A Review of Nuclear Costs and Revenues in PJM

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ABOUT POTOMAC ECONOMICS

Potomac Economic has worked as the Independent Market Monitor for the Midcontinent ISO (MISO), the New York ISO (NYISO), ISO New England, and ERCOT for the past 20 years. In these roles, Potomac Economics is responsible for evaluating the performance of the markets and identifying attempts to exercise market power. This includes monitoring the conduct and reviewing the costs of the generators that participate in these markets, including nuclear resources. Therefore, we have substantial experience reviewing and evaluating the costs and performance of nuclear resources.

I. Introduction and Purpose

Compared to other types of electricity generators, a much larger share of nuclear units' total revenues are derived from the energy markets because of their relatively low variable production costs and consistently high output levels. Therefore, the sharp reductions in energy prices in recent years have disproportionately reduced the net revenues of nuclear units. These trends have led some states to make supplemental out-of-market payments to nuclear resources to forestall retirement. Likewise, there has been much debate regarding economics of these resources and the extent to which they are covering the costs of remaining in operation through the RTO markets. Much of this debate has occurred in PJM where nuclear resources constitute almost 18 percent of the installed capacity and produce more than one third of the energy.

The Nuclear Energy Institute has asked Potomac Economics to make an independent evaluation of the economic viability of nuclear powered generating resources operating in PJM wholesale electricity markets. Our assessment of the economic outlook for the nuclear resources in PJM is based on our estimates of future revenues and costs for nuclear power plants. The costs that are relevant for purposes of participants deciding to keep a resource operation or retire the resource are the resource's "going forward costs", i.e., the costs of remaining in operation than can be avoided by retiring. We compare our estimates of these costs to the expected revenues from the energy, ancillary services, and capacity market.

The analysis presented in this report provides overall indicators and trends regarding the economic climate facing the nuclear resources in PJM. Although we present limited unit-specific results for resources in eastern and western PJM, these results are based on aggregated cost data from EUCG. The results for any particular resource may vary from our results. A summary of our key findings in this study include:

- The analysis shows that the declining energy prices and associated revenues in recent years have substantially reduced all of the nuclear resources' net revenues.
- As energy prices have fallen to their lowest levels in decades in 2020, we find it unlikely that any of the nuclear resources in PJM are covering their costs.
- Although all of the forward energy prices are significantly higher than the prevailing prices in 2020, we find that it is unlikely that the market revenues will be sufficient to allow any of the resources to be viable to remain in operation, with the possible exception of very lowest-cost resources.
- To the extent that the markets evolve to better reflect the value of carbon emissions, the economic outlook for the nuclear resources would improve since they emit no carbon dioxide.

II. Evaluation of Retirement Incentives

Electricity generators have an incentive to retire when expected revenues are less than its going-forward costs that can be avoided by retiring. The going forward costs include the fixed and variable cost of remaining in operation that can be avoided by shutting down, as well as the operating risks that the generator may avoid by shutting down, net of any option value of the plant remaining in operation.[1] In this section, we discuss the types of going-forward costs that are avoidable for nuclear resources, as well as the sources of revenues we evaluated in PJM. We then show the results of our evaluation at the end of this section.

A. Summary of Nuclear Cost Categories and Data

To calculate going-forward costs, we mainly used aggregated data from the Electric Utility Cost Group (EUCG). This included all categories and subcategories of costs summed from 2017 to 2019, all adjusted to 2019 dollars. We did not use unit-specific data. Instead, the costs were provided by PJM region, separated between Eastern and Western PJM. To recognize the dispersion in the costs, NEI provided the EUCG data for the 25th percentile, the 75th percentile, and the mean for the units in each region.

Costs Not Included as Avoidable. As described in Section C below, we reviewed each category and subcategory of costs to determine those that are “avoidable”. The identification of avoidable going forward cost can be viewed as a comparison of two scenarios: the cost of remaining in operation and the costs after retirement. For example, there is a cost for on-site staff. After retirement there is initially still some on-site staff, but just a small percentage of the operating level costs. This means that a great percentage of these costs are avoidable going-forward. However, for nuclear facilities, most of these remaining costs are covered by decommissioning trust funds discussed below and can change the extent to which they are considered avoidable going-forward costs.

In addition to excluding costs that would not be avoided by retiring, we excluded certain capital costs that would not be expected to repeat in the future or would not be undertaken by units that may be retiring. These include:

- Capital costs undertaken to comply with regulatory requirements stemming from the issues that occurred at the Fukushima nuclear plants;
- Capital costs to enhance a nuclear resource’s operation or expand its capability;

1 The option value is the potential positive value that can be generated from an asset if market conditions change favorably, net of the cost of operating at a loss while the retirement decision is deferred. It can be one reason that a generator does not retire immediately when its net revenues become negative, although the option value will likely fall substantial when net revenues are negative for an extended period. This option value is lost when a nuclear resources enters the decommissioning process.

- Capital costs associated with extending the life of a nuclear resource if the remaining time on the permit for resource is greater than 5 years.

