OPG Nuclear Cost Performance Benchmarking

A Study of Factors Impacting TGC / MWh Performance with Normalizing Adjustments to Facilitate Closer Comparison

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1. BACKGROUND

Context

Pickering Nuclear Generating Station (PNGS) is one of two nuclear stations operated by Ontario Power Generation (OPG). PNGS has six operating units (two additional units ended commercial operations in 1997), a net output of 3,094 megawatts (MW) and produces about 14 percent of Ontario's electricity needs. The site has been operating since 1971.

Darlington Nuclear Generating Station (DNGS) is one of two nuclear stations operated by Ontario Power Generation (OPG). DNGS is a four-unit station with a net output of 3,512 megawatts (MW), and it has been producing almost 20 percent of Ontario's electricity needs since the early 1990s. OPG is performing a major mid-life refurbishment of the four reactors at DNGS (Refurbishment), which involves the replacement of certain life-limiting components. The execution of the Refurbishment "mega-project" started in October 2016 with breaker-open on Unit 2.

OPG tracks and benchmarks the performance of PNGS and DNGS against industry peers under its nuclear cornerstones of Safety, Reliability, Human Performance, and Value for Money. Value for Money is measured relative to an Electric Utility Cost Group (EUCG) panel of nuclear plants in North America using a suite of four cost metrics. One of these metrics, Total Generating Cost per Megawatt-Hour (TGC/MWh), has recently shown DNGS and PNGS ranking below the median relative to the panel.

OPG benchmarks performance in TGC/MWh relative to peers and sets goals for performance each year. Based on operating experience, OPG believes that certain characteristics that cannot be controlled by how well they operate DNGS and PNGS are having a meaningful influence on TGC/MWh performance. ScottMadden agrees that such static characteristics impact performance as measured by TGC/MWh. Thus, OPG asked ScottMadden to perform an independent study to determine whether and how such site characteristics influence TGC/MWh performance for a nuclear plant.

Current TGC/MWh Performance

Using the EUCG data provided by OPG, TGC/MWh performance for the most recent three-year time period (2015-2017) for PNGS and DNGS appear in the fourth quartile relative to the other sites. However, TGC/MWh performance for DNGS must be adjusted to account for the ongoing Refurbishment. ScottMadden provided OPG with a specific methodology for performing this adjustment under a separate study. The result of the adjustment was a relative improvement in TGC/MWh performance for DNGS to the third quartile, as illustrated below.

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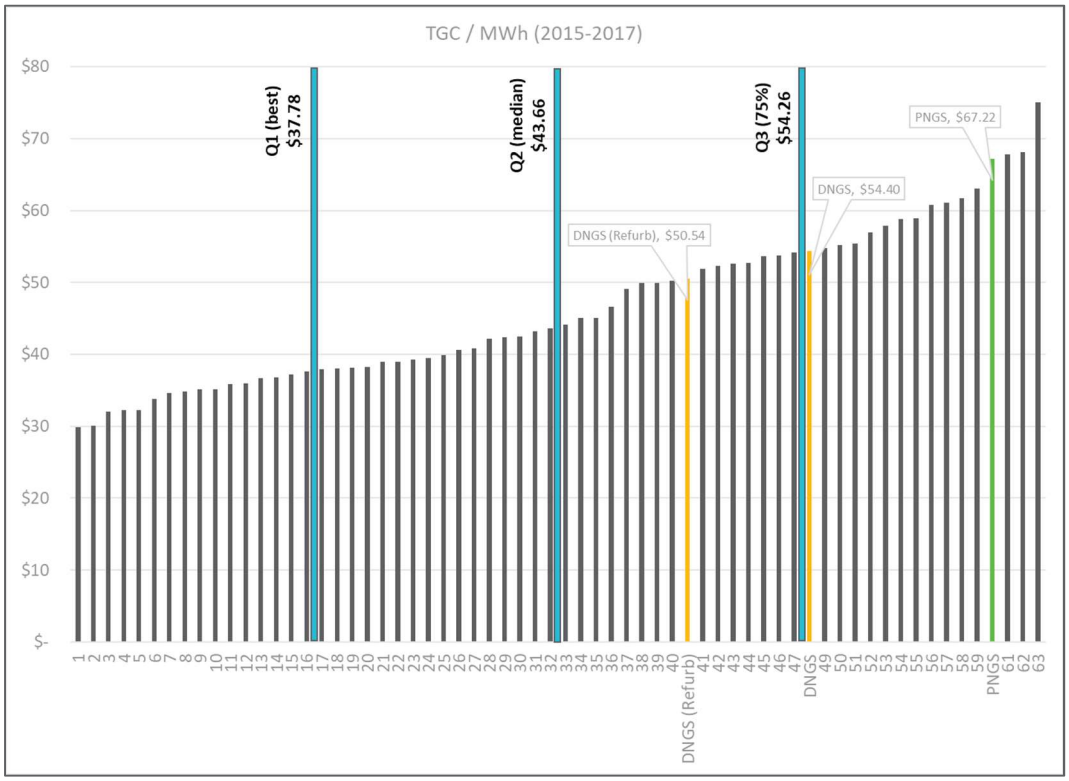
TGC/MWh performance 2015-'17 for EUCG Panel with DNGS Adjusted for Refurbishment



