IPM Model – Nuclear Power Plant Costs

Nuclear Power Plant Life Extension Cost Development Methodology

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1. PURPOSE

The primary purpose of this report is to provide generic order-of-magnitude costs for operating nuclear power plant life extension from 40 to 60 years as well as from 60 to 80 years. Cost estimates developed for the integrated planning model (IPM) are based primarily on a statistical evaluation of cost data available from various industry publications as well as Sargent & Lundy's proprietary database and do not take into consideration site-specific cost issues. By necessity, the cost methodology was designed to approximate the operating fleet of nuclear power plants as a whole.

1.1 BACKGROUND

The Clean Air Markets Division (CAMD) of the U.S. Environmental Protection Agency (EPA) directed Eastern Research Group, Inc. and Sargent & Lundy LLC to perform the following task:

Collect industry-wide publicly-available data to provide a consistent methodology for estimating costs for 40 to 60 years and 60 to 80 years life extension of U.S. nuclear power plants.

It is understood that EPA will use this information to update their Integrated Planning Model (IPM) to evaluate electric generating units for impact on the goals of the Clean Air Act (CAA).

2. METHODOLOGY AND INPUTS

Costs for life extension are developed based on best estimates of anticipated costs associated with life extension. These costs are considered along with the plant age associated with their time of occurrence.

2.1 REFERENCE PLANTS

A hypothetical nuclear power plant profile is developed to be representative of the entire U.S. fleet of Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) plants, in aggregate. In order to capture any differences between the two technologies, one PWR Reference Plant and one BWR Reference Plant are developed.

Plant operation during 40 to 60 years is referred to as the "period of extended operation" or "1st PEO." Plant operation during 60 to 80 years is referred to as the "2nd PEO."

The profile for each reference plant is as follows.

2.1.1 PWR Reference Plant

The following attributes are assumed for the PWR Reference Plant:

- 1000 MW Capacity
- Licensed in 1978 for 40 years of operation
- Replaced steam generators in 2000
- Replaced feedwater heaters in 2002
- Replaced reactor vessel head in 2002
- Obtained renewed license in 2005 – now licensed to operate until 2038
- Upgraded to turbine digital controls in 2009
- Enters 1st PEO in 2018
- Will submit application for second license renewal in 2026
- Will enter 2nd PEO in 2038

2.1.2 BWR Reference Plant

The following attributes are assumed for the BWR Reference Plant:

- 1000 MW Capacity
- Licensed in 1974 for 40 years of operation

- Replaced feedwater heaters in 2002
- Replaced reactor vessel head in 2002
- Obtained renewed license in 2008 – now licensed to operate until 2034
- Upgraded to turbine digital controls in 2009
- Entered 1st PEO in 2014
- Will submit application for second license renewal in 2022
- Will enter 2nd PEO in 2034

2.1.3 Reference Plant Life Extension Activities

As U.S. nuclear plants exceed their original 40-year licenses, several activities are expected to be required for their continued operation through 60 and 80-year lifetimes. The major activities can be broken down into three categories: development of a license renewal application (including NRC review & approval), implementation of commitments related to the renewed license, and equipment replacement or refurbishment.

These activities are listed in Table 2-1 along with the expected plant age at the time of implementation.

Table 2-1 — Life Extension Activities

Activity	Plant Age at Expected Implementation (yr)	Remarks
Development of a License Renewal Application		
2nd License Renewal	45	
Implementation of Commitments Related to Renewed License		
1st PEO License Renewal	40	
2nd PEO License Renewal	60	
Equipment Replacement / Refurbishment		
Main Turbine Replacement	40	
Heat Exchanger Replacements	45	
Service Water Piping Replacement	50	
Replacement or refurbishment of main	50	