Property Taxes. Finally, while the EUCG data includes most classes of costs, it does not include property taxes that could be substantially reduced by retiring. Therefore, we estimated the property tax costs and added it to our avoided cost data.

Retirement Costs. In general, retirement costs are not avoidable – suppliers must incur these costs whether they retire in the near term or the long term. Commercial nuclear power facilities in the United States are different than other generators in that they are required to maintain a Nuclear Decommissioning Trust (NDT). Regulations require that sufficient funds be set aside to cover the total cost of decommissioning the facility prior to it being retired. This is important because it can affect the suppliers' economics of remaining in operation or retiring a resource. It should have little effect if the NDT funding is approximately equal to the actual costs of decommissioning, but this may not always be the case.

In cases where decommissioning can be accomplished at a lower cost by the owner or by another company, the excess value of the NDT could provide incentives for accelerated retirement. Some owners have sold nuclear resources along with the NDT to realize any over-funding benefit and eliminate the remaining risk associated with decommissioning. We have not attempted to estimate the effects of these factors on potential retirement incentives of the nuclear resource owners in PJM because we lacked the data necessary and it is beyond the scope of this study.

B. Nuclear Resource Revenues

Nuclear Resources receive revenues from two primary sources: the energy market and the capacity market. Compared to most other types of generators, a much larger share of nuclear resources' revenues are accrued in the energy market because of their relatively low variable operating costs, their high capacity factors, and high output levels. Therefore, factors that raise or lower energy prices have a disproportionately large effect on the net revenues of nuclear resources. To estimate the energy revenues for each resource in PJM, we utilized recent LMP revenues at each units' location and scaled these revenues by the change in forward prices in each future year studied at locations that are mapped to each resource. Section III provides additional discussion of our estimation of the energy revenues for each resource in PJM.

Capacity market revenues are generally a smaller, but significant source of revenues for nuclear resources. It is rational for nuclear resources that intend to remain in operation to accept any clearing price that is higher than the perceived risks of selling capacity and costs of satisfying the capacity obligations. Suppliers that are considering retiring a nuclear resource, however, may offer the resource's avoidable going forward costs of remaining in operation and proceed to retirement if the resource does not clear at that cost level. The PJM capacity market is known as the Reliability Pricing Model (RPM). We use the RPM prices by zone to estimate the capacity market revenues for each nuclear resource. We also include additional income reflecting the expected performance benefits associated with nuclear resource's high expected capacity factors during the shortage events. Because a small number of nuclear resources did not clear in some of the RPM market auctions, we estimated the price that would have prevailed if they had cleared.[2] This is important because it provides a more accurate indication of whether each of the resources may be economic to retire. Section III further describes our estimates of the capacity prices and revenues for each nuclear resource.

Risk to Revenues. Nuclear units face three substantial risks associated with their revenues. First, when they suffer unplanned outages during a reserve shortage event, they are at risk of incurring performance penalties currently priced at $3000 per MWh. Nuclear units are particularly susceptible to such penalties because reserve shortages are likely to be correlated with the units' large outages.

Second, having sold capacity three years ahead in the RPM, an owner of a nuclear unit is at risk of incurring significant costs to buy back its capacity obligation if its unit incurs outages prior to the planning year that cause it to be substantially derated or unavailable. Given the large size of most nuclear resources, the price that would likely prevail after the loss of a nuclear resource to buy back its obligation would be much higher than the initial auction clearing price.

Third, energy price uncertainty and volatility introduce market risks that can be hedged through forward contracting. Such hedging may be imperfect depending on the location of the plant and liquidity of the forward market.

In addition to these risks that could be quantified, we recognize that resource owners will take into account additional risks that vary pursuant to the owners' willingness to take on such financial risks on a three-year forward basis. For purposes of this report, however, NEI requested that we evaluate the viability of the nuclear plants without attempting to quantify and include the costs associated with these various risks. Risks are described in more detail in Section III of this report.

C. Summary of Net Revenue Results

As described above, the decision to retire any resource should be determined by whether the resource's expected revenues exceed its going-forward costs, which includes an acceptable investment return on any required capital expenditures. The following figure compares the revenues and costs of nuclear resources in eastern and western PJM through 2025.

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2 We used the results of a comparable simulation the PJM IMM performed for the 2021/2022 planning year to estimate the prices that would prevail in each zone assuming all nuclear resources cleared the auction. See *Analysis of the 2021/2022 RPM Base Residual Auction: Revised*, Table 46, p. 117 (August 24, 2018).

