the largest ever built, featuring improved efficiency, construction in modules and passive safety systems in most designs. Along with these large designs, a new class of small modular reactors is vying for the fossil fuel market share of electricity generation. Experience with the nuclear fuels cycle has shown that operating costs of commercial light water reactors are well understood. A simple model of fuel cost based on publicly available nuclear fuels market and reactor design parameters is employed to estimate fuel cost for comparison among the new reactor designs. Such a comparison of the variable cost of nuclear energy can benefit a utility or nation in planning for new power plants. Additionally, the reactor design parameters of the model are incremented in a sensitivity study to determine optimum design improvements for lowest fuel cost. At current design parameters, small and modular reactors are found to have fuel costs roughly 50% higher than those of large Generation III reactors.

DEDICATION

I dedicate this thesis to my family: my supportive parents Carolyn and Paul, my inspiring sister, Katie, and to the new family I have found at the Wesley Foundation at Texas A&M University, my home away from home.

ACKNOWLEDGMENTS

This project began as a late semester visit to a professor’s office during office hours. I would like to acknowledge Dr. Radek Skoda for motivating the initial research question and continually pushing me to further my knowledge and analytical skill. I would also like to acknowledge the Nuclear Power Institute at Texas A&M University and the Texas A&M Nuclear Engineering Department for supporting me to present findings at the 2011 ASME Small and Modular Reactor Symposium in Washington, D.C.

NOMENCLATURE

ABWR	Advanced Boiling Water Reactor
AP	Advanced Passive series of Westinghouse reactors
BWR	Boiling Water Reactor
EIA	Energy Information Agency
ESBWR	Economically Simplified Boiling Water Reactor
GCR	Gas Cooled Reactor
iPWR	Integral Pressurized Water Reactor
INCAS	INtegrated model for the Competitiveness Analysis of Small modular reactors
LWR	Light Water Reactor
NEI	Nuclear Energy Institute
PWR	Pressurized Water Reactor
PHWR	Pressurized Heavy Water Reactor
SEMER	Système d’Évaluation et de Modélisation Économique des Réacteurs
SD	Separative Duty
SC	Separative Capacity
SMART	System-integrated Modular Advanced ReacTor
SMR	Small or Modular Reactor
SWU	Separative Work Unit
U_3O_8	Natural Uranium (Pitchblende)
UF_6	Uranium Hexafluoride

US-APWR	US Advanced Pressurized Water Reactor
US-EPR	US Evolutionary Pressurized Reactor
UxC	The Ux Consulting Company

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CHAPTER I

INTRODUCTION

In the early twenty-first century, there has been a movement to build new nuclear power plants, labeled a renaissance of nuclear power. This renaissance is motivated to provide greenhouse emissions-free baseload electricity generation with passive safety systems and proven light water reactor (LWR) technology (Marques, 2010). In terms of reactor design generations, the large LWRs designed from the 1990s to present, including the ABWR, ESBWR, AP 1000, US-APWR, and US-EPR, are considered Generation III designs. A more recent focus in reactor design is on building light water moderated small or modular reactors (SMRs) for civilian electrical or industrial applications. These designs include the NuScale, mPower, SMART, HI-SMUR, and Westinghouse SMR. It is the objective of this thesis to develop a simple model to compare these two classes of reactor designs on the basis of electricity generation cost for the benefit of utilities or nations that might consider building a new reactor in the near future.

Proponents of nuclear generated electricity often cite the low fuel cost as an advantage over fossil fuels. As a component of total cost of electricity, fuel costs make up less than 30% of the total cost for nuclear energy. Whereas in coal and natural gas plants, fuel cost

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This thesis follows the style of Energy Economics.

was 77% and 90%, respectively in 2010 (NEI, 2011a). As a result, nuclear generated electricity cost is much less sensitive to fuel price changes than either coal or natural gas. Fig. 1 shows recent and historical speculation in fuel markets, uranium and enrichment included, due to inherent volatility in commodities prices. Large volatility in natural gas prices has been evidenced as recently as 2005 and 2008, when natural gas prices peaked above twice its 2011 value. The relative independence of nuclear electricity cost to changes in fuel cost allows utilities to better forecast future costs to make financial decisions on electric generation such as plant maintenance, new plant construction and plant retirement over a long time scale. Due to fossil fuel market volatility and political concerns over carbon dioxide and other emissions, forecasting of fossil generation costs is more risky. Total cost of nuclear power plant electricity generation is less dependent on fuel price changes than fossil fuel electricity.

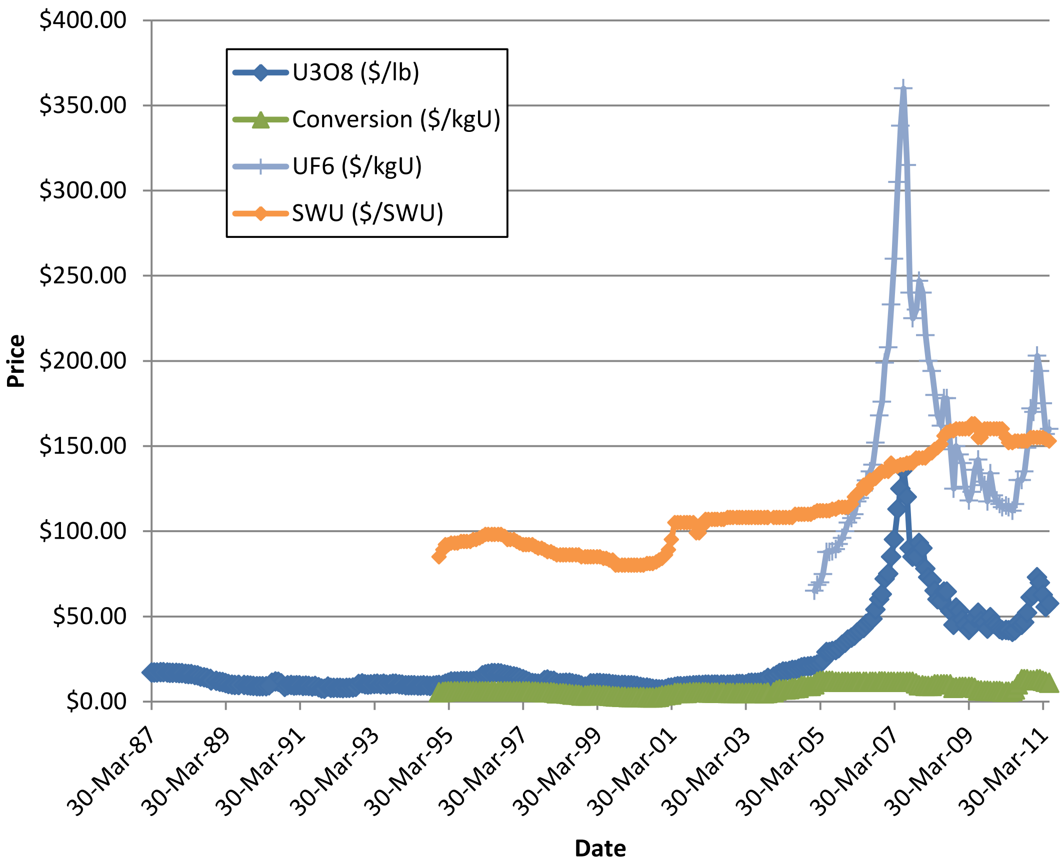

Fig. 1. Uranium Price Indicators. This figure shows the North American spot prices for natural uranium (U_3O_8), Conversion from U3O8 to UF6, UF6, and SWU. In 2007, speculation caused a jump in uranium price. Data courtesy of UxC.

Non-fuel costs of nuclear electricity generation are relatively stable over time. These costs, apart from amortized initial investment costs, are mainly plant operations, maintenance, and security. As reported by the Nuclear Energy Institute, a comparison of quarterly operating cost of nuclear power plants shows a slight increase from the three-year rolling average from 2006 to 2010 (NEI, 2011b). As an exception, large maintenance expenses such as steam generator replacement or containment wall repair are less predictable one-time expenses that are amortized over time. If proponents of expanding nuclear energy can support their position on the merits of low variable costs, they must conversely overcome the issue of extremely high construction cost.

With a half century of commercial experience, the economics of the nuclear fuels cycle are well known. For gaseous diffusion uranium enrichment, given the parameters of desired fuel enrichment, natural uranium (U_3O_8) price, cost of conversion from U_3O_8 to UF_6, and price of SWU (separative work units of enrichment), the depletion of the uranium tails from the enrichment process can be optimized for lowest price of enriched uranium (Benedict and Pigford , 1957). With this additional parameter of uranium tails depletion, the price of enriched uranium is determined. With the reactor design parameters of average fuel burnup, plant net efficiency and average fuel enrichment and the price of enriched uranium, one can estimate the fuel cost of nuclear electric generation (Pannier and Skoda, 2011).

There are published models of varying complexity that attempt to model costs of nuclear power. In the computer code SEMER, the French agency CEA uses a combination of financial and design data to assess the costs of proposed new nuclear plants in France and compare them to coal and gas-fired alternatives (Nisan et al., 2003). Key to the success of this code is the overarching influence of the French government in the nation's energy policy. Design details that are proprietary in the United States are available to the French CEA to include in a precise model of reactor costs. The volatility of the market and propriety of American nuclear reactor vendors and utilities makes such a code impractical in the United States.

In the model created by Politecnico di Milano, INtegrated model for the Competitiveness Analysis of Small modular reactors, or INCAS, nuclear electricity production cost is modeled accounting for the economic advantages of the different reactor designs. The model takes investment and external factors inputs and applies weighting factors from expert experience to produce an attractiveness index for a proposed new nuclear reactor. It accounts for financing costs, time delay in construction, economies of scale, fixed cost sharing through co-siting, cost reduction through learning curves, modular construction and mass production (Boarin et al., 2011). Like the SEMER code, many market and reactor inputs are required to obtain a precise cost.

Small and modular reactors

The development of small reactors began in the early 1950s for naval propulsion of American and Russian nuclear submarines. In the twentieth century, several countries developed SMR designs that can be broadly classified as integral pressurized water reactors (PWRs), marine-derivative PWRs, boiling water reactors (BWRs)/pressurized heavy water reactors (PHWRs), gas-cooled, lead and lead-bismuth cooled, sodium-cooled, and various non-conventional designs.

In terms of timeline of deployment, SMRs can be grouped into two broad categories: those for early deployment based on a proven LWR technology, and those for longer-term deployment based on other advanced design concepts.

The SMRs could be beneficial in providing electric power to remote areas that are deficient in transmission and distribution infrastructures, but could also be used to generate local power even for larger population centers. Overall, SMRs offer the following advantages over current nuclear power reactors:

- Power generation for remote areas, where traditional fuels are expensive due to transportation cost,
- Modular construction that reduces the amount of work on-site, making it simpler and faster to construct,
- Long refueling cycle (perhaps 2-5 years),
- Design simplicity,
- Passive safety,
- Increased potential siting locations,
- Smaller nuclear island and footprint of entire nuclear power plant,
- Low operation and maintenance costs,
- Low initial costs and investment risks,
- Proliferation resistance.