Table 2-1 — Life Extension Activities

Activity	Plant Age at Expected Implementation (yr)	Remarks
generators, rotors (fields), exciters and voltage regulators		
Feedwater Heater Replacement	40 and 60	
Radiation Monitoring Upgrade	45	
Digital Control System Upgrade	45	
Pressurizer Replacement	50	PWR only
Condenser Tubing Replacement	50	
Large Cable (4160V) Replacement	60	
Additional Storage Casks and Base Pads for ISFSI	60	
Steam Generator Replacement	60	PWR only
Main Condenser Replacement	60	
Reactor Coolant Pump Refurbishment	60	
Replacement of heaters and associated controls for the pressurizer	60	PWR only
Replacement of an emergency diesel generator and supporting equipment/systems	60	
Fire Protection System Upgrade	60	

The expected activities shown above provide context for the historical and projected expenditures presented in this report. It should be noted that not all the plants will require all the improvements which make it very difficult to generalize all the modifications. Therefore, the capital cost expenses would be in a wide range. However, we have attempted to narrow down the range based on industry wide data.

3. HISTORICAL PLANT EXPENSES

S&L conducted a literature survey to identify the available capital and O&M cost data. The best source of reliable data was identified as data collected by Federal Energy Regulatory Commission (FERC) since 1994. FERC Form No. 1 collects financial and operational information from public electric utilities. FERC Form 1 reports are considered to be non-confidential public use information. The select data was provided to S&L for capital and O&M cost analysis by EPA's Clean Air Markets Division.

Sargent & Lundy extracted the publically available FERC data for the U.S. nuclear fleet (from 1994-2016) regarding O&M and capital expenditures from 70 U.S. nuclear power plants. FERC Form 1 reports include the field Total Cost of Plant, or capital cost, the year to year change in which represents annual capital expenditures. The data input to our analyses is screened based on this field to reject years showing negative capital expenditures. Additionally, annual data is rejected for non-continuous years (e.g. 2011 … 2013, skipping 2012).

Our benchmarking analyses are presented in the following sections.

3.1 HISTORICAL CAPITAL EXPENDITURES

Historical annual capital spending data on PWR plants from FERC was plotted against the age of the plant on the horizontal axis. Also plotted was the average capital expenditure for each plant of the same age. Note that cost data is presented in 2017 dollars per kW of nameplate capacity (USD_{2017} / kW). The average annual capital expense across all PWR plant ages was approximately 45 USD_{2017} / kW.

Similarly, historical BWR capital costs were also plotted. The average annual capital expense across all BWR plant ages was approximately 40 USD_{2017} / kW.

Review of the annual capital expenses for PWR and BWR plants shows similar levels of capital expenditures. For each technology, generally higher spending is accompanied with a larger variance as the plants approach 40 years of age and beyond. Particularly for the BWR data, fewer data points are available and variation is higher.

Since the historical spending between PWR and BWR was roughly similar, the capital expenditures across the entire nuclear fleet was approximately 44 USD_{2017} / kW.

Average annual capital expenses were seen to be increasing with plant age. This data was consistent with the expectation that capital expenditures would increase as equipment aging necessitates replacement. Furthermore, additional capital may be required to meet licensing commitments agreed to as part of life extension.

3.2 HISTORICAL O&M EXPENDITURES

Historical PWR annual O&M costs (ex-fuel) were analyzed. The data from FERC was plotted against the age of the plant on the horizontal axis. Also plotted was the average O&M cost spent for each plant of the same age.

The average annual O&M expense across all PWR plant ages was approximately 128 USD_{2017} / kW.

Similarly, historical BWR O&M costs (ex-fuel) were also plotted. The average annual O&M expense across all BWR plant ages was approximately 143 USD_{2017} / kW.

Review of the O&M expenses for PWR and BWR plants showed similar levels of expenditures with BWR expenditures modestly exceeding those for PWR plants. It was noted that fewer data points are available for BWRs than for PWRs.

The historical O&M expenditures across the entire nuclear fleet across all U.S. were approximately 132 USD_{2017} / kW; however, expenses were seen to increase modestly with plant age. This increase may be the result of component aging necessitating additional upkeep and monitoring.