2. ABOUT THE SCOTTMADDEN APPROACH

Scope and Objectives

The ScottMadden study of the influence of site characteristics on TGC/MWh focused on two major areas of investigation:

- **Econometric Analysis** – analysis of EUCG data to understand and quantify the impact of certain site characteristics on total generating cost (TGC)
- **Custom Nuclear Outage Benchmarking Study** – primary research and analysis on nuclear outages across the industry to determine expected impacts on energy production (MWh)

The objectives of this investigation were to 1) determine whether and to what extent relatively static characteristics of a nuclear site influence TGC/MWh performance and 2) if possible, quantify and adjust for these characteristics to produce normalized TGC/MWh values that account for site characteristics that have a significant impact on TGC/MWh performance.

Assumptions and Qualifications

In performing this study and preparing this document, ScottMadden assumes that all EUCG data provided by OPG for this effort and all industry responses to the nuclear outage benchmarking study led by ScottMadden were complete and accurate.

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This ScottMadden report is also subject to the following qualifications:

- ScottMadden does not imply the performance of any additional, specific research beyond what is described in this document.
- ScottMadden does not express an opinion in this document on the effectiveness of management practices at OPG or the appropriateness of any of OPG's costs, outage durations, or other performance characteristics.
- The ScottMadden methodology was prepared for the benefit of OPG and is limited to the subject matter expressly stated in this document; no additional ScottMadden opinion is implied or may be inferred.

3. EXECUTIVE SUMMARY

ScottMadden focused on two major areas of investigation, econometric analysis and a custom nuclear outage benchmarking study.

In the econometric analysis, ScottMadden analyzed nine years of EUCG data (from 2009 to 2017) and 567 data points to understand which site characteristics most influence TGC over a sustained period and to what extent. We used multiple linear regression (MLR) to quantify the relationships between various combinations of reactor type, site capacity, number of units, unit size, and unit age (the independent variables) and the EUCG data for site costs (TGC, the dependent variable). Through this analysis, we were able to develop a powerful predictive model for TGC that explains ~79% of the variability in TGC across the dataset using reactor type, site capacity, and unit age. The model indicates:

- CANDU technology increases predicted TGC by over C$250[1] million per year relative to non-CANDU plants
- Each MW of site capacity increases predicted TGC by C$261 thousand per year
- Each month of average unit age increases predicted TGC by C$346 thousand per year

Once ScottMadden established a mathematically-sound quantification of the impact these site characteristics have on TGC, we adjusted for all sites in the EUCG dataset to account for these factors. However, to be conservative and ensure adjustments were easy to understand, we only performed adjustments for reactor type and unit age.

- The result of these adjustments on TGC/MWh performance was an improvement in relative performance for PNGS from 60th to 51st out of the 63 sites in the EUCG panel.
- DNGS improved from 48th to 31st after performing the same adjustments and also adjusting for refurbishment work, as previously documented and validated.

ScottMadden also initiated a custom nuclear outage benchmarking study to understand better how outage work differs across reactor technologies (BWR, CANDU, and PWR) and operators. The study used a variety of data sources, chief among them a direct survey of nuclear operators, in which

[1] All C$ values in this document are in 2017 dollars, unless otherwise indicated

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responses were confidential and participation was sufficient to represent each of the three reactor technologies (19 CANDU plants, 9 BWR plants, and 19 PWR plants) in the results.