However, the following disadvantages of SMRs must be overcome if the SMRs are to be deployable in the near future:

- Uncertainty of long run economic advantages of SMRs over large LWRs,
- Spent nuclear fuel could be located in remote areas which will make its transport more difficult,
- Similarly, spent fuel will be located in many more sites rather than being concentrated at a limited number of locations,
- Public acceptance of new concepts,
- Obtaining design certification and license may take longer time than expected.

Since the fuel of current LWRs is very similar to the fuel of several SMRs derived from them, it is straightforward to compare fuel costs of the two concepts. In this thesis, the fuel cost of SMRs and Generation III LWRs are compared in perspective to the initial capital investment, economy of scale and overall cost of construction in (Pannier and Skoda, 2011).

In reactor operation, the degree to which the potential energy of the uranium in a fuel element has been “burned” is described by its burnup in units of MWd/t, or megawatt days per metric ton uranium. Early LWRs operated fuel up to a burnup around 33,000 MWd/t. Newer fuel materials and cladding, as well as a body of operating experience, have allowed LWRs to operate safely up to 60,000 MWd/t (IAEA, 2007). Operating at increased burnups extracts more energy from the fuel, lowering the fuel price of energy.

CHAPTER II

METHODS

A limited number of reactor designs were selected for this study considering those most likely to be deployed in the United States in the near term. The calculation of fuel price for each reactor is based in on approximations of the energy content of the fuel and the amount of energy delivered by the fuel in the reactor core. This calculation requires six cost parameters: three market parameters and three reactor design parameter. The process of calculating and optimizing fuel price is described in this section, along with necessary approximations due to the proprietary nature of the design data.

Selection of reactor designs

The SMRs chosen for the study are mainly iPWRs: the Westinghouse SMR, Babcox and Wilcox's mPower, Fluor's NuScale, Holtec International's HI-SMUR and the Korean-designed SMART. Two non-iPWR designs were also studied for comparison: the Russian KLT-40S and the GT-MHR, a gas cooled reactor. Six large light water reactors were studied: VVER-1000, ABWR, AP 1000, ESBWR, US-EPR and US-APWR. Design data were taken at their 2011 values to give a representative picture of the reactor classes as a whole. Subsequent reactor design changes will likely occur before construction of the first domestic SMR and are handled in a study of fuel cost sensitivity to burnup, enrichment and efficiency.

The Babcox and Wilcox mPower is a 125 MWe integral PWR reactor. Multiple units can be built on the same site, allowing an electricity provider to scale up in increments of 125 MWe. The design has a 4.5-year refueling cycle with a once-through core, meaning that the entire core is replaced at the end of the 4.5 years (B&W, 2010). The Babcox and Wilcox company has decades of design experience with large LWRs and naval nuclear reactors. It has signed agreements with the Tennessee Valley Authority to build up to six mPower units at the Cinch River site near Oak Ridge National Laboratory in eastern Tennessee. The Nuclear Regulatory Commission expects an application for construction permits in late 2013(Blake, 2012). With a customer announced, the mPower design will likely be the first SMR constructed in the United States in the current design generation.

The Westinghouse Electric Company is a major provider of nuclear design services and components. Before the recent industry interest in smaller reactor designs, Westinghouse completed the design of its IRIS reactor, a 100-300 MWe design that was never built (WNA, 2011). Using experience from IRIS and fuel technology from its AP1000 design as a basis, Westinghouse is working on its SMR design, the aptly named Westinghouse SMR. This iPWR has an electric capacity of 200 MWe with a 24 month refueling cycle (Westinghouse, 2011). The NRC expects an application for design certification as early as late 2012 (Blake, 2012).

The SMART reactor, or System-integrated Modular Advanced ReacTor, is an integral PWR designed by the Korean Atomic Energy Research Institute. It offers 90 MWe capacity and a facility to desalinate 40,000 tons of seawater per day. It has an option to provide district heating instead of desalination as an alternative use of its waste heat (Lee, 2010). A prototype may begin construction in South Korea in 2012 (Blake, 2012).

The NuScale reactor is much smaller than the other iPWRs considered in the study. It is marketed as a system of 45 MWe units, with up to 12 units in a reactor building (Landrey, 2010). This size allows customers to purchase and expand their facility in smaller increments, reducing the maximum capital outlay of a nuclear system of comparable size built as a single LWR. This makes the NuScale design an affordable option, more so than any other SMR, for smaller utilities or countries that could not otherwise finance construction of a larger single unit nuclear reactor.

The Russian designed KLT-40S is an SMR design currently under construction. The design derives from the KLT-40 reactors used to power Russian icebreaker ships in the Arctic. The KLT-40S will be used as a floating two unit power station in Kamchatka with other possible sites for future units (WNA, 2011).

The HI-SMUR 140, or Holtec International Safe Modular Underground Reactor is a 140 MWe SMR design released by Holtec International, a company with experience producing nuclear spent fuel casks for dry storage. The design is unique in its use of pressure and temperature difference along an unusually tall reactor pressure vessel to circulate coolant without pumps during reactor operation (Singh et al., 2011).

The only high temperature SMR chosen for this study is the Gas Turbine-Modular Helium Reactor, or GT-MHR. Because helium is naturally inert and single-phase, the helium-cooled reactor can operate at much higher temperatures than today's conventional LWR nuclear plants (Kostin et al., 2007; Gorelov et al., 1997). A plant with a higher turbine operating temperature is more thermodynamically efficient. Additional efficiency comes from the helium coolant directly driving the turbine, instead of having to produce steam in a large heat exchanger. On the other hand, higher and more expensive enrichment is required for such a reactor. This reactor is designed to burn uranium and higher actinide fuels such as from spent nuclear fuel or dismantled nuclear weapons (General Atomics, 2011). Only uranium fuel is considered in the study as prices for higher actinides are not as stable.

Six well known LWR reactors from four different countries were chosen to represent currently available options on the nuclear reactor market. The VVER 1000 class represents the standard Russian Pressurized Water Reactor offered by Atomstroyexport; it is available in several power variants and many units were built in Russia, India, China, and other countries (Elemash, 2004.). The AP 1000 is the model of the Westinghouse Pressurized Water Reactors currently being constructed in USA and China (Westinghouse, 2003). The ABWR is the Japanese Boiling Water Reactors offered by Toshiba and Hitachi and operated in Japan (Tepco, 2010). The EPR is the Pressurized Water Reactor sold by the French company Areva to Finland, France, and China (Areva and EDF, 2007). The US-EPR is the variant for the U.S. market. The US-

APWR is a large Pressurized Water Reactor manufactured by Japanese Mitsubishi Heavy Industries (Suzuki et al., 2008). Finally, the ESBWR is a Boiling Water Reactor produced by Hitachi and General Electric based on natural circulation (Shiralkar et al., 2007). With the exception of the VVER 1000, each of these large reactors has been proposed for construction at various sites in the United States.

Nuclear fuel economics

Due to the moderation properties of light water, a LWR using uranium fuel requires fuel enriched to U-235 concentration above that of natural uranium. There are two main processes currently used to enrich natural uranium to make reactor fuel: gaseous diffusion and gas centrifuges, both requiring chemical conversion of solid natural uranium to a gas form. The economics of uranium enrichment are well known (Cochran and Tsoulfanidis, 1999). To calculate fuel price in a nuclear system using enriched uranium fuel, one must know the price of enriched uranium used to make the fuel. This price depends on the enrichment of the fuel, a reactor design parameter. Furthermore, three market parameters are needed to calculate the price of enriched uranium: price of U_3O_8 from a uranium mill, price of conversion of U_3O_8 into the gaseous UF_6 for enrichment, and price of SWU. The number of SWUs, or separative work units, required to enrich to a certain level is a measure of the electric energy required to perform the enrichment. All three of these costs are publicly available from the Uranium Consulting Company’s uranium price indices.

The cost of fabricating nuclear fuel assemblies from enriched uranium is proprietary and strongly dependent on the type of fuel assembly chosen for a reactor. Integral PWR fuel is not expected to vary from the fuel fabrication techniques used in large LWRs. In a 1994 OECD/NEA study, fuel fabrication prices are given with a range between \$200 and \$400 per kg U, with higher costs for fuel designed to withstand a higher burnup. In that study, a value of \$275/kg U is assumed for fabrication cost (NEA, 1994). As fabrication is around 10% of the cost of nuclear fuel in LWRs, it will be omitted in this study for comparative analysis of fuel price of different reactor designs.

Enrichment economics

Three concentrations govern the enrichment process: weight fractions of U-235 in feed material, product and depleted uranium tails. Let these be denoted x_F for feed uranium enrichment, x_P for product enrichment and x_W for tails depletion, each as a weight fraction of U-235. The feed enrichment, x_F, is naturally constant worldwide at 0.711%. The product enrichment is determined by the reactor designers, but typically ranges from 3-5% for LWRs. This leaves x_W as a free variable to be optimized by the enrichment plant. Typical values for x_W are 0.2-0.3% (Cochran and Tsoulfanidis, 1999). Having a more depleted uranium tailings saves on total amount of uranium feed used, but requires more energy; conversely, having a less depleted tailings uses more natural uranium but less energy to produce the same enriched product (Benedict and Pigford, 1957). Performing an optimization based on tails depletion gives the value of x_W that results in the lowest price of enriched product based on the market values of uranium feed and SWU.

Optimization of tails depletion

The separative duty (SD), of an enrichment plant, is defined by the following formula:

$$SD = W \cdot (2x_W - 1) \cdot \ln \frac{x_W}{1 - x_W} + P \cdot (2x_P - 1) \cdot \ln \frac{x_P}{1 - x_P} - F \cdot (2x_F - 1) \cdot \ln \frac{x_F}{1 - x_F}, \tag{1}$$

where W represents the rate of production of tails in kilograms per unit time, P for product rate in kilograms per unit time, F for feed rate in kilograms per unit time, x_W is tails depletion, x_P is product enrichment, and x_F is feed uranium enrichment, each as a weight fraction of U-235. Separative duty measures the rate at which isotopes are separated in a cascade (Benedict and Pigford, 1957) . In the isotope separation plant, the initial cost of constructing the separation plant is proportional to the separative duty of the plant, and the annual operating costs are proportional to the separative work done per year. Replacing the flow rates in Eq. (1) with amounts of tails, product and feed in moles give an equation for separative work, SW, in Eq. (2).

$$SW = E_W \cdot (2x_W - 1) \cdot \ln \frac{x_W}{1 - x_W} + E_P \cdot (2x_P - 1) \cdot \ln \frac{x_P}{1 - x_P} - E_F \cdot (2x_F - 1) \cdot \ln \frac{x_F}{1 - x_F} \tag{2}$$

Separative work measures the amount of separation performed to produce E_W moles of waste and E_P moles of product from E_F moles of feed. The units of separative work are the same as the units of materials: waste, product, feed, and are designated separative work units, SWU.