3.3 HISTORICAL FUEL COSTS

Historical U.S. nuclear annual fuel costs were also analyzed. The data from FERC was plotted against the calendar year on the horizontal axis. Also plotted was the average fuel cost for that year.

The average annual fuel cost over the period was approximately 49 USD_{2017} / kW.

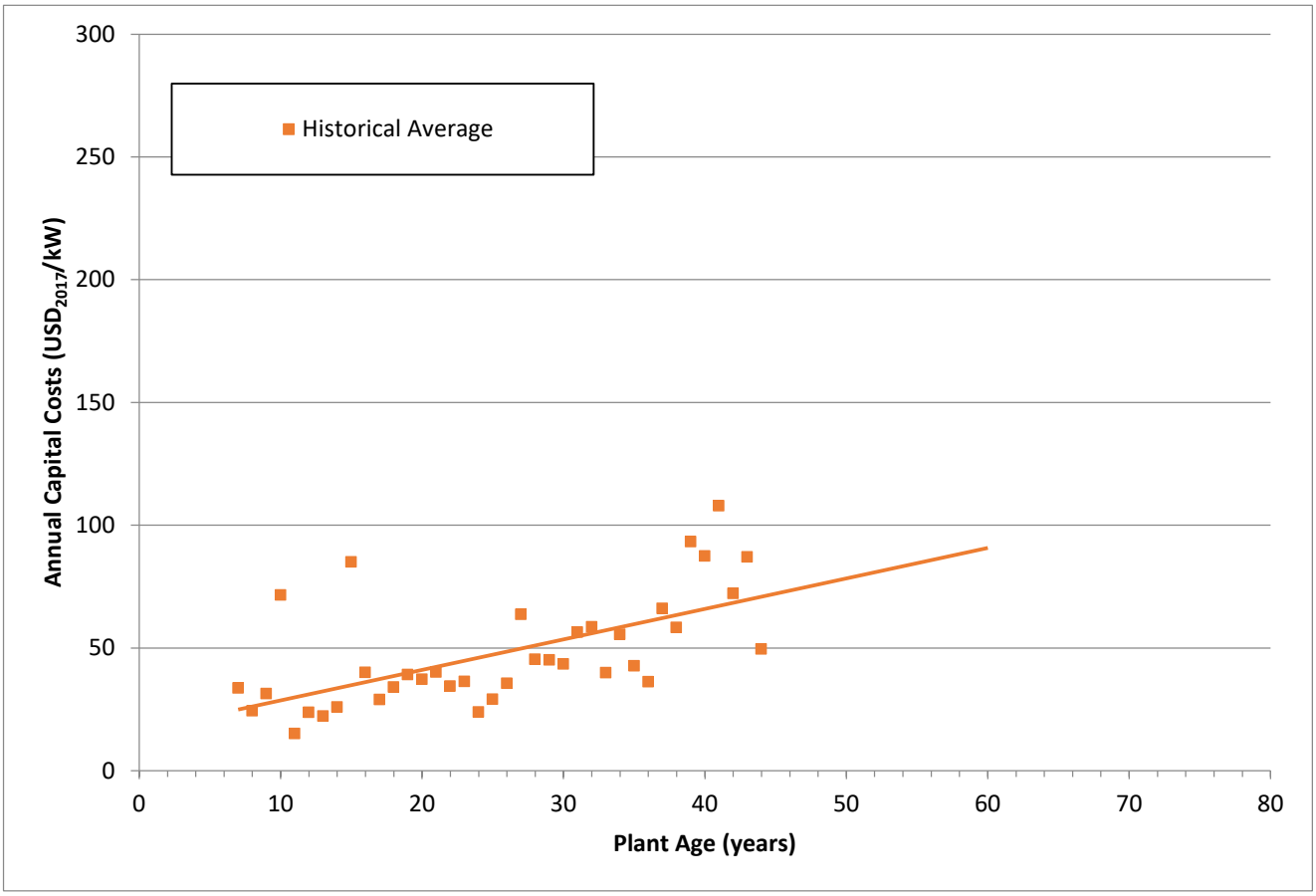
4. PROJECTED PLANT EXPENSES

Sargent & Lundy evaluates the estimated annual capital expenditures associated with life extension in the context of expected capital improvements and historical capital spending.