ScottMadden focused only on quantifying and adjusting for the impact of regularly recurring, planned maintenance outages on power generation, taking steps to arrive at an average annual value for days offline due to these planned outages. The output of this exercise is represented in the table below.

Reactor Type	Outage Cycle	Median Average Planned Outage Days Per Year	Incremental Additional Outage Days Per Year Above Shortest Duration
BWR	18-month cycle[2]	Not represented in study	
	24-month cycle	14 days	
PWR	18-month cycle	19 days	5 days
	24-month cycle	14 days	0 days
CANDU	24-month cycle	18 days	4 days
	30-month cycle	36 days	22 days
	36-month cycle	27 days	13 days

ScottMadden adjusted for these outage requirements by normalizing the annual values for MWh of production at each plant. Specifically, if a plant in the dataset had a reactor type and outage cycle combination that, on average, required additional outage days above the shortest duration, we added those incremental additional days back to total production for the year using the site summer capacity[3] at 100% utilization. If a plant had a reactor type and outage cycle combination that did not require additional outage days (i.e., all BWRs and PWRs on 24-month outage cycles), we left total production values unchanged.

- The result of these adjustments on TGC/MWh performance was further improvement in relative performance for PNGS from 51st to 47th out of the 63 sites in the EUCG panel, or third quartile.
- DNGS also further improved from 31st to 29th, or second quartile, after performing the same adjustments.

[2] Of the 63 operators in the EUCG dataset, only two single-unit plants are reported to be on an 18-month maintenance cycle during the 2015-2017 timeframe, and these plants were not represented in our survey of nuclear operators. Thus, for the purposes of this study, we assumed that 18-month cycle BWRs have the same annualized median outage duration as 24-month cycle BWRs.

[3] From the EIA 860 form, retrieved through SNL database, as opposed to nameplate capacity or winter capacity, which are often higher values

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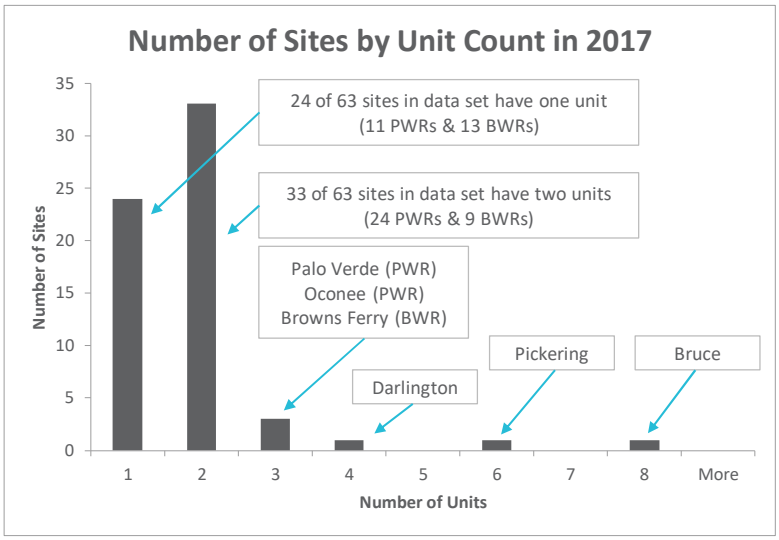
4. ECONOMETRIC ANALYSIS

About the Data

ScottMadden analyzed EUCG data to understand and quantify the impact of certain site characteristics on total generating cost (TGC) and cost performance (TGC/MWh). In this study, ScottMadden analyzed nine years of EUCG data (from 2009 to 2017) to understand which site characteristics most influence TGC over a sustained period and to what extent. The dataset used for this analysis includes:



- 63 nuclear sites and 567 total data points (one / site / year)
- Three reactor types:
  - PWRs – 37 sites
  - BWRs – 23 sites
  - CANDUs – 3 sites
- Nuclear sites with a median capacity of 1,737 MW, median unit capacity of 967 MW, and median average unit age of 397 months (~33 years)[4]
- Primarily sites with either one or two units (57 of 63), but:
  - Three sites (two PWRs and one BWR) with three units
  - One site with four units (CANDU – Darlington)
  - One site with six units (CANDU – Pickering)
  - One site with eight units (CANDU – Bruce)