Figure 1: Costs and Revenues for Nuclear Resources in PJM
2019-2025

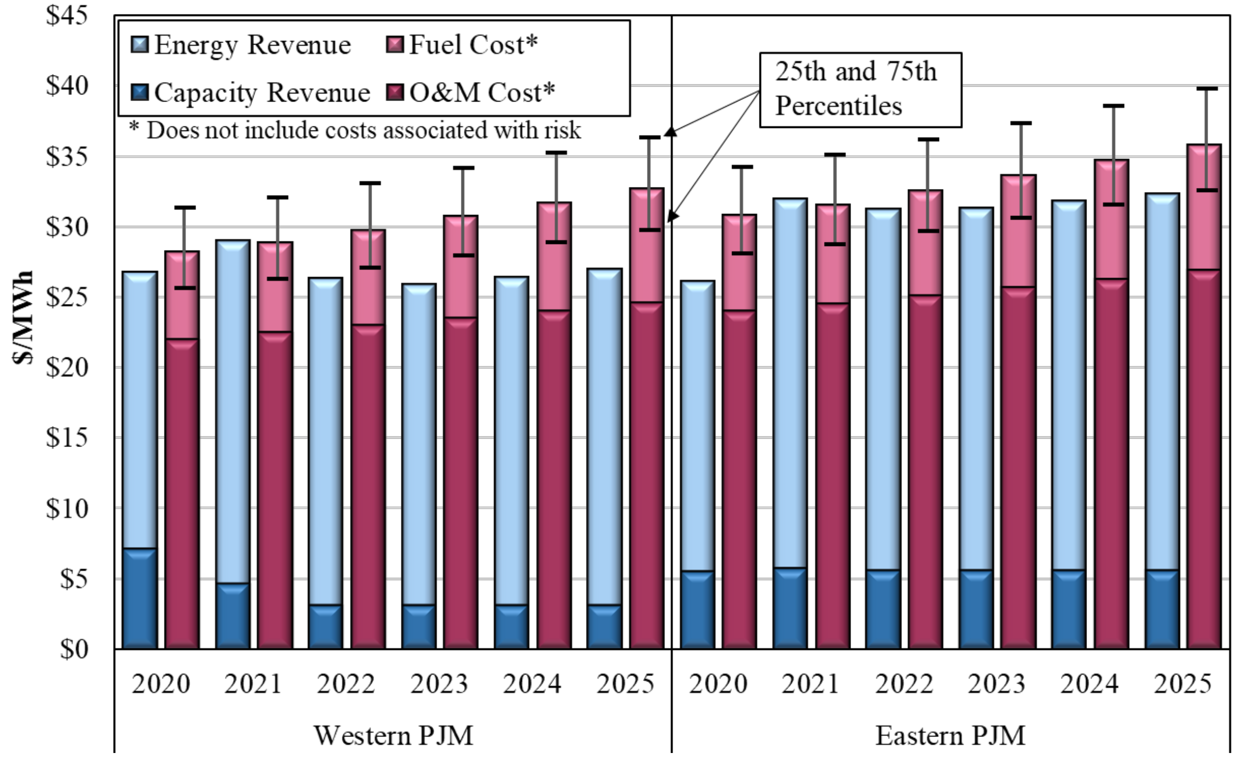


Figure 1 shows that most of the revenues are derived from the PJM energy market as discussed above. Both the energy revenues and capacity revenues have been falling in recent years and hit bottom in 2020 as natural gas prices fell to the lowest levels since the start of the market and COVID has depressed peak load levels. Although capacity revenues will continue to fall, estimated energy prices show a rebound in 2021 from 2020 levels. Hence, average revenues exceed the average going forward costs in 2019 and 2021 in both areas. However, low energy revenues in 2020 and the cost/revenue trends after 2021 show that the nuclear resources' revenues likely will not exceed their average going-forward costs.

This figure also shows the range of going-forward costs for the various units in each region by showing 25th and 75th percentile of these costs.[3] This range shows that units with higher than average going-forward costs likely would not cover these costs in any of the years shown in either region. However, because costs and revenues can vary substantially by unit, it is important to show these results at a unit level. Hence, Figure 2 shows the range of net revenues for the individual units less the units' going-forward costs in western PJM. It shows the units with the lowest and highest net revenues, as well as the average net revenues in each year. The bars assume the mean GFCs for each unit and the error bands show the effects of the 25th and 75th percentile GFCs. Figure 3 shows the same results for the resources in eastern PJM.