4.1 PROJECTED CAPITAL EXPENDITURES

Average annual historical capital spending from Section 3.1 is shown in Figure 4-1 with trendline data added and the time scale extended to 80 years. Similar to previous sections, cost data is presented in 2017 dollars per kW of nameplate capacity (USD_{2017} / kW).

Figure 4-1 — Historical U.S. Nuclear Annual Capital Expenditures (USD_{2017} / kW)



The average annual capital expense across all U.S. nuclear plants is shown to be increasing at a rate of $1.25/ kW per year. As previously noted, fewer data points are available for plants approaching 40 years in operation; however, the available data shows capital expenses rising during this period of plant age.

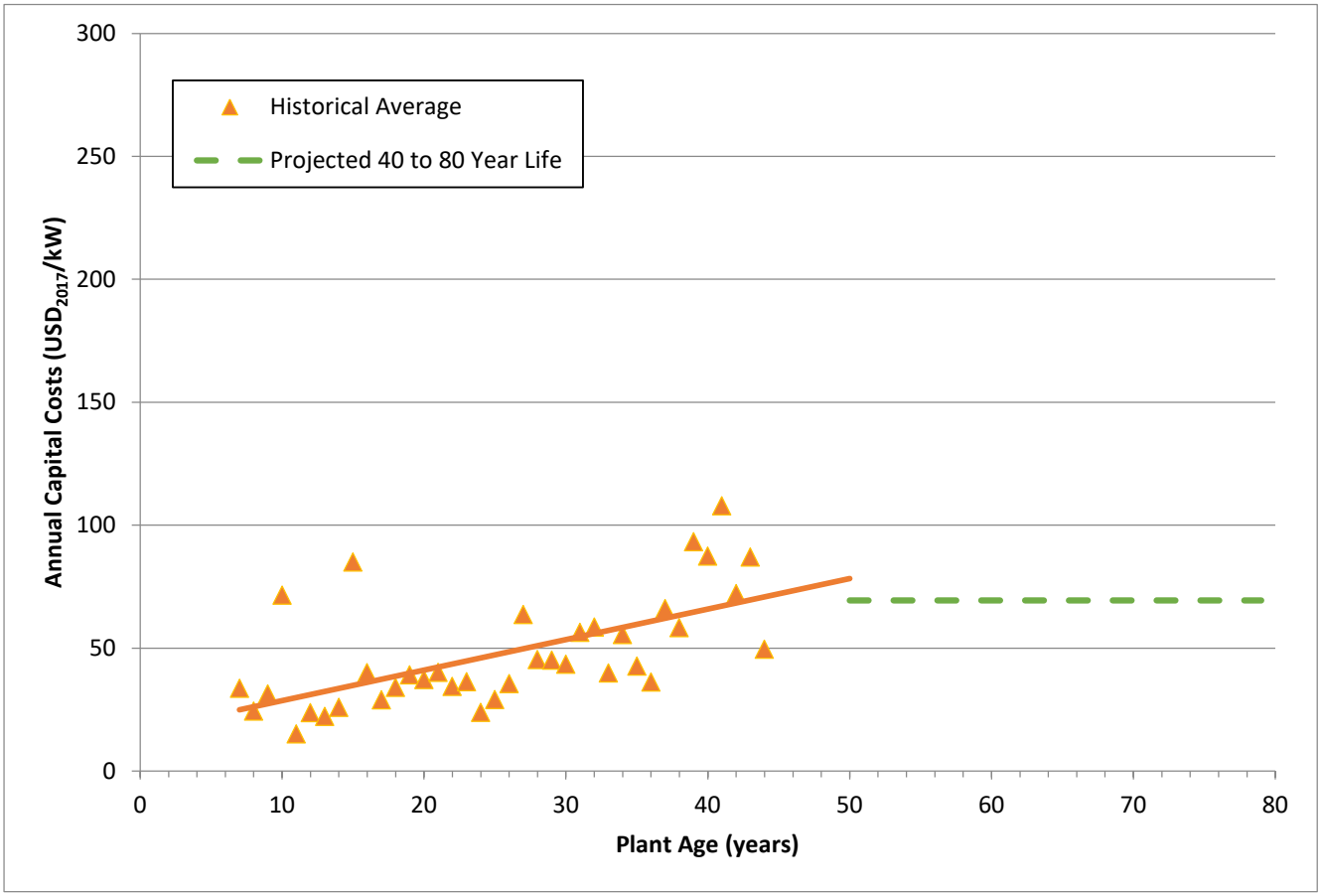
Sargent & Lundy believes the rise in expenses as plants approach 40 years of age seen in the historical data reflects preparations for extended operation through license renewal application and implementation, accompanied with limited replacement of aging components. These activities necessitate elevated capital costs at the beginning of the period of extended operation. Therefore, Sargent & Lundy is of the opinion that long term life extension costs, at least as applicable to the 1st PEO (40 – 60 years), are being captured in the publically available historical spending data and can provide a reasonable basis for projected future expenses over the 40 – 60-year period.