It is worth noting that there are few CANDU plants in the EUCG data and the technology differs in important ways from the PWR and BWR plants. For example, CANDU plants

- Have greater numbers of smaller capacity units but larger total site capacities
- Have different online and outage maintenance requirements but can be refueled online
- Operate in Canada and are subject to a different regulatory and market environment than PWRs and BWRs operating in the US

ScottMadden used the EUCG data described above to analyze how certain site characteristics influence nuclear site costs. Before performing this analysis, ScottMadden adjusted dollar values for inflation to ensure that we could establish mathematical relationships that persisted across the nine-year dataset. Specifically, we adjusted Total Generating Costs (TGC) from 2009 to 2017 for inflation using the Gross Domestic Product Implicit Price Index Final Domestic Demand (GDP-IPI FDD) in Canada from Statistics Canada, converting all TGC values to 2017 dollars. ScottMadden found this a

[4] This number is not reflective of the current median average unit age of nuclear sites in the panel because average unit age was calculated for each year in the dataset at that specific point in time

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reasonable index to use and favored it over others for this application as it is preferred by the Ontario Energy Board (OEB).[5]

Predictive Model for Total Generating Costs

ScottMadden focused the analysis on characteristics that cannot be controlled by how well a site is operated but are likely to have a meaningful influence on site costs, including:

- Reactor type – CANDU, PWR, or BWR
- Site capacity – total site capacity across all operating units (MW)
- Number of units – total number of operating units at the site
- Unit size – average capacity of the units at the site (MW)
- Unit age – average age of the units at the site (months)

Specifically, ScottMadden used Multiple Linear Regression (MLR) to quantify the relationships between various combinations of the above site characteristics (the independent variables) and the EUCG data for, separately, site costs (TGC) and cost performance (TGC/MWh). While we were unable to develop a sufficiently predictive model for cost performance (TGC/MWh) directly, we were able to develop a powerful predictive model for site costs (TGC).

Our TGC model explains ~79% of the variability in TGC with reactor type, site capacity, and unit age and indicates:

- CANDU technology increases TGC relative to PWR and BWR reactor types
- Greater site capacity increases TGC
- Higher average unit age increases TGC

The specific, mathematical model for site costs in thousands of Canadian dollars (C$k) is: $f(TGC\ per\ year) = (-255{,}421 * (PWR)) + (-283{,}946 * (BWR)) + (261 * (site\ capacity)) + (346 * (unit\ age)) + 302{,}477$. Each coefficient in the formula is the estimated change in TGC corresponding to one unit change in that associated variable when all other variables are held constant. Specifically:

- If the PWR value is 1, indicating it is a PWR reactor, predicted TGC would decrease by C$255,421k (2017); If 0, it will remain unchanged
- If the BWR value is 1, indicating it is a BWR reactor, predicted TGC would decrease by C$283,946k (2017); If 0, it will remain unchanged
- For each MW of site capacity, predicted TGC would increase by C$261k (2017)
- For each month of average unit age, predicted TGC would increase by C$346k (2017)

[5] GDP-IPI FDD is an inflation factor that is commonly-used and frequently referenced by the OEB in multiple documents, including the most recent rate decision for OPG, EB-2016-0152.

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Put more simply, with all other variables held constant:

- CANDU technology increases predicted TGC by over C$250 million per year relative to non-CANDU plants
- Each MW of site capacity increases predicted TGC by C$261 thousand per year
- Each month of average unit age increases predicted TGC by C$346 thousand per year

Once we established a mathematically-sound quantification of the impact these site characteristics have on TGC, we adjusted for all sites in the EUCG data set to account for these factors. However, we only perform adjustments for reactor type and unit age, using the process below.[6]

- Reactor Type – if the reactor is a:
  - BWR, we assign no adjustment value
  - PWR, we assign an adjustment value of ~(28,525) in 2017C$k
  - CANDU, we assign an adjustment value of ~(283,946) in 2017C$k
- Unit Age – For each month of average unit age:
  - Above the median value in the dataset (call this value "a"), we assign an adjustment value of "a" multiplied by ~($346) in 2017C$k
  - Below the median value in the dataset (call this value "b"), we assign an adjustment value of "b" multiplied by ~$346 in 2017C$k
- Inflation – We sum all assigned adjustment values and then, for any year other than 2017, we use the appropriate GDP-IPI FDD value to inflate or deflate the cost adjustment to a value for that specific year

We do not adjust costs for differences in site capacity, despite this being a significant driver of cost, since this would also have required a complex adjustment to generation.[7]

Lastly, to adjust cost for a given year, we use the GDP-IPI FDD to modify the adjustment value to the appropriate year (e.g., to adjust TGC in 2015, we take the TGC impact from the model above, which is in 2017 dollars, modify it to 2015 dollars, and adjust the value for 2015). Finally, we divided the adjusted TGC by actual MWh of generation to get the updated comparison shown in the chart below.