The annual charges for enrichment plant investment plus annual operating costs, excluding cost of feed, in dollars per year are equal to SD·c_S, where SD is the annual separative duty in kilograms of uranium per year, and c_S is the unit cost of separative work in dollars per kilogram of uranium of separative work units in \$/kg SWU. If M_F kg of feed is charged per year at a unit cost of c_F in \$/kg feed, the total annual cost, c is:

$$c = SD \cdot c_S + M_F \cdot c_F\,. \tag{3}$$

If P kg of product is made per year, the unit cost of product, c_p, in \$/kg product is:

$$c_P = \frac{SC \cdot c_S}{M_P} + \frac{M_F \cdot c_F}{M_P}\,. \tag{4}$$

The masses of waste, product and feed are related in conservation of mass in Eq. (5), that is all uranium introduced into the cascade as feed must end up either as product or depleted waste.

$$\mathrm{M_F} = \mathrm{M_P} + \mathrm{M_W}. \tag{5}$$

The mass of U-235 is conserved in Eq. (6).

$$x_F \cdot M_F = x_P \cdot M_P + x_W \cdot M_W. \tag{6}$$

From the conservation equations, Eqs. (5) and (6), it follows that

$$\frac{M_F}{M_P} = \frac{x_P - x_W}{x_F - x_W}, \tag{7}$$

and

$$\frac{M_W}{M_P} = \frac{x_P - x_F}{x_F - x_W}. \tag{8}$$

But the cost of separative work required in the stripping down-stream section varies from zero when $x_W = x_F$ to infinity when $x_W = 0$. Conversely, the cost of feed varies from infinity when $x_W = x_F$ to a minimum at $x_W = 0$. There is therefore an optimum tails assay, x_0, between $x_W = 0$ and $x_W = x_F$, at which the sum of the cost of separative work and the cost of natural uranium feed is a minimum (Benedict and Pigford, 1957). Optimum tails composition, x_0, occurs when:

$$\left(\frac{\partial c_P}{\partial x_W}\right)_{x_P, x_F} = 0 \tag{9}$$

$$c_P = c_F \frac{x_P - x_W}{x_F - x_W} + c_S(2x_P - 1)\ln\frac{x_P}{1-x_P} + c_S \frac{x_P - x_F}{x_F - x_W}(2x_W - 1)\ln\frac{x_W}{1-x_W} - c_S \frac{x_P - x_W}{x_F - x_W}(2x_F - 1)\ln\frac{x_F}{1-x_F}. \tag{10}$$

Then,

$$0 = \frac{c_F}{c_S} - (2x_P - 1)\ln\frac{x_F(1-x_0)}{x_0(1-x_F)} + \frac{(x_F - x_0)(1-2x_0)}{x_0(1-x_0)} \tag{11}$$

The value of x_0 that satisfies Eq. (11) gives the optimum tails depletion.

Fuel cost calculation

To specify the cost of mining, conversion and enrichment components of nuclear fuel cost per kWh, Eq. (12) is used to account for the energy content of the fuel. When the price of nuclear material is known, the fuel cost of electrical energy produced by unit of nuclear fuel can be evaluated as:

$$P = \frac{U}{\eta \cdot B \cdot 240} \, [UScent/kWh], \tag{12}$$

where P is fuel price per kWh in US cent, U is price of enriched uranium product in US$ per kg in US$, η is net plant efficiency, and B is average fuel burn-up in MWd/kg.

Sensitivity studies

Reactor experience has shown that reactor operators will pursue cost-saving improvements to the reactor after operations have commenced. Improvements in fuel technology and increased experience with fuel in the core allow for higher burnups. In order to increase burnup, higher fuel enrichment is necessary.

Improvements in plant equipment such as pipe insulation, heat exchangers, preheaters, and ultimate heat sink allow for increased thermodynamic efficiency. Thermodynamic efficiency is strongly dependent on site specific layout of the plant, for example the energy losses depend on length of piping and ambient temperatures. For this reason, plant net efficiency is given as an estimate for unbuilt designs.

The fuel price calculations for each reactor design are repeated for increased burnup, enrichment, and a range of plant efficiencies. Burnups are incremented up to 20,000

MWd/t above design specifications. Enrichment is incremented up 4% above design parameters. Efficiency is varied 4% above and 4% below design specifications. Each separate sensitivity calculation is performed in 20 increments.

CHAPTER III

RESULTS

The enriched uranium cost for the selected power plants, the prices of material, conversion, and enrichment were taken at 2011 values, shown in Table 1.

Table 1

Mean front end cycle cost parameters.

Parameter	Unit	Cost
U_3O_8	\$/lb in U_3O_8	57.5
Conversion	\$/kg U as UF_6	11
SWU	\$/SWU	153

The volatility of U_3O_8 price and SWU price is shown in Figures 2 and 3, respectively. To account for this volatility in the market price of nuclear fuel inputs, a historical Monte Carlo simulation of future market prices was performed. This gave a distribution of future market prices around the present price with variations based on the relative changes in market price in the past.

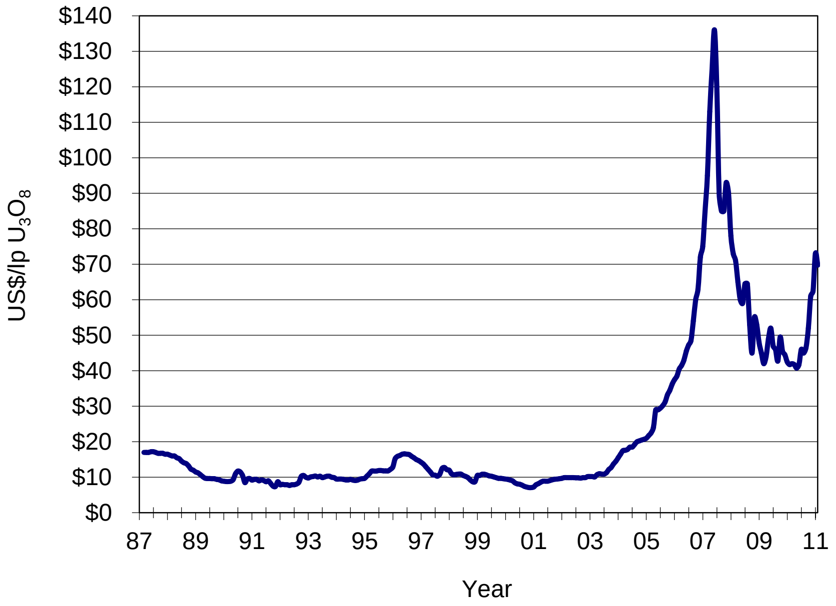

Fig. 2. Price of Uranium. Data courtesy of UxC.

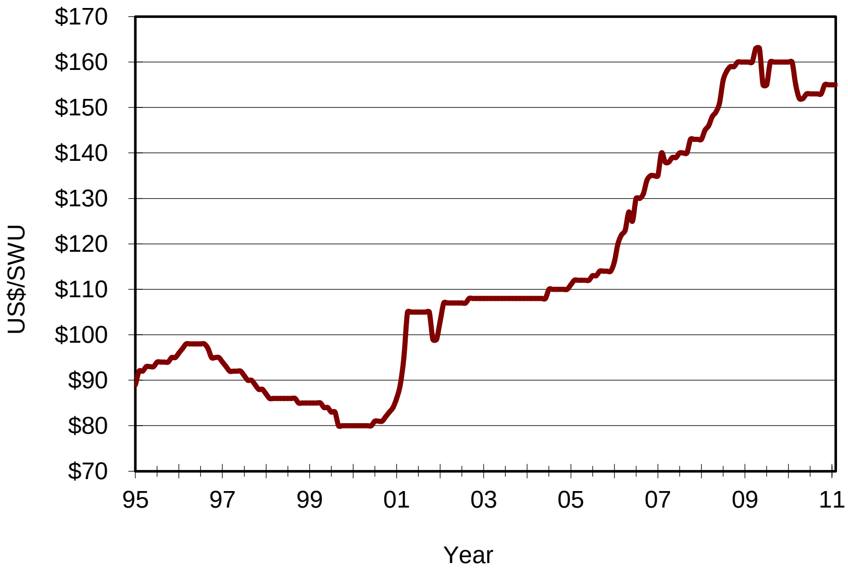

Fig. 3. Price of SWU. Data courtesy of UxC.

For a comparison with operating commercial nuclear power plants, performances and parameters of the selected modern LWRs and SMRs are presented in Table 2. Reactor parameters for each design vary from site to site and change as design decisions are made before and during construction. The values used in the analysis reflect 2011 design parameters:

Table 2

Parameters of studied nuclear power plant designs.

Reactor	Fuel Enrichment	Fuel Burnup [GWd/t]	Net electric power [MWe]	Thermal power [MWt]	Plant net efficiency
SMR					
KLT-40S	14.10%	45.4	30	150	20%
NuScale	4.95%	50	45	160	28%
SMART	4.88%	60	90	330	27%
mPower	5.00%	40	125	400	31%
HI-SMUR	4.95%	35	140	450	31%
W-SMR	4.95%	54	200	600	33%
GT-MHR	15.50%	121	286	600	48%
LWR					
VVER1000	3.50%	43.4	1000	3000	33%
AP1000	4.55%	60	1100	3400	32%
ABWR	3.70%	45	1315	3811	35%
US-APWR	5.00%	62	1600	4451	36%
US-EPR	5.00%	60	1600	4500	36%
ESBWR	4.20%	50	1561.5	4500	35%

The calculated fuel cost for large LWRs is around US$ 5.5/MWh. Selected SMR fuel costs are between US$ 6.6-11.1/MWh as shown in Table 3 and graphically in Figure 4. The results predict an increase between +40% to +100% for the SMR fuel cost compared to large LWRs.

Table 3

Mean fuel cost and standard deviation for the studied reactors.