However, capital investments for activities associated with the 2nd period of extended operation are likely not reflected in the available historical spending data since the majority of investments identified in Section 2.1.3 have not been undertaken by the U.S. nuclear fleet. Therefore, capital spending for the 2nd PEO is expected to be higher than current data shows, particularly near the beginning of the 2nd period of extended operation.

The nature of capital investment at nuclear power plants follows the familiar path of large up-front expenditures recovered over subsequent years of operation. As such, capital spending is expected to be above average in the beginning of the operational period and below average at the end as the remaining years of useful life available to recover the capital diminish. The projection of the time dependent path of capital expenditures is beyond the scope of this study. Instead, an average yearly capital expense is developed in context of expected and historical plant expenses over the term associated with life extension.

Sargent & Lundy's estimated capital costs associated with life extension are shown in Figure 4-2.

Figure 4-2 — Projected U.S. Nuclear Annual Capital Expenditures (USD_{2017} / kW)



In Figure 4-2 above, the historical spending data (triangles) is shown with a regression trendline extrapolated to plant age 50 years. As a result of the data variance and inherent difficulty of future projections, linear regression is chosen for simplicity, which provides a reasonable fit of the observed data and trend. As previously discussed, extrapolation of current spending is reasonable to estimate the costs of the 1st PEO (40-60 years). For the 2nd PEO (60-80 years), additional capital will likely be required beyond current spending. However, that spending will occur in advance of the 2nd PEO as plants make preparations and extend the period available for capital recovery. Based on the timeframe presented in Section 2.1.3, Sargent & Lundy expects plants to begin investment for 2nd PEO at approximately plant age 50 years. Accordingly, Figure 4-2 presents a constant annual capital expenditure during 50 to 80 years. The annual capital expenditures leading up to and during the 2nd PEO will vary depending on the plant condition and electric market situation. For simplicity, Sargent & Lundy assumed a constant \$70 USD_{2017}/kW.

A projection of \$70 USD_{2017}/kW annual capital expenditures beginning in year 50 is nearly coincident with the average historical spending trendline. This projection is further bolstered by surveys of operating nuclear utilities' projected capital expenditures, which are consistent with the level of projected spending shown in Figure 4-2. Projections about future spending involve considerable uncertainty, however, the consideration of both observed historical spending trends as well as utility expectations for the future provide context to consider these projections reasonable.