[6] Precise adjustment values were C$(28,525,521.81) / yr for PWR, C$(283,946,104.12) / yr for CANDU, and C$346,088.63 per month of average unit age at the site by a multiple of (median of the average value in months across all sites minus the average value of the specific site in months)

[7] Adjusting for site capacity would follow the logic of other adjustments to cost. In this model, that would mean adjusting costs by ~C$261k per MW per year for each site by a multiple of (median capacity in MW across all sites minus the capacity of the specific site in MW). However, such an adjustment for site capacity would also require that we adjust the MWhs produced by the site in kind. This adjustment would require determination of, for example, the capacity factor to use when determining the change in MWh, further complicating the adjustment and magnifying differences across sites in certain periods. ScottMadden thus felt it more conservative and intuitive to adjust only for technology and age of equipment.

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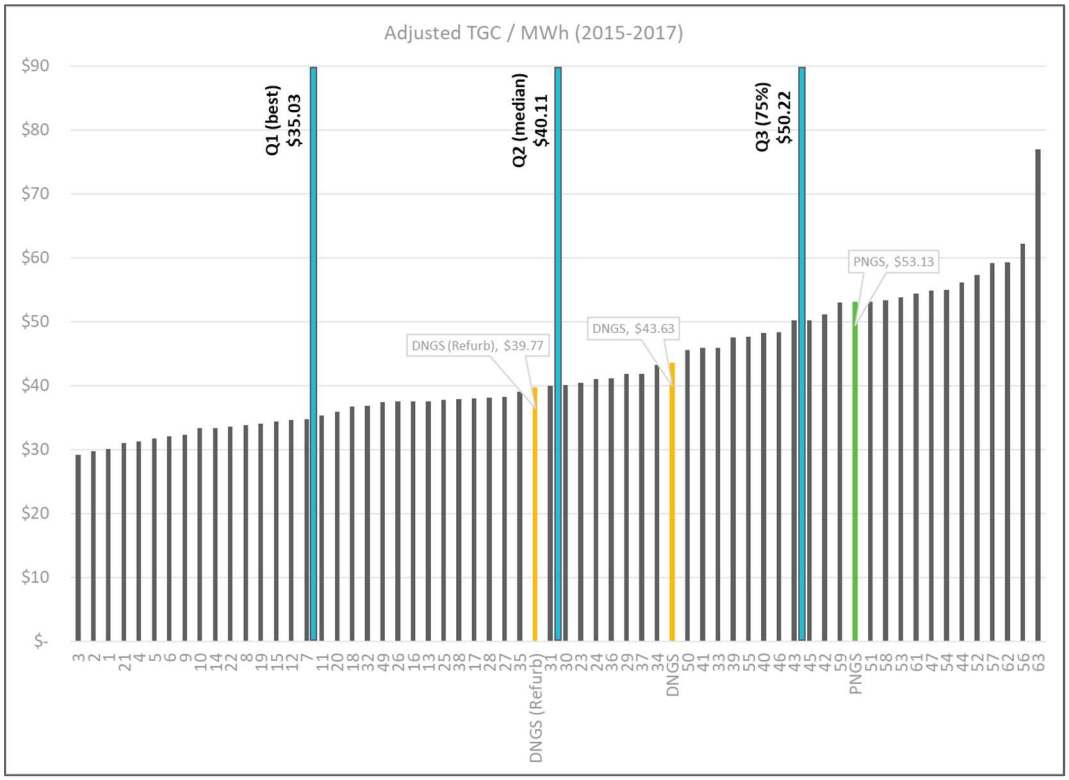
TGC/MWh performance 2015-'17 for EUCG Panel with All Sites Adjusted Based on Econometric Analysis and DNGS Also Adjusted for Refurbishment



By making these adjustments for reactor type and average unit age Pickering's relative performance improves from the 60th to 51st out of the 63 sites in the EUCG panel. Darlington's relative performance improves from 48th to 39th out of the 63 sites in the EUCG panel. Also adjusting for Darlington's refurbishment improves Darlington's relative performance to 31st out of the 63 sites in the EUCG panel.