3 This includes only the cost data from EUCG.

Figure 2: Net Revenues Less GFCs for Nuclear Resources in Western PJM
2020-2025

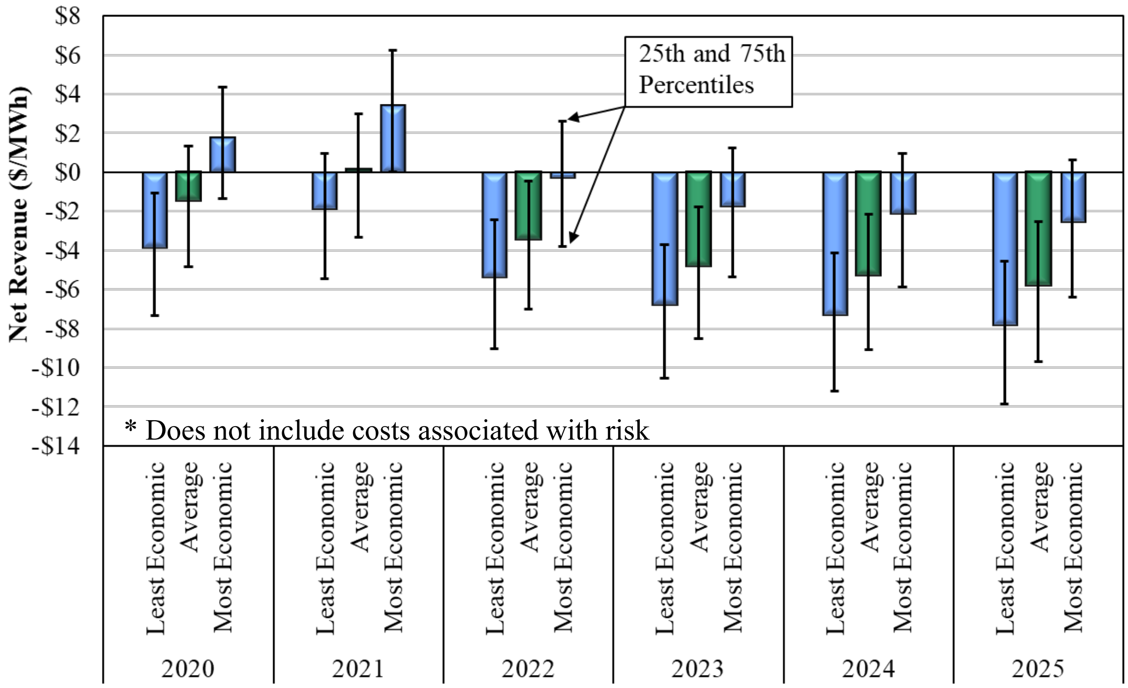
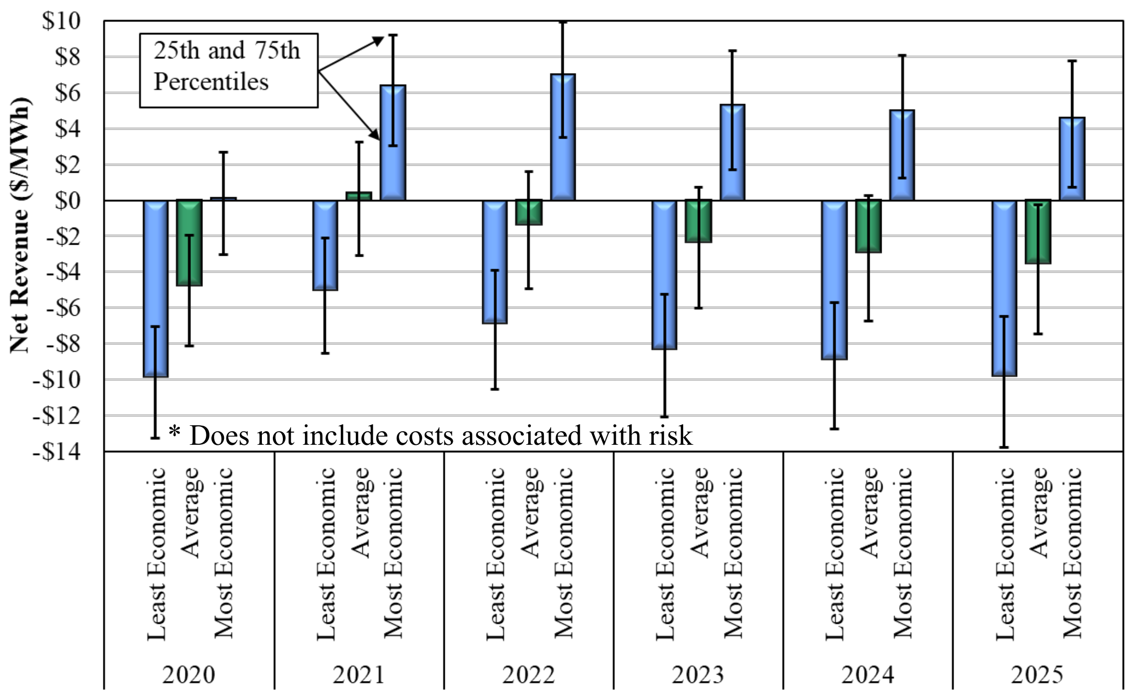


Figure 3: Net Revenues less GFCs for Nuclear Resources in Eastern PJM
2020-2025



This figures both indicate the eroding economics for the nuclear resources from 2020 through 2025. After 2021, none of the resources in western PJM are projected to cover their going-forward costs at the mean unit going-forward cost levels (the bars in the figure). Those with higher than average going-forward costs would exhibit substantially negative revenue position.

Like the units in western PJM, the low prices and load levels in 2020 lead all of the units in eastern PJM to exhibit substantially negative net revenues. Although estimated energy prices in 2021 are more attractive than actual prices in 2020, two thirds of the units in eastern PJM are not projected to cover their costs by 2023 at mean going-forward cost levels. Only one resource would remain economic if they experience higher than average costs (costs that exceed 75 percent of the resources in the region).