Reactor Type	Fuel Cost US$/MWh	Standard Deviation
US-APWR	5.438	0.215
ABWR	5.447	0.225
VVER1000	5.461	0.228
AP 1000	5.586	0.224
US-EPR	5.681	0.225
ESBWR	5.681	0.230
W-SMR	6.669	0.264
SMART	7.198	0.286
GT-MHR	7.489	0.262
NuScale	8.517	0.337
mPower	9.774	0.386
HI-SMUR	11.039	0.437
KLT-40S	42.854	1.501

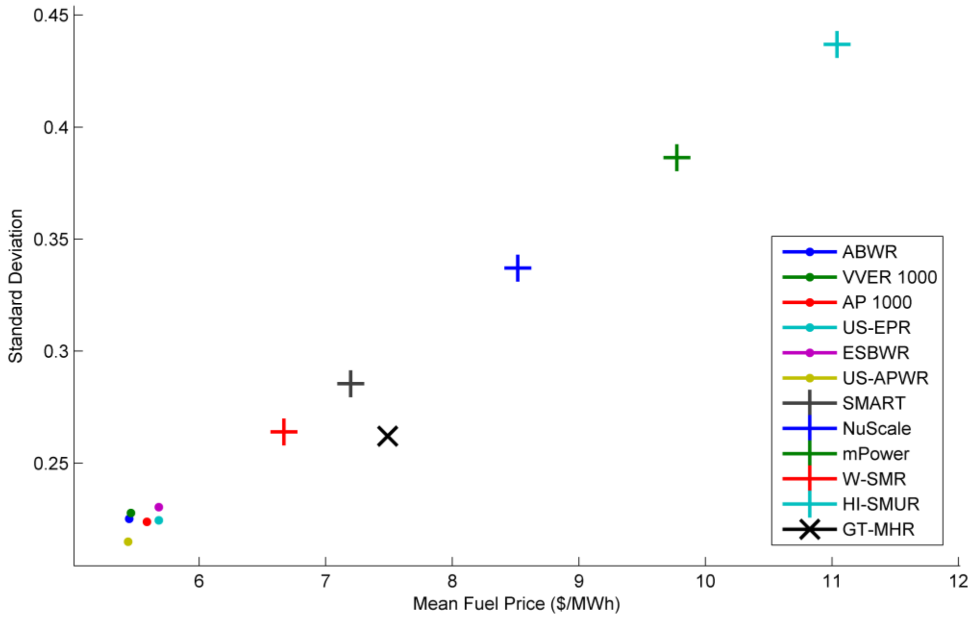

Fig. 4. Standard Deviation Versus Mean Fuel Price

The only exception to the moderate fuels cost increase of SMRs over LWRs was the KLT-40S reactor, for which using a relatively high enrichment and low burn-up gives fuel cost more roughly 5 times higher than other studied SMRs. Since this reactor is directly derived from an existing naval plant, its lower construction fixed cost and R&D cost may compensate for the higher fuel cost. The availability Russian legacy enriched uranium below market enrichment prices for the KLT-40S can also improve the total cost balance for this design.

Acknowledging the economy of scale, lower neutron leakage and better thermal insulation for larger reactors, one would expect a lower fuel cost for larger SMR units. In this respect the Westinghouse SMR and SMART have lower fuel costs than the smaller NuScale. However the mPower and HI-SMUR do not follow this trend because of their low burnup. The GT-MHR reactor has a higher fuel cost due to its higher enriched fuel.

Sensitivity analysis directly shows which parameters influence the fuel cost. The strongest cost dependency is on burnup, so mean fuel prices at higher burnups were calculated to demonstrate the sensitivity. The results are shown in Figure 5. From the history of the industry, one can expect operators will try to improve fuel economy by pushing burnups higher.

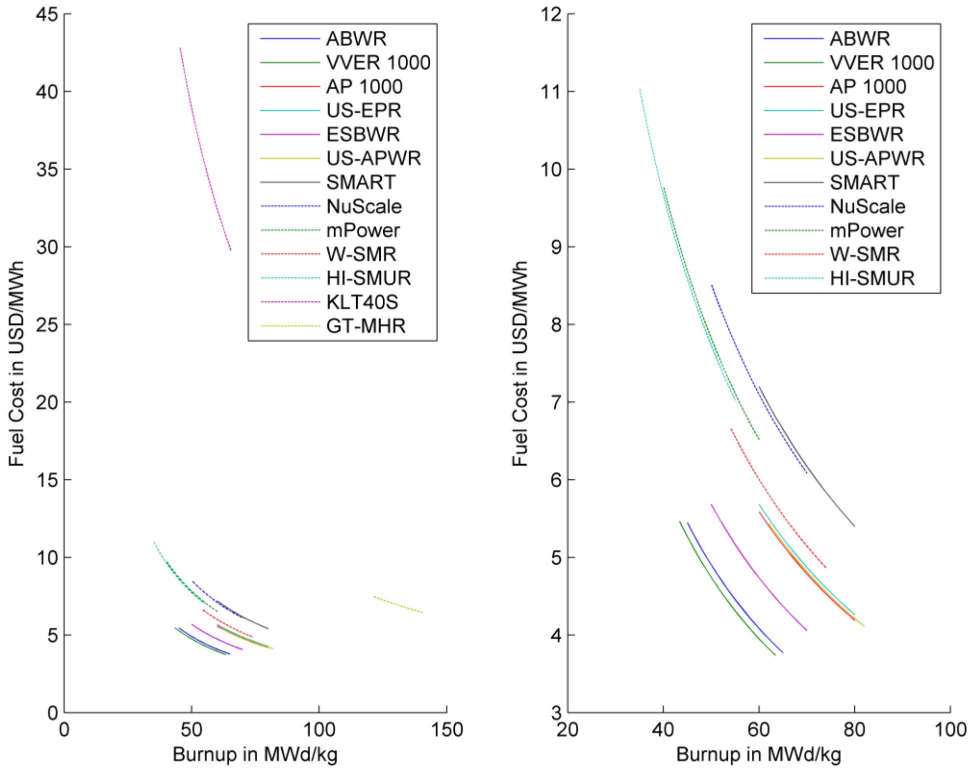

Fig. 5. All Design Burnup Fuel Cost Sensitivity. Fuel cost dependency on discharge burn-up for all reactors studied. Left: Current LWR designs are given with solid lines. Right (detail): Near term reactor fuel cost dependency on discharge burn-up for selected designs. Current LWR designs are given with solid lines and SMRs with dashed lines

Plant net efficiency is not only design but also strongly site dependent; hence the sensitivity was calculated and the results are shown in Figure 6. Similarly, deducing from improvements in net efficiency over the last 40 years, one assumes fuel economy will be improved by better net efficiency.

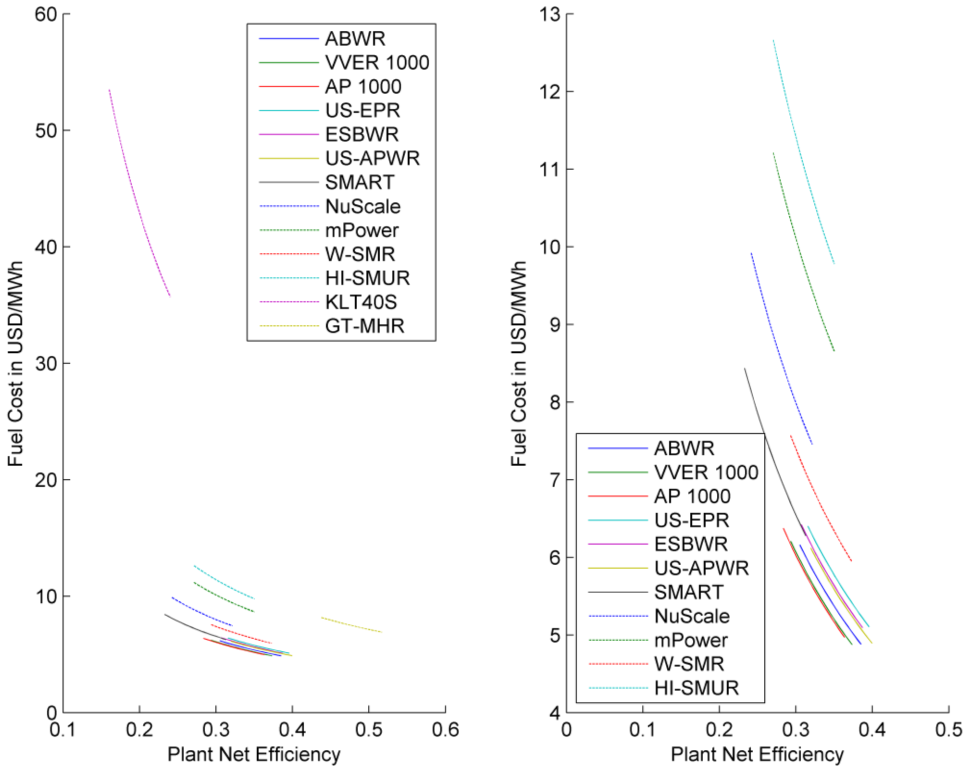

Fig. 6. All Design Efficiency Fuel Cost Sensitivity. Fuel cost dependency on plant net efficiency for all reactors studied. Left: Current LWR designs are given with solid lines. Right (detail): Near term reactor fuel cost dependency on plant net efficiency for selected designs. Current LWR designs are given with solid lines and SMRs with dashed lines.

Higher fuel enrichment on its own, as illustrated in Figure 7, has a negative impact on fuel economy. However, as a higher fuel enrichment goes hand in hand with a higher burnup (other fuel limits and parameters permitting), one should always study the enrichment dependency together with the burn-up dependency to have a complete picture.

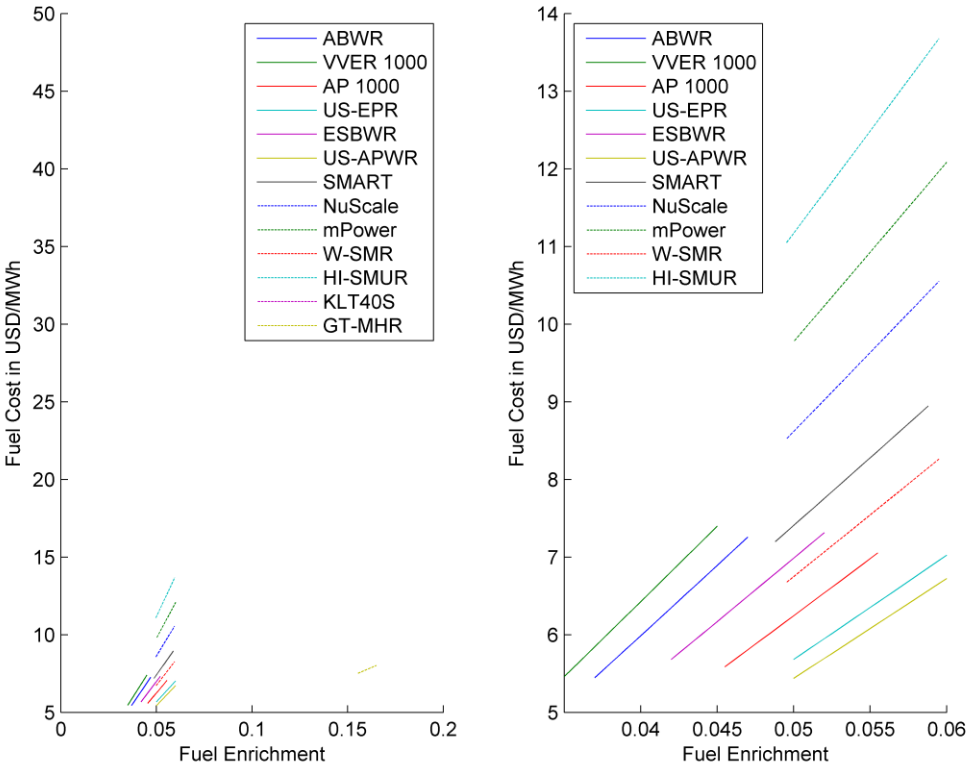

Fig. 7. All Design Enrichment Fuel Cost Sensitivity. Fuel cost dependency on average fuel enrichment for all reactors studied. Left: Current LWR designs are given with solid lines. Right (detail): Near term reactor fuel cost dependency on average fuel enrichment for selected designs. Current LWR designs are given with solid lines and SMRs with dashed lines.