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5. CUSTOM NUCLEAR OUTAGE BENCHMARKING STUDY

ScottMadden initiated a study of nuclear plant outages on behalf of OPG to better understand how outage work differs across reactor technologies (CANDU, PWR, and BWR) and operators. The study included research of various public and private sources[8], EUCG data provided by OPG, and confidential[9] responses to a custom ScottMadden survey from nine nuclear operators. Participants in the outage survey provided sufficient representation for each of the three reactor technologies and included 19 CANDU plants, 19 PWR plants, and 9 BWR plants. Operators were asked to provide information on:

- The overall refurbishment profile of each unit (including major component replacements, full refurbishments, etc.)
- Historical and future planned outages, including major scope, critical path and near-critical path activities, life-extension work, completion timelines, and costs
- Other, infrequent outages (e.g., vacuum building outages for CANDUs), including scope, schedule, and cost information

While some operators chose not to respond to cost information and other items in the survey, we received robust data on historical and future planned outage scopes and durations. From our various data sources and for this study, we focused on the differences in future planned outage durations across technology types and outage frequencies.

All reactor types have planned maintenance outages on either 18, 24, 30, or 36-month cycles. Planned maintenance outages for PWRs and BWRs are incorporated into refueling cycles and occur every 18 or 24 months. Planned maintenance outages for CANDU reactors occur every 24, 30, or 36 months. Work to significantly extend the operating life of a plant (life-extension activities) is also approached differently across technologies. For PWR and BWR plants, it is more common to complete this work as part of planned refueling and maintenance outages over a series of multiple outages to minimize time in outage. The scope for this work also differs from one plant to the next due to differences in plant design, market construct, and other factors. Comparable life-extension activities for CANDU plants largely occur during very long-duration refurbishment outages where multiple, major plant components are replaced, though some related work can also be incorporated into more frequently recurring planned maintenance outages.

Due to the higher variability and lower frequency of life-extension activities that occur across reactor technologies and operators, ScottMadden focused only on quantifying and adjusting for the impact of recurring, planned maintenance outages on power generation. We took the following steps to arrive at an average annual value for days offline due to these planned outages.

1. We calculated the median planned maintenance outage days for each technology type and maintenance cycle
2. We projected this schedule of outages over a 30-year period, which was the least common multiple in number of years for the different outage cycles, to determine planned maintenance outage days over a long period
3. We annualized these 30-year values into a number of days per year to determine the average annual outage days required for planned maintenance by technology type and outage cycle

[8] Primarily, S&P Global, US Nuclear Regulatory Commission, Ontario Energy Board, and New Brunswick Energy and Utilities Board

[9] ScottMadden acted as the blinding agent for all survey responses so that no participants, including OPG, would be able to view this sensitive data from other operators.

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4. Finally, we calculated the incremental additional annual outage days required for any technology (CANDU, PWR, and BWR) and cycle (18, 24, 30, or 36-month) combination compared to those technologies and cycles requiring the fewest average outage days per year (which were BWRs and PWRs on 24-month cycles)

We represent the output of this exercise in the table below.

Reactor Type	Outage Cycle	Median Average Planned Outage Days Per Year, Annualized	Incremental Additional Annualized Outage Days Per Year Above Shortest Duration
BWR	18-month cycle[10]	Not represented in study	
	24-month cycle	14 days	
PWR	18-month cycle	19 days	5 days
	24-month cycle	14 days	0 days
CANDU	24-month cycle	18 days	4 days
	30-month cycle	36 days	22 days
	36-month cycle	27 days	13 days

To adjust for these outage requirements, we normalized the annual values for MWh of production at each plant. Specifically, if a plant in the dataset had a reactor type and outage cycle combination that, on average, required additional outage days above the shortest duration, we added those incremental additional days back to total production for the year using the site summer capacity[11] at 100% utilization. If a plant had a reactor type and outage cycle combination that did not require additional outage days (i.e., all BWRs and PWRs on 24-month outage cycles), we left total production values unchanged.