These results paint a dim picture for the financial viability of most of the nuclear resources in the PJM region, absent an unexpected rise in natural gas prices that would increase these resources' energy revenues. Those resources with higher than average going-forward costs will likely be under heightened economic pressure to retire.

To the extent that some of the resources proceed to retirement, the economics for the remaining units may increase modestly as capacity prices rise. However, such retirements would not likely restore economic viability in the near-term because they would not increase energy prices substantially because natural gas-fired resources would continue to be marginal in most hours even in light of the retirements. However, to the extent that the markets evolve to better reflect the value of carbon emissions, the economic outlook for the nuclear resources would improve since they emit no carbon dioxide.

III. Nuclear Costs and Revenues in PJM

A. Evaluation of Going Forward Costs by Category

This section of the report provides additional detail on the costs that we evaluated and found to be avoidable when a nuclear resource retires.

Nuclear Fuel Costs

The nuclear fuel costs are only the cost of the uranium fuel, including the costs of activities associated with the procurement, conversion, and enrichment of uranium. Spent fuel storage costs and reimbursements are not included in fuel costs because these costs are an obligation of the US Department of Energy (DOE).[4] Fuel costs are incurred over a significant time span starting with the forward date for fabricating fuel, but once installed in the reactor core, the fuel lasts for a few years before being "spent" and permanently removed. Outages taken for refueling are significant, typically lasting from thirty to fifty days. This is when a range of maintenance activities and upgrades are performed. This timing likely affects the specific date that a nuclear facility would likely retirement, i.e., at the end of a fueling cycle.

For our purposes, we are using regional cost data that is incurred over a three year period which should capture a refueling and maintenance outage for each nuclear unit. The EUCG fuel cost data is reported separately for the east and west regions and is based on the year when it is to be used as opposed to the date of the forward purchase. We allocate the fuel costs among the nuclear units using their installed capacity and the average capacity factor from 2017 through 2019. The fuel costs are escalated using Uranium U3O8 futures prices.

Nuclear fuel costs make up about twenty-two percent of the total nuclear costs in the EUCG data. They are fully avoidable by a retiring plant because the purchase can be avoided by retiring. Any spent fuel storage cost is assumed to be the obligation of the DOE, as discussed above.

Capital Costs

Capital costs are expenditures in plant and equipment that support future operations, in contrast to operating costs that are an expense required for day-to-day operations. To the extent that capital costs are avoidable, they should be included in the going-forward costs. Capital costs reported in the EUCG data are allocated to individual nuclear units based on capacity and other unit characteristics. The following are the key capital cost categories:

4 Under the Nuclear Waste Policy Act of 1982 (NWPA), the Department of Energy collected a fee from nuclear generators to cover the costs of its obligation until the fee was suspended in May 2014 when the development of Yucca Mountain was halted. However, the NWPA is still effect and the fees could be reinstated.

Life Extension Enhancements. Life extension costs are associated with license renewals. The remaining operating license life on the nuclear units in PJM range from four years to thirty-four years. Some of the shorter-term units can continue to operate with a license renewal. Original terms for licenses are 40 years. Most are renewed to 60 years and some are doing a second renewal to 80 years. These costs are relevant for some units, but not others. Nuclear units with more than five years on their license do not have a near-term need for these expenditures, and those that cancelled their license renewal efforts would not have these expenditures. We forecast this as avoidable cost for the other nuclear units because these units would have to be incurring these costs as license renewal approaches if they do not retire.

Uprates Enhancements. Uprates increase the MW capacity. An example is low pressure turbine blade replacement. These costs are not forecasted for a unit that is at the end of its economic life and thus on the brink of retirement. As any unit approaches retirement, it should reflect reduced investments in uprates as that time approaches. While these costs are avoidable, we do not expect there to be significant uprates for units anticipating retirement so we do not include them as avoidable.

Other Enhancements. There are other categories enhancements that include: reliability improvement, operating cost reductions, and outage time shortening. We include these capital costs because they deliver benefits in the short-term and would, therefore, likely be made unless and until the resource owner makes the decision to retire.

Infrastructure. These are cost that are not associated with the power block, such as the roads, parking lots, lighting and buildings needed to house plant personnel. We treat these costs as avoidable in our analysis. To the extent that some of these may continue post retirement, these costs would be part of the decommissioning costs.

Information Technology. These costs are for equipment like computers, software, telecommunications, and related investments. These costs are avoidable by retiring the resource.

Regulatory. These costs are required by regulation and we find that most of them are avoidable. However, we did not include Fukushima Response Costs because this was a one-time cost and not expected to repeat in the future. There is a risk that new categories of regulatory driven capital cost expenditures arise, but we do not attempt to quantify this risk.

Capital Spares. Costs for spares of major equipment such as a reactor coolant pump motor. These costs are avoidable.

Sustaining. Cost for the replacement or refurbishment of major equipment such as a feedwater heater replacement or main generator rewind. These costs are avoidable.