The projected annual capital expenses shown in Figure 4-2 are summarized to be used in the IPM as follows: Approximate correlation for first 50 years of life is derived as

$$\text{Annual Cost } (\mathbf{USD_{2017}/kW}) = \mathbf{17 + 1.25\ AGE}$$

For example, the annual capital cost at 40 years would be: 17 + 1.25 *40 = \$67/kW

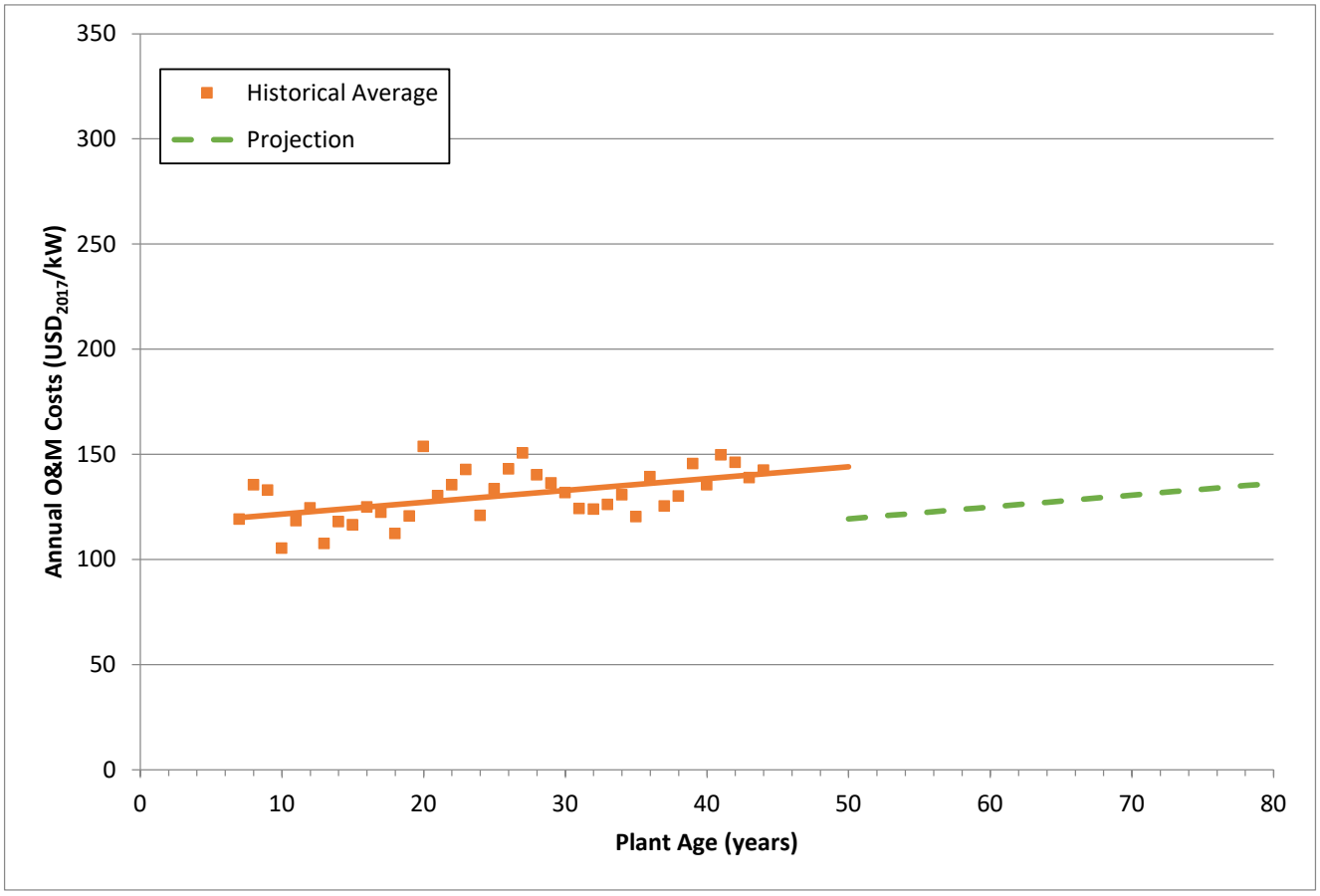
The annual capital cost after 50 years is projected to be approximately \$70/kW.