Although the median average planned outage durations fall in the range of 14 days to 36 days annually per unit for all reactor types, historical outages between 2015-2019 have shown many outages extending beyond stated planning assumptions, mainly due to discovery or other emergent issues identified by the operator. This indicates that, while operators aim to complete outages on schedule, these planning assumptions have recently proven to be conservative estimates, at least for our purposes.

ScottMadden adjusted the MWh values for all 63 sites from 2015-2017, as described above, to account for the impact of differences in planned outage durations across technology types and outage frequencies. The chart below shows the adjusted TGC values from the econometric analysis divided by the adjusted MWh values from the custom nuclear outage benchmarking study.

[10] Of the 63 operators in the EUCG dataset, only two single-unit plants are reported to be on an 18-month maintenance cycle during the 2015-2017 timeframe, and these plants were not represented in our survey of nuclear operators. Thus, for the purposes of this study, we assumed that 18-month cycle BWRs have the same annualized median outage duration as 24-month cycle BWRs.

[11] From the EIA 860 form, retrieved through SNL database, as opposed to nameplate capacity or winter capacity, which are often higher values

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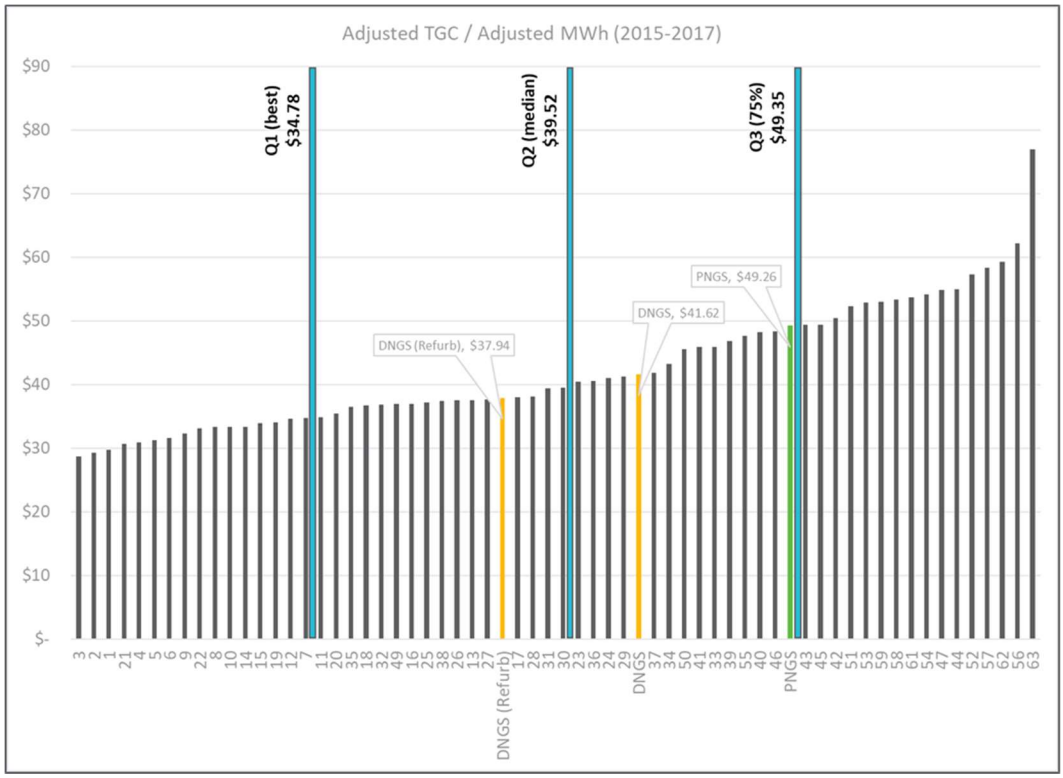
As a result of these adjustments:

- Pickering's relative performance improves further to 47th out of the 63 sites in the EUCG panel or third quartile
- Darlington's relative performance without accounting for Refurbishment improves to 37th out of the 63 sites in the EUCG panel; after accounting for Refurbishment, Darlington's relative performance is 29th out of the 63 sites in the EUCG panel or second quartile

TGC/MWh performance 2015-'17 for EUCG Panel with All Sites Adjusted Based on Econometric Analysis and Outage Study and DNGS Also Adjusted for Refurbishment



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