The reactor fuel cost was calculated for each simulated future market price data point consisting of U_3O_8, SWU, and conversion price. The results are displayed as histograms for four representative LWR and four SMR designs and the GT-MHR in Figs. 8-10. Histograms for all reactors studied are presented in the Appendix.

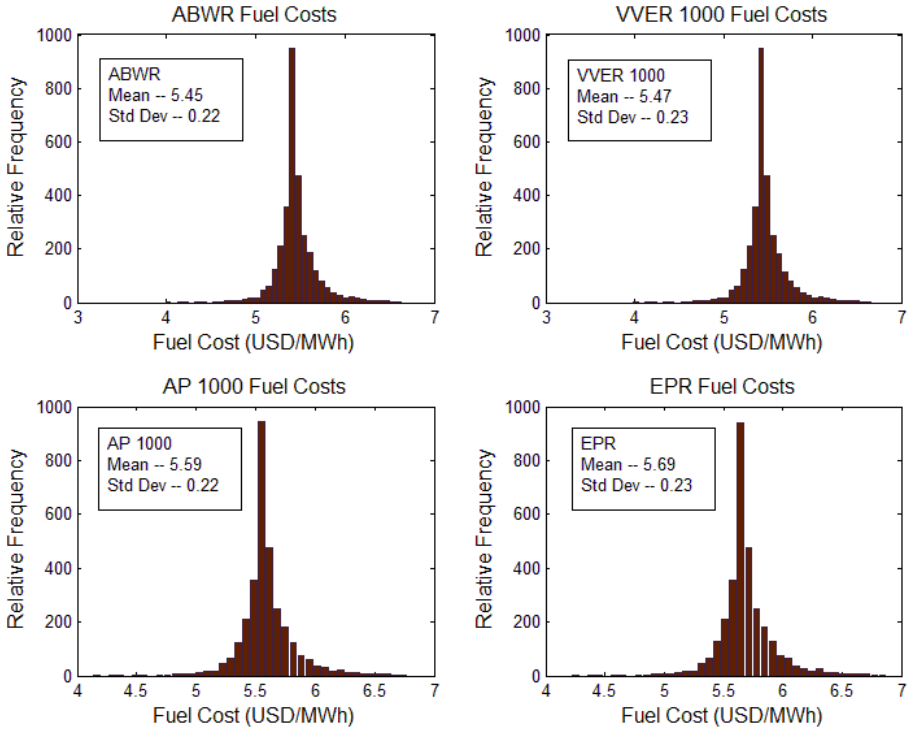

Fig. 8. LWR Fuel Cost. Fuel cost of large LWR designs.

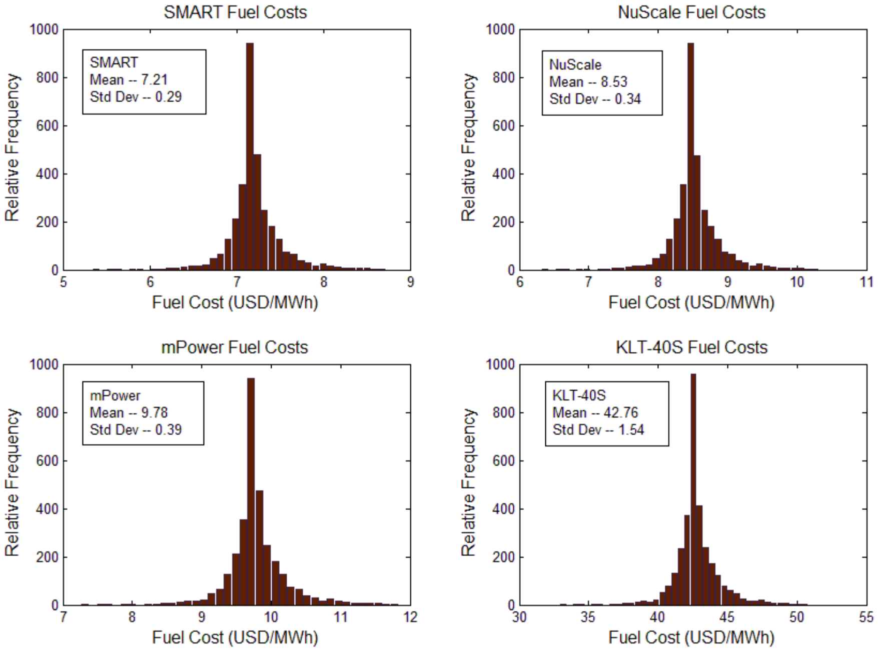

Fig. 9. SMR Fuel Cost. Fuel cost of SMR designs.

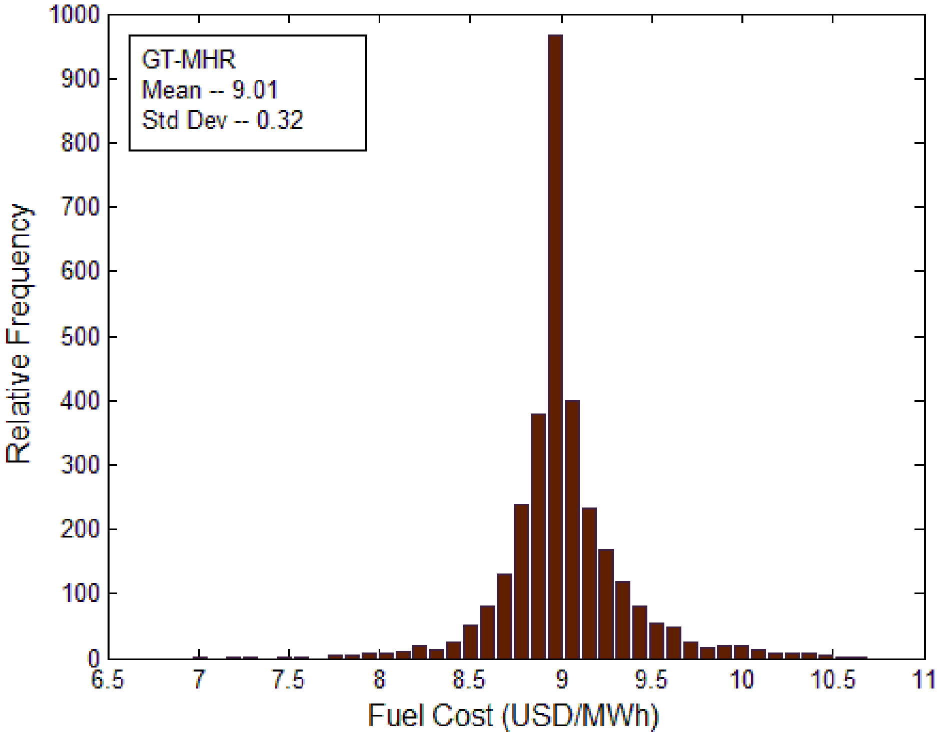

Fig. 10. GT-MHR Fuel Cost. Fuel cost of GT-MHR design.

CHAPTER IV

SUMMARY AND CONCLUSIONS

In all cases, the large LWRs had lower fuel costs than the SMRs. SMR fuel cost varied from +40% to +100% above large LWR fuel cost. Increased burnup of SMR designs made their fuel price more competitive with currently operating LWRs. However, raising burnups requires additional technological and regulatory costs, so it is unlikely to be implemented in the first generation of SMRs. In addition, the sensitivity results, plotted in Figs. 5-7, can be used to compare various designs at a nominal burnup, efficiency, or enrichment.

The increased fuel cost of SMRs is not likely to slow the development of iPWR technology or their near term deployment as the many other benefits of small reactors will be realized by vendors and utilities. However, there will for the foreseeable future be a place for new large LWRs to generate baseload electricity in regions of high demand. Utilities large enough to afford financing of a large LWR have already and will choose to this lower fuel cost option to meet baseload power generation needs.

The aim of this research is to compare SMR and large LWR variable costs. This simple model based on publicly available reactor design parameters successfully demonstrates a significant difference between the fuel costs of these two designs due to design burnup, efficiency and enrichment. To achieve a more complete view of long term economics of the two reactor classes, one must also calculate fuel fabrication, operations, maintenance, and disposal costs on a per unit energy basis. This analysis is no doubt of interest to the reactor design vendors and utilities that also have access to more specific proprietary data on reactor variable costs.

From the comparison of variable costs, it appears that SMRs are not competitive with large LWRs in traditional nuclear reactor sites for utilities that can afford large LWR financing. However, SMRs may compete with fossil fuel generation in the near future, especially if the government taxes carbon dioxide emissions. A future area of interest would be a comparison of SMR variable costs to similarly sized coal and natural gas plant variable costs, with specific attention to load following operations and fuels market volatility.