O&M Costs

O&M costs are the operating and maintenance costs which are required for day-to-day operations. They are generally avoidable, but this type of costs includes the non-dedicated costs described below that may not be fully avoidable.

Engineering. The costs of technical work associated with the study, design, implementation of plant modifications. They also include monitoring and testing for compliance with standards. These costs are fully avoidable.

Loss Prevention. The costs for all activities associated with managing access control, providing physical security, managing security and administrative matters, and protecting plant resources and public safety. This includes fire protection, quality assurance and control, corrective action programs, health and safety, licensing and emergency preparedness. These costs are fully avoidable as any ongoing expenses after retirement would come from the NDT.

Materials and Services. The costs of all activities associated with inventory planning, inventory control and optimization, the development of inventory management control policies/procedures, and the identification of unneeded inventory and scrap materials. These costs are fully avoidable.

Fuel Management. These costs include all activities associated with procurement, conversion, and enrichment of uranium but not the cost of the uranium. These cost are avoidable once operations cease.

Operations. These are the costs associated with equipment operations, chemistry and environmental monitoring and controls, radiation protections and radwaste processing, and the disposal cost of low-level waste and effluents. These costs are fully avoidable as any ongoing expenses after retirement would come from the NDT.

Support Services. The costs in this category include payroll taxes, pension and benefits, employee incentive payments, cost of nuclear officers and executives, information technology, business services and human resources. These costs are treated as avoidable since any remaining cost in this area post-retirement would be covered as part of decommissioning.

Training. The costs of all activities associated with the development and conduction of training programs, including instructor preparation and instruction delivery time, production of class materials and the assessment of the training. These costs are avoidable.

Work Management. The costs associated with all activities directly associated with the planned, periodic, and preventive maintenance of structures, systems, components or equipment including planning and scheduling costs. These costs are avoidable.

Property Tax

Data on property tax is not included in the EUCG data. We included site-specific data when we could find it. Otherwise we used a general estimate of $15 million per site year in 2019 dollars, which was a reasonable representative value based on the information we were able to find. Although property taxes would generally continue at a sharply reduced level following retirement, it is likely covered by the NDT, so we treat the entire property tax amount as avoidable.

Non-Dedicated Costs

The most nebulous costs in our review were the "non-dedicated" costs that included costs that would fall as nuclear resource retire, but that are not directly attributable to individual nuclear resources – human resources and IT are examples of such costs included in the EUCG data. The non-dedicated costs were relative minor; about five percent of the total. Some non-dedicated costs are not avoidable because they include an allocation of costs that would remain with the company if their nuclear operations no longer existed. Since we do not have a reliable estimate of how these costs would be affected by resources' retirements, we assume these costs would fall by 50 percent. The results of the analysis, however, are not substantially affected by this assumption given the low level of costs in this category.

B. Revenues in the PJM Markets

Revenues for Nuclear Facilities through the PJM markets include the following:

- Day-ahead energy revenues,
- Capacity market revenues, and
- Incremental energy and ancillary service revenues.

Since nuclear facilities typically run at full output whenever they are available and generally sell their entire output in the day-ahead market, they do not qualify for providing most ancillary services and receive very little revenue from the real-time energy and ancillary services markets. Therefore, our analysis includes only the day-ahead energy market revenues, capacity market revenues, and the reactive power ancillary service revenues.

Historical day-ahead energy market revenues are calculated for the PJM nuclear facilities on a monthly basis as the product of their 2019 ICAP, historical capacity factors, the monthly average day-ahead LMP at their nodes, and the number of hours in the month. We calculate these revenues from January 2017 through May 2020. For the remaining months in 2020, we used the capacity factors based on the average of the associated monthly values from 2017 through 2019. The historical LMP prices extend through June 2020. Energy market revenues for the months after June were calculated by adjusting the previous year's revenue value for that month using future prices. In particular, we create an index value as the ratio of the forward price specific to the zone where each nuclear facility is located and the location's most recent average monthly price. Similarly, for future years we calculate energy market revenues by adjusting the 2019 annual revenues based on the ratio of annual forward price and the 2019 annual average price for the zone. For resources that experienced unusually high capacity factors in 2019, we adjusted the future expected capacity factor to equal the lower of their three-year average capacity factor or 95 percent.

Capacity revenues are calculated for each PJM nuclear resource on an annual basis using the resource's zonal Base Residual Auction (BRA) clearing prices, the ICAP value for the resource as reflected in the BRA, and an outage rate based on the weighted average EFORd for all nuclear units (1.101%). Capacity revenues were calculated through the 2021/2022 planning year. At this time PJM has suspended all auctions after the 2021/2022 planning year, so the last auction results were assumed to prevail into future years. We also included revenues reflecting an estimate of the capacity performance payments nuclear resources would likely receive by virtue of exhibiting relatively high capacity factors during the shortage events. This additional revenue averaged $0.06 per MWh for the nuclear resources.