The overnight capital expenditure would be in the range of \$750 to \$1,200/kW depending on the discount rate and approximately 30 years of recovery period.

4.2 PROJECTED O&M EXPENDITURES

Average annual historical O&M spending from Section 3.2 is shown in Figure 4-3 with a trendline added and the time scale extended to 80 years. Similar to previous sections, cost data is presented in 2017 dollars per kW of nameplate capacity (USD_{2017} / kW).

Figure 4-3 — Projected U.S. Nuclear Fleet Annual O&M (Ex-Fuel) Costs (USD_{2017} / kW)



Review of the historical data shows that the average annual O&M expenditure (ex-fuel) is increasing at a rate of 0.56 USD_{2017} / kW for each year of plant age. However, aging equipment requires higher O&M expenditures to maintain. As increased capital is deployed to replace equipment, lower O&M costs are expected as a result of increased reliability and a reduction in the need for continual monitoring. Additionally, nuclear utilities are undertaking significant steps to reduce O&M costs industry-wide. Sargent & Lundy expects the refurbishment efforts for life extension to result in cost savings during the initial deployment of new equipment, which is expected to occur around plant age 50 years. As such, the historical trendline is reset downward at year 50 in

Figure 4-3 to the average annual cost for the first 10 years of available plant ages (120 USD_{2017} / kW). This reflects the expectation that O&M annual costs for a refurbished plant will resemble those of a younger plant as well as the fact that recent plant closings have been single unit facilities, leaving a higher fraction of multiple unit and fleet-operated facilities for which economies of scale provide operating cost savings. Beyond 50 years of age, the projected trend is the same as the historical trend observed. This reflects the expectation that O&M annual costs for a refurbished plant will increase similarly to those observed for the aging of the original plant equipment. The following trend can be used to simulate the annual data.

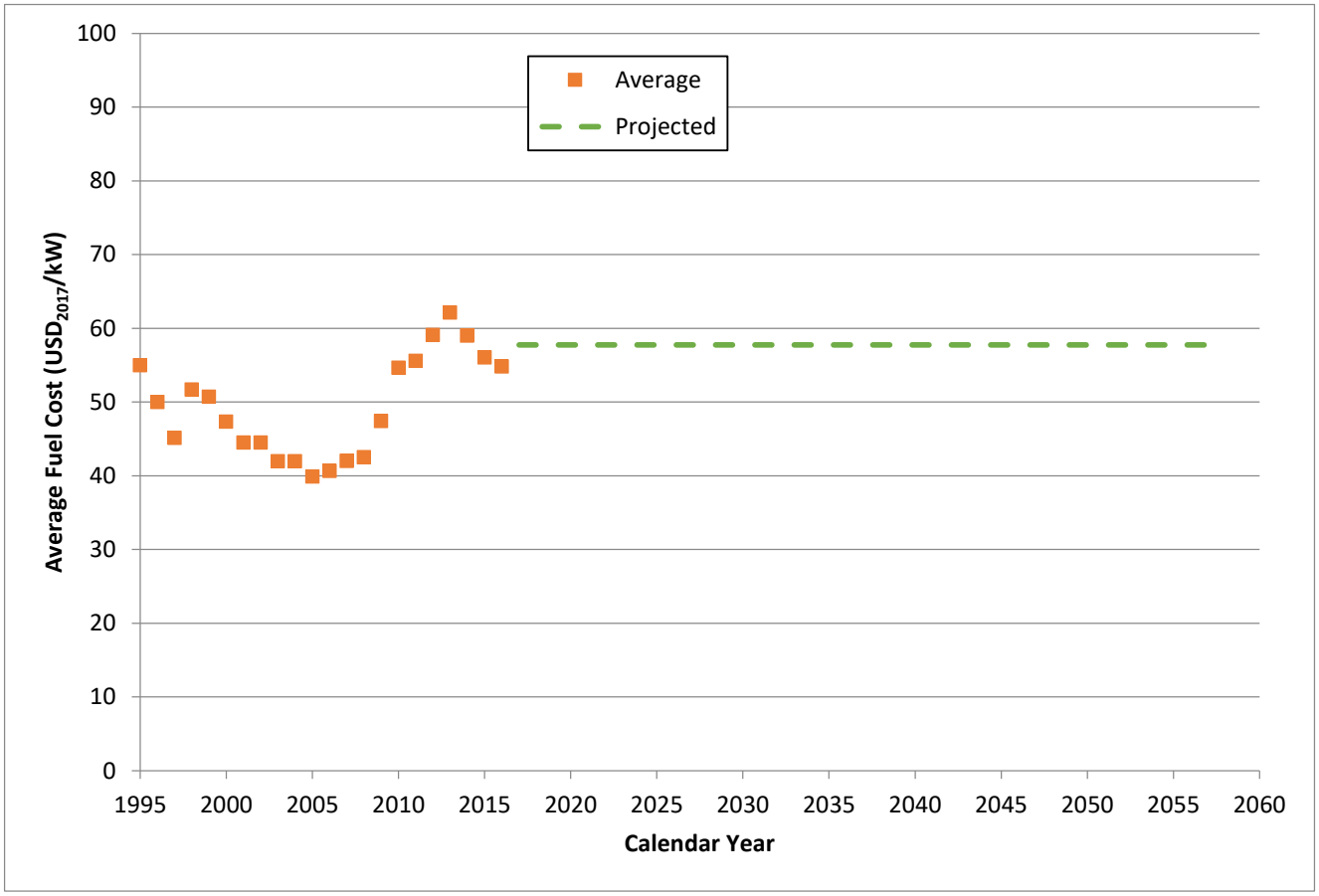
1) From 10 year to first 50 year - Annual cost $/kW = 116 + 0.56 * (Plant Age)