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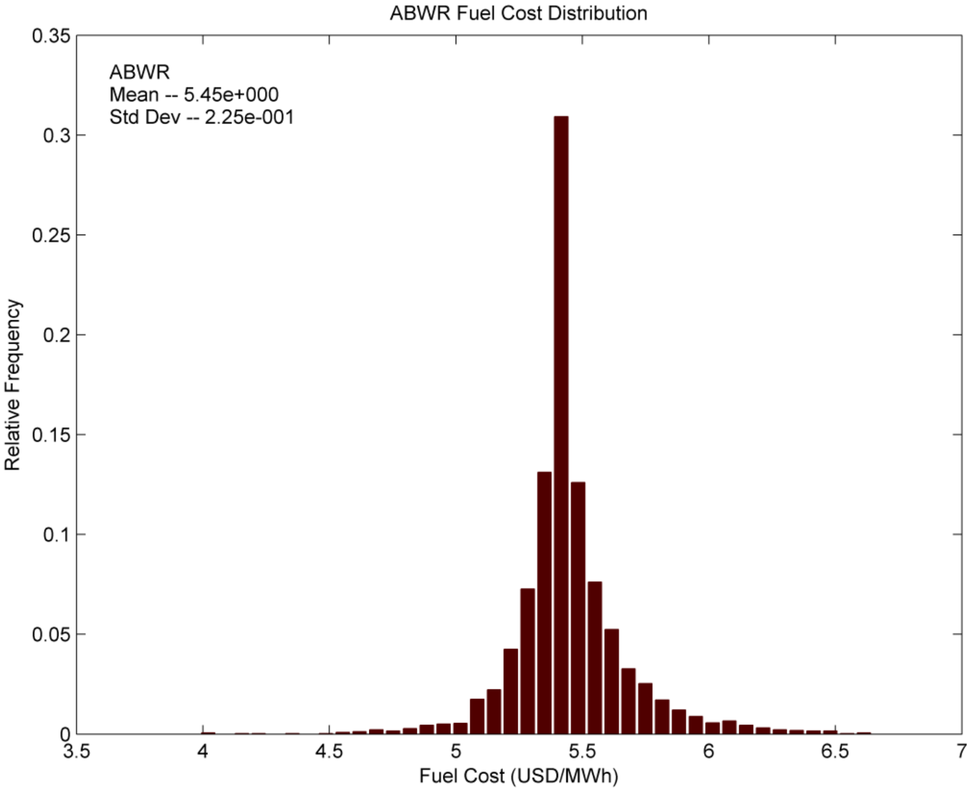
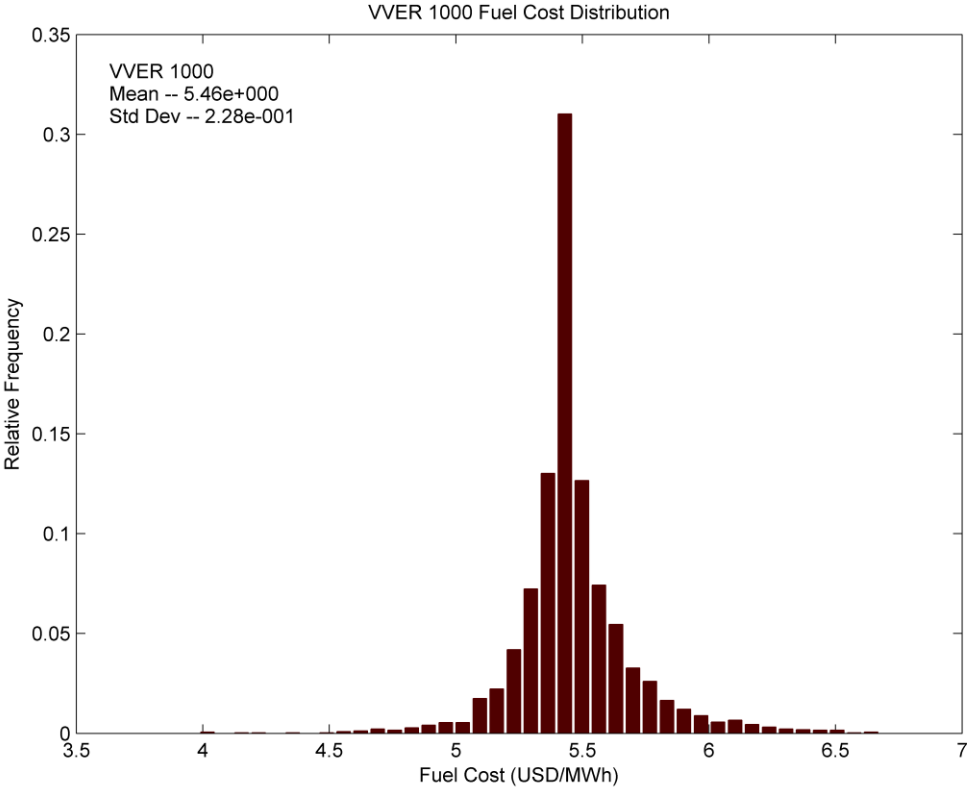
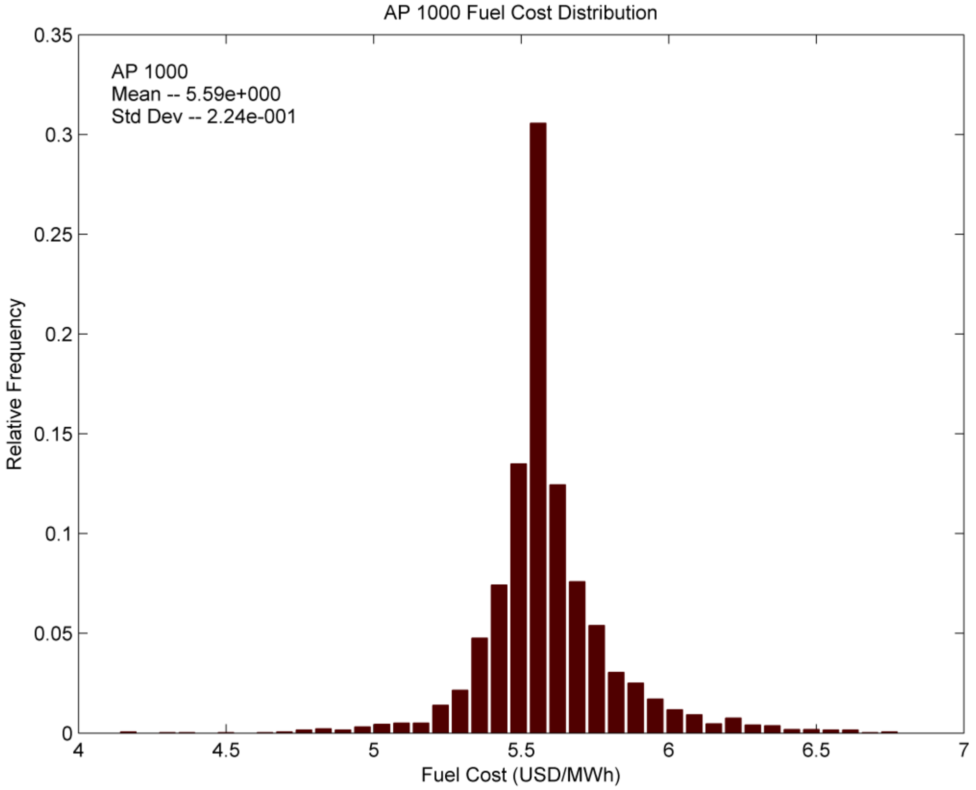
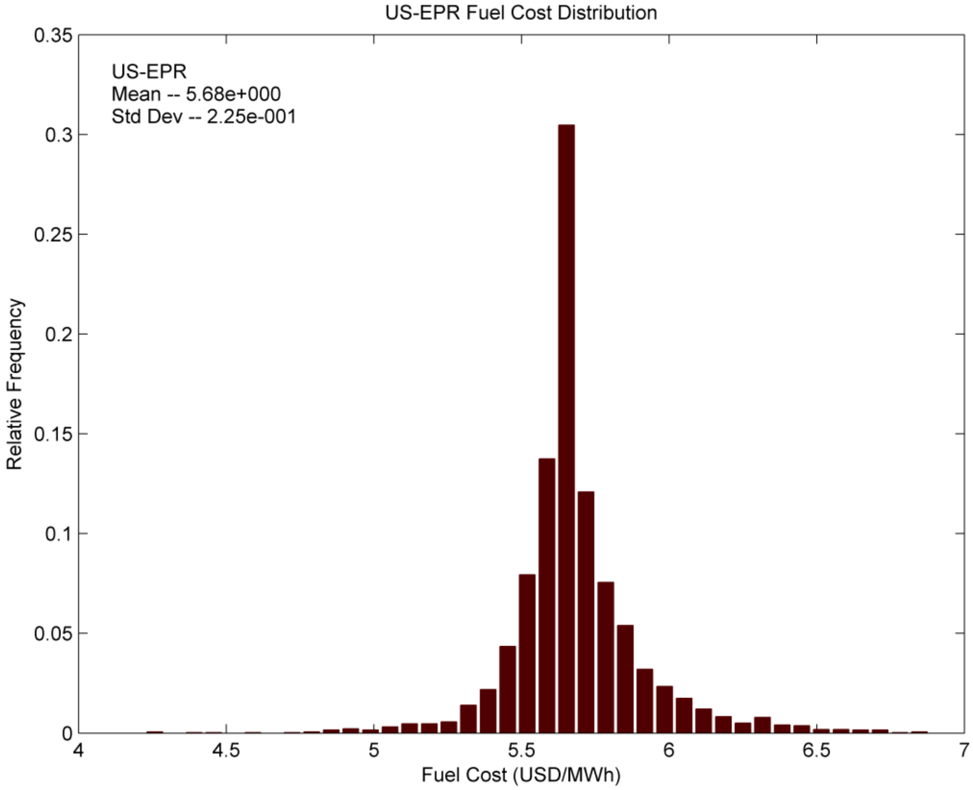
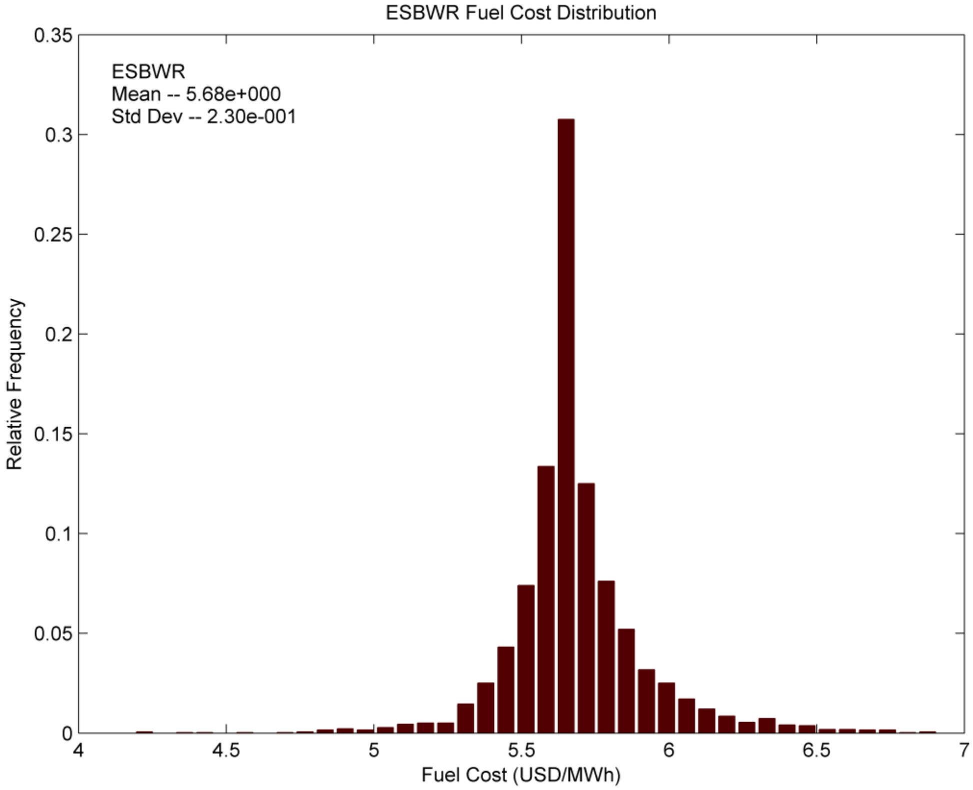
APPENDIX: FUELS COST DISTRIBUTIONS