All units are assumed to have cleared the BRA. An economically rational capacity offer for any supplier considering retirement should reflect the costs that can be saved by retiring the unit. If the capacity market does not cover these costs and the unit does not clear, then it should retire. Any unit that intends to remain in operation should offer as to accept the revenue provided by the capacity market. In this case, the rational capacity offer reflects just the costs of meeting the obligations associated with being a capacity resource and accepting the performance risks. Offers based on these costs would likely have cleared the auctions in the study timeframe.

We understand that some nuclear facilities have not been clearing some auctions and not retiring. Had they offered consistent with the description above and cleared, the clearing prices would have been lower. We estimated and used the lower clearing prices for cases where a retirement announcement did not follow a failure to clear the auction by any of the nuclear resources we studied. This was done using the information in the "Supply Curves for Base Residual Auction" that are posted on the PJM website. However, for the 2021/2022 BRA auction, we used simulated zonal capacity prices produced by the PJM IMM, which are not available for prior auctions.[5]

5 See *Analysis of the 2021/2022 RPM Base Residual Auction: Revised*, Table 46, p. 117 (August 24, 2018).

C. Market and Performance Risks Facing Nuclear Resources

Our analysis of nuclear plant viability in the prior section includes the plants' costs and revenues, but does not include the risks that an asset owner faces in operating a generator. Nuclear resources face a variety of risks that we discuss in this section. In addition to the risk-neutral valuation of the various risks we discuss in this section, we recognize that nuclear resource owners are likely risk averse to some extent. We discuss the effects of this risk aversion on their perception of the magnitude of the risks.

Energy Market Risk

Significant risks exist for owners of nuclear resources associated with both the resources' energy and capacity revenues. With respect to energy revenues, which is the major source of revenue for nuclear units, resources face risk associated with energy price volatility and uncertainty that would motivate resource owners to contract forward to hedge these risks. The costs of hedging such risks are likely higher than forward market prices may suggest for two reasons. First, forward price indices do not capture the bid-ask spread that market participants must cover to close a transaction. Second, the large volumes of energy sold by a nuclear resource owner would affect the forward prices if liquidity is limited.

Performance Risks

Aside from these general energy market risks, there are substantial risks in both the energy and capacity markets for nuclear units associated unplanned outages or equipment failures. One risk relates to incurring performance penalties as a result of experiencing a forced outage during tight market conditions. The other is the risk of having to buy back a resource's capacity obligation as a result of a major outage prior to the planning year.

Energy Performance Risks. Most of the economic value of nuclear resources are captured through its energy production and sales. When a nuclear resource suffers an outage and cannot produce electricity for an extended period, it incurs costs in two ways:

- It will incur liquidated damages associated with its forward sales, having to purchase energy at the prevailing spot price to satisfy the forward contract; and
- It loses the margin it would otherwise have captured between its marginal cost and its forward contract price.

To understand these two costs, consider the following hypothetical. Assume a nuclear resource with a marginal cost of $5 per MWh has sold its energy forward at a price of $20 per MWh. It then suffers an outage and must purchase at a spot price of $26 per MWh to satisfy the forward sale. Before the outage, the owner expected to earn a margin of $15 per MWh ($20 - $5). After the outage, it incurs a loss of $6 ($26 - $20). The total cost of the outage in this case is $21 per

MWh. This is the same loss of spot market revenue that would be incurred if the resource owner does not sell its output forward and simply sells all output at the spot price.

The lost margin of $15 per MWh on the forward sale in this case is fixed and known *ex ante*. Some have referred to this as a cost risk since it occurs because most of the costs are fixed, but the energy revenues are proportional to the resource's output. In reviewing the data for the individual units, it is clear that the capacity factor of the units was an important determinant of the variation in the units' net revenues. Since this risk is asymmetric, a risk averse owner would not likely value this risk based on its unit's average performance.

While the costs per MWh of the lost margin are known in advance, the liquidated damages costs are not known. On an expected value basis, if forward energy prices reflect the expected spot energy prices, the liquidated damages costs should not be large. For example, if a resource owner is buying at spot prices to satisfy the forward contract that are equal to the forward contract price, then the net buy-back cost is zero. The concern of many owners, however, is that the nuclear resource outage may lead to tight market conditions and cause the spot prices to be much higher than the forward prices. Additionally, there is a distribution of potential spot prices that include shortage pricing that would be orders of magnitude higher than the forward price. Therefore, a risk-averse owner would value this risk at a much higher level than a risk-neutral owner, which we discuss later in this section.

Capacity Performance Penalty Risk. A performance hour is an hour of tight system supply when capacity is most needed for meeting load and reserve requirements. When a capacity resource is unavailable during a performance hour, it is penalized based a penalty rate equal to $3000 per MWh. The relatively small number of performance hours reflects the prevailing surplus of capacity in PJM in the near term, but this frequency will likely increase as resources retire and capacity margins fall. If performance hours occur when a nuclear resource is forced out of service or unexpectedly during a maintenance hour, the costs incurred by the nuclear resource owner can be substantial.

Capacity buyback risk. Capacity buyback risk is borne by any nuclear resource that sells capacity three years in advance has a small probability of suffering an outage or derating that causes them to fail to satisfy their capacity obligations. This exposes them to the potential costs of buying back its capacity obligation.