2) From 50 year onward - Annual cost $/kW = 91 + 0.56 * (Plant Age)

4.3 PROJECTED FUEL COSTS

Average annual U.S. nuclear fuel costs from Section 3.3 is shown in Figure 4-4. Similar to previous sections, cost data is presented in 2017 dollars per kW of nameplate capacity (USD_{2017} / kW).

Figure 4-4 — Projected Annual Fuel Costs (USD_{2017} / kW)



Review of the historical data shows that fuel costs have oscillated over time. Costs have increased since 2010 but declined in the last three years. The market conditions associated with fuel costs are beyond the scope of this evaluation. However, stable long-term demand for uranium is expected as the number of users is not expected to grow dramatically. No significant degradation in efficiency is expected for nuclear power plants which would yield increased fuel consumption for the same level of generation. Sargent & Lundy notes that the average fuel cost for the last five years of available data is approximately 58 USD_{2017} / kW. Based on the historical trends, a reasonably conservative estimate for fuel costs is the projection of the previous five-year fuel costs over the duration of 1st and 2nd PEO.

5. CONCLUSION

The industry-wide publicly-available cost information obtained for this report indicates that expenditures planned for the activities listed in Section 2 for operation during 40 to 60 years and 60 to 80 years are commensurate with the projected costs described in Section 4.

5.1 Capital Cost

Approximate correlation for first 50 years of life is derived as

$$\text{Annual Cost } (\mathbf{USD_{2017}/kW}) = \mathbf{17 + 1.25\ AGE}$$

The annual capital cost after 50 years is projected to be approximately $70/kW.

The overnight capital expenditure would be in the range of $750 to $1,200/kW depending on the discount rate and approximately 30 years of recovery period.

5.2 O&M Cost

The following trend can be used to simulate the annual O&M cost.

1) From 10 year to first 50 year - Annual cost $/kW = 116 + 0.56 * (Plant Age)

2) From 50 year onward - Annual cost $/kW = 91 + 0.56 * (Plant Age)