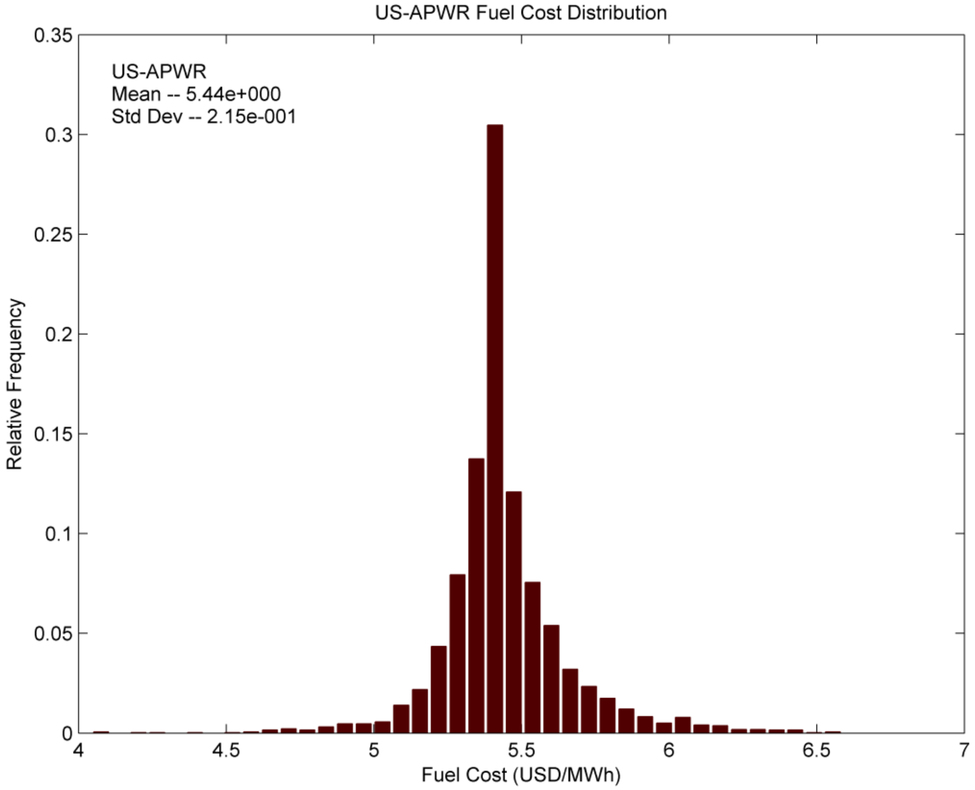


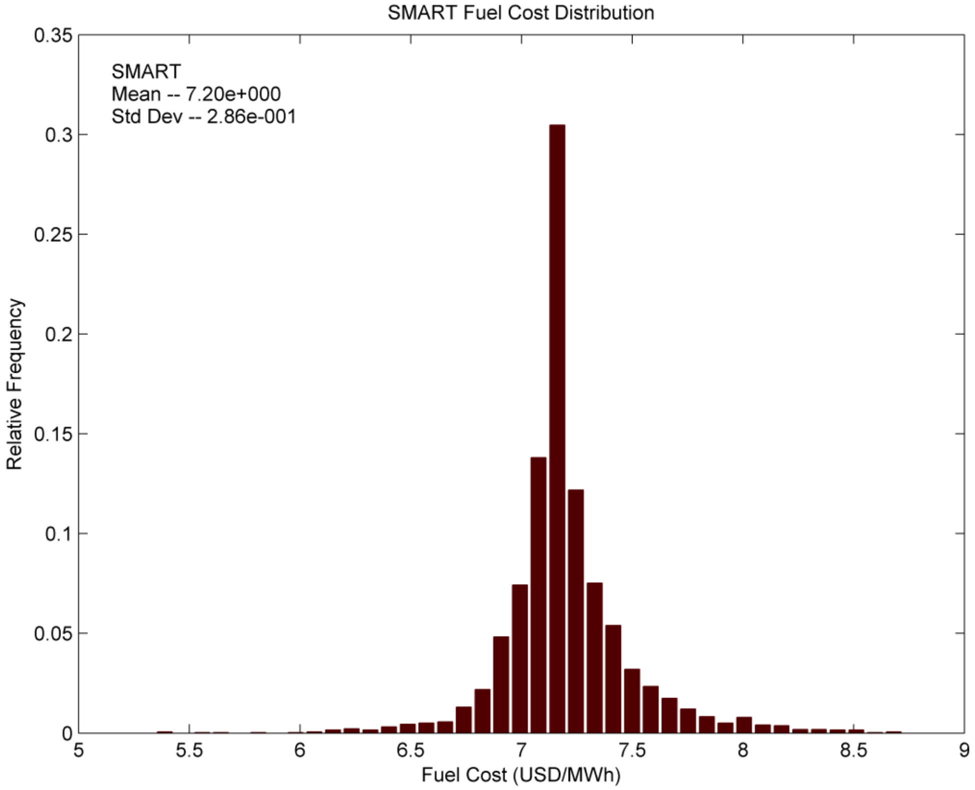

VVER 1000 Fuel Cost Distribution
VVER 1000
Mean -- 5.46e+000
Std Dev -- 2.28e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3.5
4
4.5
5
5.5
6
6.5
7
Fuel Cost (USD/MWh)

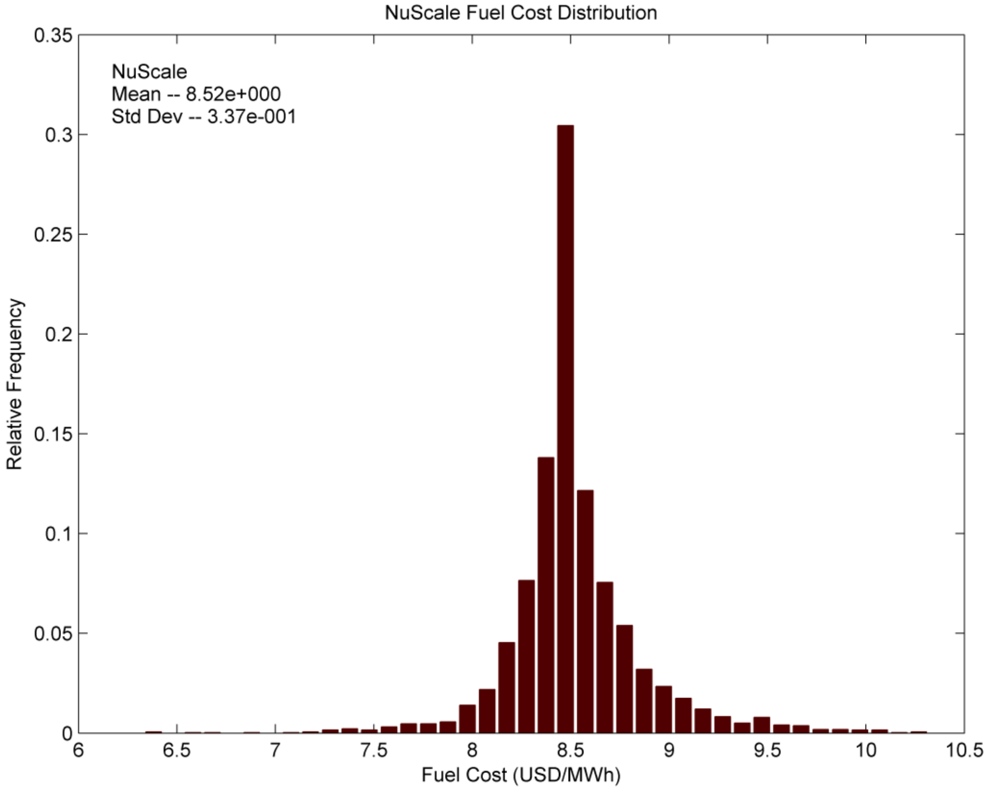

AP 1000 Fuel Cost Distribution
AP 1000
Mean -- 5.59e+000
Std Dev -- 2.24e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
4
4.5
5
5.5
6
6.5
7
Fuel Cost (USD/MWh)

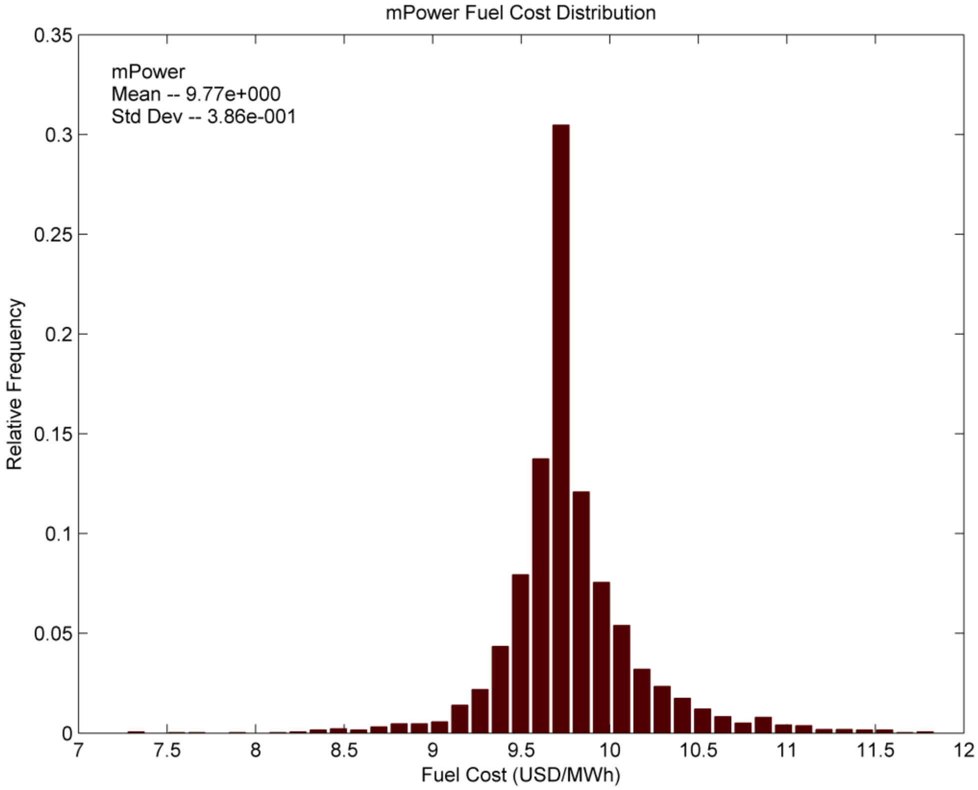

US-EPR Fuel Cost Distribution
US-EPR
Mean -- 5.68e+000
Std Dev -- 2.25e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
4
4.5
5
5.5
6
6.5
7
Fuel Cost (USD/MWh)