Effects Risk Aversion. Ultimately, many of the costs that may be borne by the owner of a nuclear resource have a wide distribution with a mean that is close to zero. If resource owners are risk averse and require that the costs associated with most potential outcome be covered, its valuation of such risks will be significantly higher than a risk-neutral valuation.

IV. Nuclear Retirements in PJM

The declining net revenues for nuclear facilities that are forecasted in this study are consistent with recent actions of the owners of PJM's nuclear facilities. A number of these owners have noted operating losses and made the decision to retire their resources. Two retirements have occurred in the past two years, which include: Three Mile Island (TMI) Nuclear Station Unit 1 and the Oyster Creek Nuclear Generating Station.

Three Mile Island Nuclear Station. TMI Unit 1 is an 803 MW pressurized water reactor owned by Exelon Generating Co., LLC. Its operating license was issued on April 19, 1974 and then renewed on October 22, 2009. The renewal extended the license to April 19, 2034. However, the owner announced in 2017 that it had been operating at a loss since 2015 so they were considering ceasing operations. Finally, since the economic outlook did not improve, it shut down for retirement on September 20, 2019 with over 14 years left on its operating license.

Oyster Creek Nuclear Generating Station. Oyster Creek was a 608 MW boiling water reactor owned by Exelon Generating Co., LLC. Its operating license was issued on July 2, 1991 and then renewed on June 3, 2009 to expire on April 9, 2029. On September 17, 2018, Exelon announced plans to retire the facility in 2019, citing on the cumulative effect of negative economic factors that had caused Oyster Creek's value to decline. These factors included low market prices and the plant's need for continuing large capital expenditures. Retiring at that time enabled them to avoid installing cooling towers. It retired with 10 years left on its operating license. It was sold to Holtec International in 2018 who accelerated the decommissioning timeline.

In addition to these recent retirements, there have been four additional announced retirements of nuclear facilities scheduled to occur beginning in 2022. The planned closures of the Davis-Besse Nuclear Power Station, and Perry Nuclear Power plant were subsequently rescinded following a contentious law to delay retirement. In August, however, Exelon announced its intention to close the Byron and Dresden Generating Stations in 2021 because of market conditions.

Byron Station. Bryon Units 1 and 2 pressurized water reactors owned by Exelon Generating Co., LLC that are both approximately 1150 MW in size. Unit 1's operating license was issued on February 14, 1985 and expires on October 31, 2044. Bryon Unit 2's operating license was issued on January 30, 1987 and expires on November 6, 2046. Both units were announced to retire with over 23 years left on their operating licenses.

Dresden Nuclear Power Station. Dresden Units 2 and 3 are both roughly 900 MW boiling water reactor owned by Exelon Generating Co., LLC. Unit 2's operating license was issued on February 20, 1991 and then renewed on October 28, 2004. The renewal extended the license to

December 22, 2029. Dresden Unit 3's operating license was issued on January 12, 1971 and then renewed on October 28, 2004. The renewal extended the license to January 12, 2031. Hence, both units were announced to retire with 8 to 10 years left on their operating licenses.

Based on the results shown in this study, other PJM nuclear units are at risk of early retirement due to deteriorating economic conditions and the fact that carbon emissions are not effectively priced in the PJM region. However, some of the PJM states have enacted controversial provisions to provide supplemental compensation to forestall these nuclear resource retirements, including Illinois, New Jersey, and Ohio.

V. CONCLUSIONS

Our analysis in this report provides overall indicators and trends regarding the economic climate facing the nuclear resources in PJM. Although we present unit-specific results in eastern and western PJM, these results are based on aggregated cost data provided by EUCG. The results for any particular resource may vary from our results.

Nonetheless, the analysis shows that the declining energy prices and associated revenues in recent years have substantially reduced all of the nuclear resources' net revenues. As energy prices have fallen to their lowest levels in decades in 2020, we find it unlikely that any of the nuclear resources in PJM are covering their costs. Forward energy prices for 2021 are higher and cause a few of the units to potentially cover their going-forward costs in the near term. Even the owners of these units, however, may deem them uneconomic if they are risk averse and value them at relatively high levels.

Beyond 2021, however, the expected economic results deteriorate. It is unlikely that any but the lowest-cost nuclear units will cover their going-forward costs and be viable to remain in operation. If some of the nuclear resources retire and capacity margins tighten in PJM, energy and capacity prices will likely rise and improve the economic conditions for the remaining nuclear resources. These retirements are uncertain given recent state actions to provide supplemental support for nuclear resources. Nonetheless, absent an increase in natural gas prices that would raise average energy prices in PJM, it is unlikely that the nuclear resources will achieve economic viability in the near term even if some of the resources retire.

The most significant potential development that would improve the economic conditions for nuclear resources would likely be the pricing of carbon emissions in PJM. To the extent that the markets evolve to better reflect the value of carbon emissions, the economic outlook for the nuclear resources would improve since they emit no carbon dioxide.