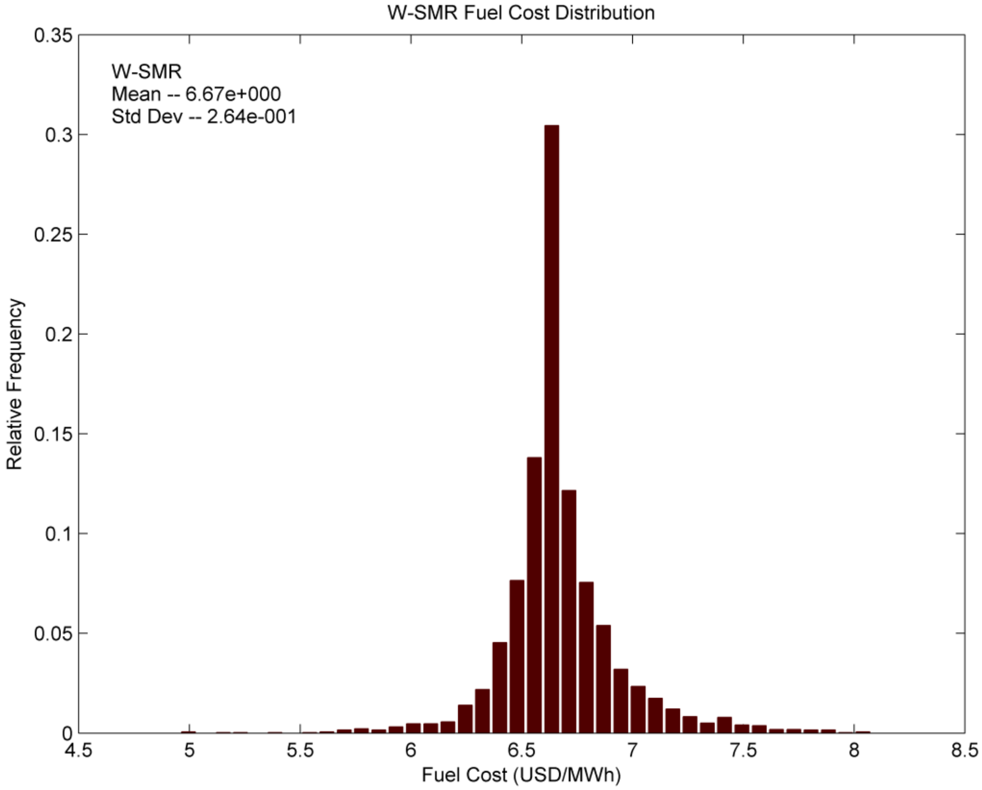

ESBWR Fuel Cost Distribution
ESBWR
Mean -- 5.68e+000
Std Dev -- 2.30e-001
Relative Frequency
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Fuel Cost (USD/MWh)
4
4.5
5
5.5
6
6.5
7

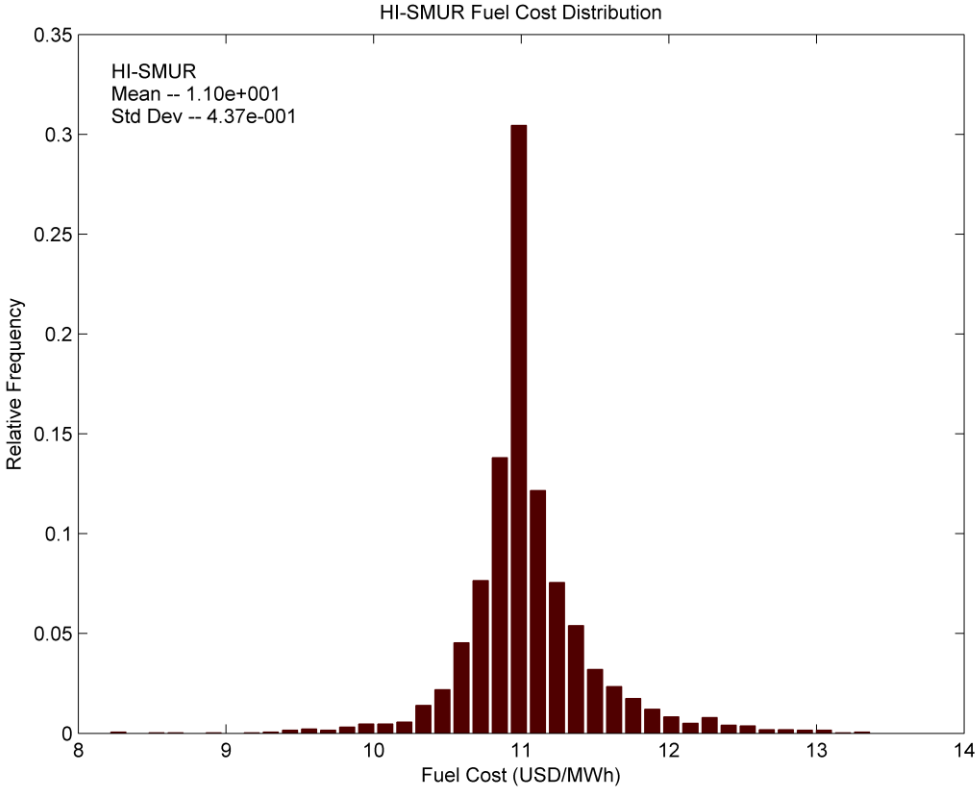

US-APWR Fuel Cost Distribution
US-APWR
Mean -- 5.44e+000
Std Dev -- 2.15e-001
Relative Frequency
Fuel Cost (USD/MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
4
4.5
5
5.5
6
6.5
7

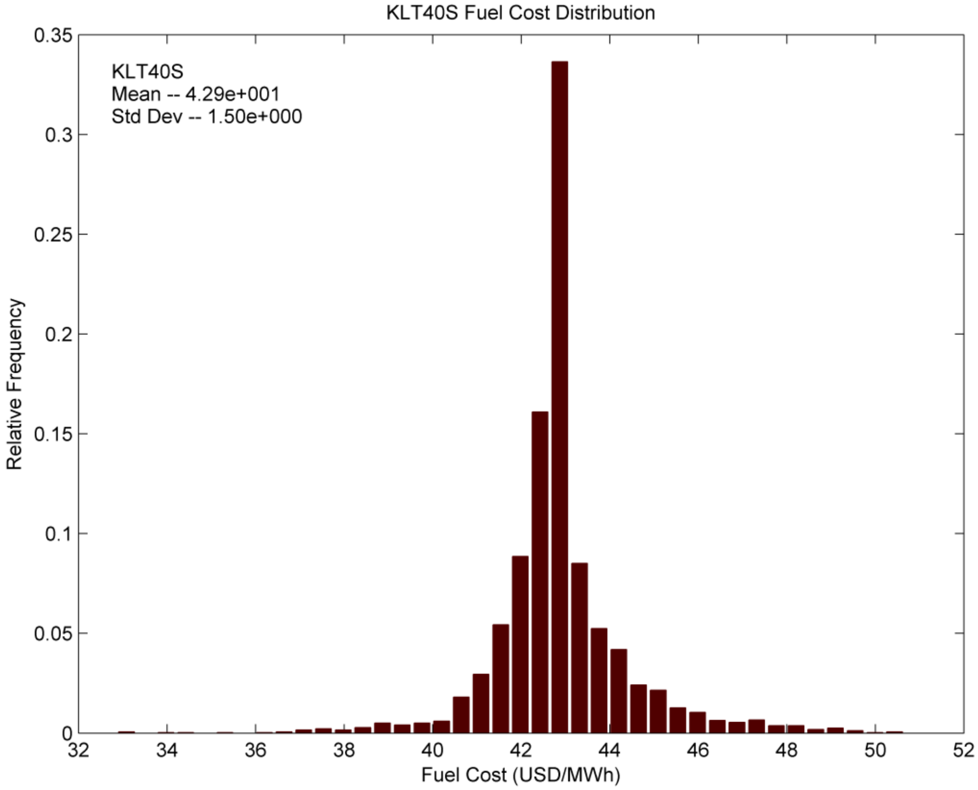

SMART Fuel Cost Distribution
SMART
Mean -- 7.20e+000
Std Dev -- 2.86e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
5
5.5
6
6.5
7
7.5
8
8.5
9
Fuel Cost (USD/MWh)

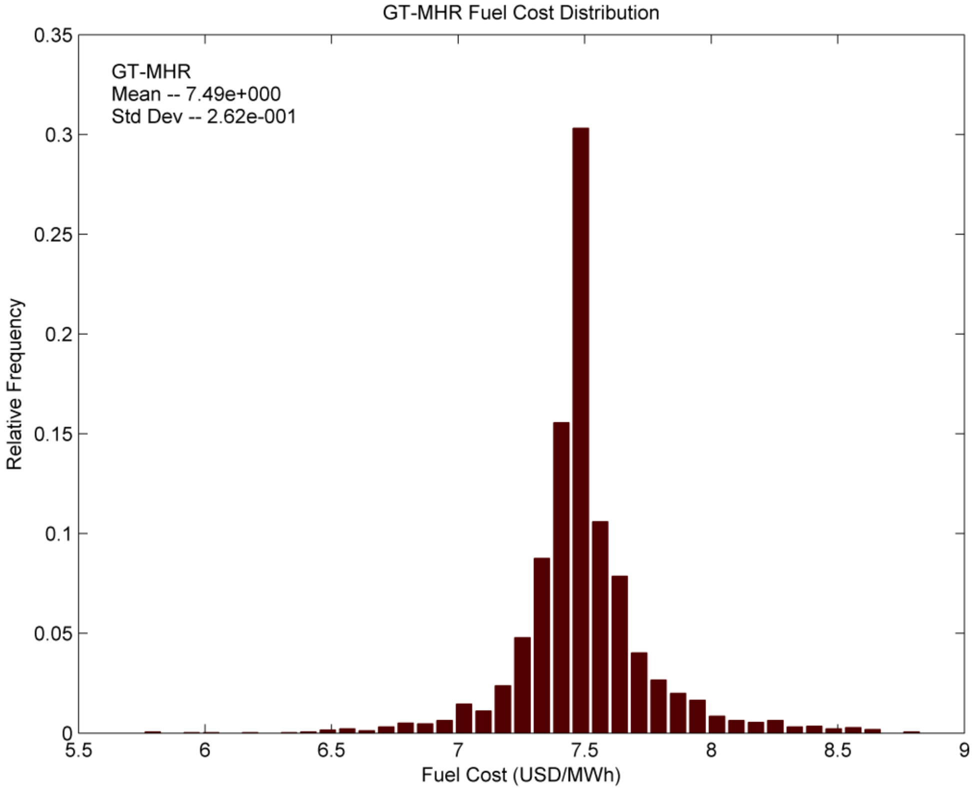

NuScale Fuel Cost Distribution
NuScale
Mean -- 8.52e+000
Std Dev -- 3.37e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
Fuel Cost (USD/MWh)


mPower Fuel Cost Distribution
mPower
Mean -- 9.77e+000
Std Dev -- 3.86e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
Fuel Cost (USD/MWh)


W-SMR Fuel Cost Distribution
W-SMR
Mean -- 6.67e+000
Std Dev -- 2.64e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
4.5
5
5.5
6
6.5
7
7.5
8
8.5
Fuel Cost (USD/MWh)


HI-SMUR Fuel Cost Distribution
HI-SMUR
Mean -- 1.10e+001
Std Dev -- 4.37e-001
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
8
9
10
11
12
13
14
Fuel Cost (USD/MWh)


KLT40S Fuel Cost Distribution
KLT40S
Mean -- 4.29e+001
Std Dev -- 1.50e+000
Relative Frequency
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
32
34
36
38
40
42
44
46
48
50
52
Fuel Cost (USD/MWh)


GT-MHR Fuel Cost Distribution
GT-MHR
Mean -- 7.49e+000
Std Dev -- 2.62e-001
Relative Frequency
Fuel Cost (USD/MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
5.5
6
6.5
7
7.5
8
8.5
9

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